Aerodynamic Interactions in Vortex Tube Separator Arrays

Adit S. Acharya

Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Aerospace Engineering

K. Todd Lowe, Co-chair
Wing F. Ng, Co-chair
Olivier Coutier-Delgosha
Shane Ross

April 5, 2023
Blacksburg, Virginia

Keywords: Vortex tube separators, engine air-particle separation, cyclone filtration, swirling flow

Copyright 2023, Adit S. Acharya
Aerodynamic Interactions in Vortex Tube Separator Arrays

Adit S. Acharya

(ABSTRACT)

Helicopter turboshaft engines may ingest large amounts of foreign particles (most commonly sand/dust), which can cause significant compressor blade damage and even engine failure. In many helicopters, this issue is mitigated by separating the particles from the intake airstream. An effective device for engine air-particle separation is the vortex tube separator (VTS), which uses centrifugal forces in a vortical flow to radially filter foreign particles from a duct with an annular exit. Dozens or hundreds of these devices are linked together on a shared manifold known as a VTS array. There is a distinct lack of scientific literature regarding these arrays, which likely feature significantly more complex flowfields than singular VTSs due to aerodynamic interactions between the devices. The research presented in this dissertation identifies and explains flow features unique to arrays by means of an experimental investigation downstream of various VTS configurations in a wind tunnel. Mean PIV flowfields reveal that the VTS array rapidly generates a strong central recirculation zone while a single VTS does not, implying the existence of axial flow gradients within associated separators that could affect filtration efficiency. The key factor here is the global swirl intensity, which is increased in array flows due to high angular momentum contributions from separators that are radially distant from the duct center. A preliminary momentum integral model is constructed to predict the onset of recirculation in VTS flows. Analysis is then extended to the unsteady flowfield, where it is shown that VTS-generated turbulence contains only low levels of anisotropy. Spectral proper orthogonal decomposition is conducted on the array flow; it reveals the existence of low-frequency harmonic behavior composed of back-and-forth pumping motions downstream of the central VTS. Additionally, a unique precession motion is found in the same region at a slightly higher frequency. Similar precessing vortex cores have been shown to reduce separation efficiency in other cyclone separators. Both of these coherent structures may be associated with the central recirculation zone and may interfere with VTS array filtration given their timescales relative to potential particle relaxation timescales. This dissertation opens the door for future experimental and computational studies of fluid and particle dynamics in VTS flows with the goal of improving VTS array-specific design philosophies.
Aerodynamic Interactions in Vortex Tube Separator Arrays

Adit S. Acharya

(GENERAL AUDIENCE ABSTRACT)

Vortex tube separators (VTSs) help protect helicopter engines by filtering harmful particles (sand, dust, snow, ash, sea spray, etc.) they would otherwise ingest. This is done by creating a vortex in which centrifugal forces eject particles outwards, separating them from the main airstream. These devices are effective when dozens are grouped together into VTS arrays, but little is understood of the complex air and particle dynamics that result from the many interacting vortices both in and around such arrays. This dissertation describes an early effort to study these aerodynamics and open the door for subsequent particle dynamics research. A laser-based measurement technique called particle image velocimetry is used to determine flow velocities downstream of a VTS array placed in a wind tunnel. When velocities are averaged together over time, they reveal a central recirculation zone (a known feature of intensely swirling flows) downstream of the VTS array that vanishes when only a single separator in the array is active. A mathematical model is developed to predict such recirculation. It demonstrates that a VTS array comprises many separators that are far from the center of the duct they are contained within, and these contribute greatly to the overall swirl intensity. Other data analysis techniques are used to investigate the instantaneous velocity flowfield, which differs significantly from averaged quantities. One such technique is spectral proper orthogonal decomposition, which extracts so-called “coherent structures” from the flow - correlated high-energy motions that exist at certain frequencies and may not be visible in the raw data. This analysis finds two interesting structures at the very center of the duct, possibly associated with the recirculation zone: a back-and-forth pumping motion at a very low frequency (and some of its harmonic frequencies), and a “precessing” (unsteadily rotating) vortex at a slightly higher frequency. These motions, as well as the central recirculation zone itself, are impactful because they may affect the filtration process within the VTS upstream of where they were measured. Such effects will be investigated in future experiments and, if confirmed, may influence the design of VTS arrays.
Acknowledgments

My time at Virginia Tech was defined by many events, from late-night studying to fun conferences to a pandemic that shut down the world. If I truly attempted to acknowledge all the people who gave me their help, support, and friendship during these years, this section would take up the majority of my dissertation. That said, I will do what I can in a few paragraphs.

First I give my heartfelt thanks to my advisors, Dr. Todd Lowe and Dr. Wing Ng, for their encouragement and guidance throughout my Ph.D. Their ability to push me academically while remaining patient and understanding at all times was instrumental in my development as a student and researcher. I will strive to emulate their passion and dedication to fluid dynamics, as well as their leadership skills and technical knowledge, as I attempt to make my own mark on the field. I would also like to thank my other committee members, Dr. Olivier Coutier-Delgosha and Dr. Shane Ross, for their detailed and valuable feedback. Their willingness to spend a great deal of time evaluating and discussing my progress was greatly appreciated. In addition, I am grateful to Dr. William Copenhaver for his guidance when I first began my Ph.D., and Dr. Gwi Bo Byun for never hesitating to assist me in lab. I must also mention TurboLab technician Gregg Perley and APPL machinist Randall Monk - their expertise was essential to the success of my experiments.

I would additionally like to express my gratitude to the Department of Defense and Office of Naval Research for awarding me the National Defense Science and Engineering Graduate (NDSEG) Fellowship. It greatly benefited both my graduate studies and career opportunities, and I am honored to have been selected.

As for my fellow students, I’d first like to acknowledge Aldo Gargiulo, Kris Olshefski, and Dhruv Apte, who formed the “No Stupid Questions” (NSQ) discussion group with me. Our countless conversations ignited my curiosity and deepened my technical knowledge of fluid dynamics as much as my coursework. I am the researcher I am today because of NSQ, and I was glad to become friends with them along the way as well. I also received much help and friendship from many others in the department, including Sean Powers, Jeremiah
Whelchel, Vidya Vishwanathan, Chi Moon, Ashley Saltzman, Dennis Marquis, and Cairen Miranda. Thanks also goes to undergraduate researchers Jubel Kurian and Pranay Patel for their assistance and for taking on the mantle of vortex tube separator work once I step away.

Last but not least, I’d like to mention those in my personal life who have been instrumental to my success in graduate school. My girlfriend Lauren O’Connor has been nothing but encouraging and supportive throughout my entire time at Virginia Tech while we both pursue our own Ph.D.s at separate institutions, hours apart from each other, balancing busy schedules and exhausting travel. My undergraduate friends from Bucknell University stayed close with me over great distances and through the pandemic. R.G. - y’all know who you are. Lastly, I am grateful to my parents, Prathima and Sudhi Acharya, who have given me unwavering love and encouragement from North Carolina for my entire education - and plenty of delicious homecooked Indian food that was very much appreciated. Thanks also goes to the rest of my family for their support - especially my Thatha, who I hope would be proud of this dissertation.
Contents

List of Figures ix

List of Tables xv

1 Introduction 1

1.1 Structure and Content 2
1.2 Attributions 3
1.3 Achievements 3
1.4 List of Publications 4

2 Review of Literature 6

2.1 Engine Air Particle Separation 6

2.1.1 Inlet Barrier Filters 6
2.1.2 Inertial Particle Separators 7
2.1.3 Vortex Tube Separators 7

2.2 VTS Filtration Theory 10

2.2.1 Assumptions 10
2.2.2 Force Balance and Equilibrium Radius 12
2.2.3 Filtration Parameters 13
2.2.4 Pressure Drop 15

2.3 Design of Vortex Tube Separators 17

2.3.1 The Individual VTS 18
2.3.2 VTS Arrays 20

2.4 VTS Scientific Studies 25

2.5 The Array Problem 28

2.6 VTS Scaling 33
3 Mean Flow Characteristics Downstream of a Vortex Tube Separator Array

3.1 Introduction

3.2 Experimental Methods
   3.2.1 Wind Tunnel Facility
   3.2.2 Scaled VTS Array Model
   3.2.3 Particle Image Velocimetry

3.3 Experimental Results and Discussion
   3.3.1 Centerline Data
   3.3.2 Planar Data
   3.3.3 Central Recirculation Zone Literature

3.4 Momentum Integral Model
   3.4.1 Mathematical Construction
   3.4.2 Model Results and Discussion

3.5 Conclusions

4 Turbulence and Coherent Motions Downstream of a Vortex Tube Separator Array

4.1 Introduction

4.2 Experimental Methods
   4.2.1 Wind Tunnel Facility
   4.2.2 VTS Array Model
   4.2.3 Particle Image Velocimetry
   4.2.4 Spectral Proper Orthogonal Decomposition

4.3 Results and Discussion
   4.3.1 Mean Velocity Data
   4.3.2 Central Recirculation and Swirl Intensity
   4.3.3 Turbulence Statistics
4.3.4 SPOD Results .................................................. 109
4.3.5 Coherent Motion Discussion ................................. 113
4.4 Conclusions ....................................................... 116

5 Conclusions and Outlook ........................................ 122
  5.1 Conclusions ..................................................... 122
  5.2 Outlook ........................................................ 123

Appendices .......................................................... 125

Appendix A Efforts to Support Numerical Simulations .......... 126

Appendix B Fluorescent Particle Image Velocimetry using Atomized Liquid Particles ........................................ 130
  B.1 Introduction ..................................................... 131
  B.2 Experimental Methods .......................................... 132
  B.3 Results .......................................................... 134
    B.3.1 Particle Sizes ............................................. 134
    B.3.2 PIV Imaging ............................................... 135
    B.3.3 Boundary Layer Comparisons ............................. 136
  B.4 Conclusions ..................................................... 138
List of Figures

2.1 Simple schematic of a single vortex tube separator (transparent side view). 8

2.2 Side-views (top row) and top-views (bottom row) of a tangential counterflow separator (left), an axial counterflow separator (middle), and a vortex tube separator (right). Intake air, exhaust air, general chamber streamlines, and dust pathlines also provided. Adapted from Dziubak et al. [11]. 9

2.3 Diagram of an individual VTS, adapted from Pall’s 1968 patent [1] and with major components labeled. 18

2.4 Diagram of an individual VTS, adapted from Pall’s 1969 patent [20] and with alphabetical labels added for all relevant dimensions (see Table 2.1). 20

2.5 Side-view diagram of a VTS array, adapted from Pall’s 1968 patent [1] and with cutaways on each side to show individual VTSs within. Modified to include labels for major components. 21

2.6 Front-view cross-sectional diagram of a VTS array, adapted from Pall’s 1968 patent [1] and modified to include labels for major components. 22

2.7 Front-view (flow into page) picture of a Pall™ Centrisep™ VTS array used for Hughes™ 369 helicopters. 24

2.8 Picture of a Centrisep™ VTS array used for Bell™ 206 helicopters. 24

2.9 Diagram of PIV experimental setup by Pillei et al. [28] to study gas flow in the separation region of an individual VTS. 26

2.10 Diagram of a VTS array (“uniflow multicyclone”) used in the study by Muschelknautz [33]; side view cross-section (top) and front view facing inlets (bottom). 29

2.11 Experimental dye visualizations of two co-rotating vortices: (a) before; (b) during, and; (c) after merger [37]. 30

2.12 Experimentally measured planar velocity vectors in the flow downstream of a combustion swirler array; 3 mm downstream (top left), 13 mm downstream (top right), and 63 mm downstream (bottom). Adapted from Cai et al. [41, 42]. 31

2.13 Streamlines in a combustion swirler flow with a central recirculation zone and other swirling jet features. Adapted from Huang and Yeng [44]. 33

2.14 $St_{50}$ vs. $Re$ using cyclone inlet velocities, experimentally determined for a range of cyclone separators. Adapted from Overcamp and Scarlett [57]. 36
3.1 Simple schematic of a single vortex tube separator (transparent side view).

3.2 Diagram of a VTS array, with cutouts showing two individual separators within, adapted and modified from Pall’s 1970 patent [1].

3.3 Picture of Pall™ Centrisep VTS array; each black circle is an individual VTS.

3.4 Top-view schematic of High-Speed Wind Tunnel as configured for VTS array model experiments (not to scale).

3.5 Diagram of singular VTS (adapted from [6]), with labels corresponding to Table 1.

3.6 Diagram of VTS array model from a forward-looking-aft orientation. The seven separators are arranged in a staggered pattern, as on real VTS arrays.

3.7 Diagram of VTS array model upstream and downstream sections; angled view of singular VTS (top), independent upstream and downstream sections (bottom left), and conjoined upstream and downstream sections (bottom right). A = helical vane region, B = separation region, and C = clean air exit of one of the separators.

3.8 Diagram of VTS array model aluminum housing/scavenge chamber; housing alone (left) and fully assembled VTS array model (right).

3.9 Diagram of VTS array model cover plates; plates separated (left) and attached to VTS array model, producing "1-VTS" case (right).

3.10 Picture of fully assembled VTS array model; 7-VTS configuration (left), and 1-VTS configuration (right).

3.11 Side-view schematic of HSWT test section, including VTS array and PIV measurement planes A, B, and C.

3.12 Picture of PIV setup to measure flow downstream of VTS array.

3.13 Polar coordinate system for velocity data, aft-looking-forward into the VTS outlets.

3.14 Mean velocity data across duct centerline at Plane C for both 5-hole probe and PIV experiments. 95% confidence interval error bars shown for every fifth PIV data point.

3.15 Mean PIV velocity data across duct centerline at Plane C (1.77D_{VTS}) with 95% confidence interval error bars; 7-VTS case (left), and 1-VTS case (right).

3.16 Mean planar velocity heatmaps and vectors for the 7-VTS configuration; Plane A (left), Plane B (middle), and Plane C (right).
3.17 Mean planar velocity heatmaps and vectors for the 1-VTS configuration; Plane A (left), Plane B (middle), and Plane C (right). .......................... 63

3.18 Mean circumferential velocity data for the 7-VTS configuration with upstream VTS outlet locations overlaid; Plane A (left), Plane B (middle), and Plane C (right). .......................... 64

3.19 Mean circumferential velocity data for the 1-VTS configuration with upstream VTS outlet location overlaid; Plane A (left), Plane B (middle), and Plane C (right). .......................... 64

3.20 Mean radial velocity data for the 7-VTS configuration with upstream VTS outlet locations overlaid; Plane A (left), Plane B (middle), and Plane C (right). 65

3.21 Mean radial velocity data for the 1-VTS configuration with upstream VTS outlet location overlaid; Plane A (left), Plane B (middle), and Plane C (right). 65

3.22 Mean axial velocity data for the 7-VTS configuration; Plane A (left), Plane B (middle), and Plane C (right). .......................... 66

3.23 Mean axial velocity data for the 7-VTS configuration; Plane A (left), Plane B (middle), and Plane C (right). .......................... 66

3.24 Simple schematic of a CRZ in a swirling flow with a sudden expansion. Axial flow streamlines are shown as blue arrows, circumferential flow streamlines are shown as gray arrows (inlet only), and the recirculation zone is bounded by an orange dashed line. .......................... 67

3.25 Schematic of CRZ formation downstream of a VTS array. Axial flow streamlines are shown as blue arrows, circumferential flow streamlines are shown as gray arrows (inlets only), and the recirculation zone is bounded by an orange dashed line. .......................... 68

3.26 1-VTS axial velocity (normalized on centerline velocity) plotted against radial position (normalized on jet half-width) for Planes A and B. .......................... 69

3.27 Cross-section of 1-VTS outlet and downstream duct, where the dashed black line marks the duct centerline. $V_Z$ (red) and $V_\theta$ (green) profiles presented at Stations 1 and 2; blue line marks 0 velocity. .......................... 72

3.28 Cross-section of 7-VTS outlet and downstream duct, where the dashed black line marks the duct centerline. $V_Z$ (red) and $V_\theta$ (green) profiles presented at Stations 1 and 2; blue line marks 0 velocity. .......................... 74

3.29 Critical global swirl number at Station 1 to induce recirculation for 7-VTS and 1-VTS cases. PIV-computed global swirl numbers at PIV Plane A overlaid; solid black line (7-VTS) and dashed black line (1-VTS). .......................... 76
4.1 Simple schematic of a single vortex tube separator (transparent side view). 84

4.2 Side-view diagram of a single vortex tube separator adapted and modified from Pall’s 1969 patent [11]. 85

4.3 Diagram of a VTS array, with cutouts showing two individual separators within, adapted and modified from Pall’s 1970 patent [1]. 86

4.4 Picture of Pall™ Centrisep VTS array; each black circle is an individual VTS. 86

4.5 Top-view schematic of High-Speed Wind Tunnel as configured for VTS array model experiments (not to scale). 89

4.6 Diagram of singular VTS (adapted and modified from [11]), with labels corresponding to Table 1. 90

4.7 Diagram of VTS array model from a forward-looking-aft orientation. The seven separators are arranged in a staggered pattern, as on real VTS arrays. 91

4.8 Diagram of VTS array model upstream and downstream sections; angled view of singular VTS (top), independent upstream and downstream sections (bottom left), and conjoined upstream and downstream sections (bottom right). A = helical vane region, B = separation region, and C = clean air exit of one of the separators. 92

4.9 Diagram of VTS array model aluminum housing/scavenge chamber; housing alone (left) and fully assembled VTS array model (right). 92

4.10 Diagram of VTS array model in 1-VTS configuration through use of cover plates; 1-VTS central configuration (left), and 1-VTS non-central configuration (right). 93

4.11 Side-view schematic of HSWT test section, including VTS array model and PIV measurement plane. 95

4.12 Polar coordinate system used for velocity data, aft-looking-forward into the VTS outlets. 98

4.13 Mean planar velocity heatmap and vectors at the plane $0.23D_{VTS}$ downstream of VTS outlets; 7-VTS configuration (left), 1-VTS central configuration (center), and 1-VTS non-central configuration (right). 99

4.14 Mean radial velocity contours at the plane $0.23D_{VTS}$ downstream of VTS outlets, with separator locations overlaid; 7-VTS configuration (left), 1-VTS central configuration (center), and 1-VTS non-central configuration (right). 100
4.15 Mean circumferential velocity contours at the plane $0.23D_{VTS}$ downstream of VTS outlets, with separator locations overlaid; 7-VTS configuration (left), 1-VTS central configuration (center), and 1-VTS non-central configuration (right).......................... 100

4.16 Mean axial velocity contours at the plane $0.23D_{VTS}$ downstream of VTS outlets, with separator locations overlaid; 7-VTS configuration (left), 1-VTS central configuration (center), and 1-VTS non-central configuration (right) . 101

4.17 Normal Reynolds stresses across duct centerline for 7-VTS, 1C-VTS, and 1NC-VTS configurations; radial stresses (top), circumferential stresses (middle), and axial stresses (bottom). 95% confidence interval error bars shown for every third data point. .................................................. 105

4.18 Shear Reynolds stresses across duct centerline for 7-VTS, 1C-VTS, and 1NC-VTS configurations; radial-circumferential stresses (top), radial-axial stresses (middle), and circumferential-axial stresses (bottom). 95% confidence interval error bars shown for every third data point. .................................................. 106

4.19 Lumley triangle showing turbulence state of centerline data for all three VTS configurations. ......................................................................................................................... 108

4.20 Visualization of SPOD mode energy at each Strouhal number for all three velocity components; radial velocity fluctuations (left), circumferential velocity fluctuations (middle), and axial velocity fluctuations (right). The first eigenvalue represents the highest-energy mode, and higher eigenvalues represent lower-energy modes. .................................................. 110

4.21 Heatmap of SPOD energy content for each mode across all analyzed Strouhal numbers (axial velocity component). Orange dashed line indicates number of modes required to capture 50% of total energy, and orange solid line indicates number of modes required to capture 90% of total energy. .................. 110

4.22 First SPOD mode contours (axial) and vectors (planar), shown across four phases, at $Str = 1.5 \times 10^{-1}$. Red contours represent positive values and blue contours represent negative values. .................................................. 112

4.23 First SPOD mode contours (axial) and vectors (planar), shown across four phases, at $Str = 9.8 \times 10^{-3}$. Red contours represent positive values and blue contours represent negative values. .................................................. 113

4.24 First SPOD mode contours (axial) and vectors (planar), shown across four phases, at $Str = 1.8 \times 10^{-2}$. Red contours represent positive values and blue contours represent negative values. .................................................. 114
4.25 First SPOD mode contours (axial) and vectors (planar), shown across four phases, at \( Str = 2.6 \times 10^{-2} \). Red contours represent positive values and blue contours represent negative values.

A.1 Schematic showing locations of boundary condition and validation measurements upstream and downstream of VTS array model.

A.2 Velocity components across the centerline of the duct 17.78 cm upstream of VTS inlets, as measured by the 5-hole probe.

A.3 Velocity components across the centerline of the duct 7.62 cm downstream of VTS outlets, as measured by the 5-hole probe.

B.1 Schematic of Venturi seeding method for a high-pressure nozzle [22].

B.2 SBL wind tunnel PIV experiment setup (not to scale), side and top views; red dashed square indicates camera field of view.

B.3 Histogram of aerodynamics diameters of particles collected by TSI 3321 spectrometer.

B.4 Example raw PIV images for select region upstream of forward-facing step (X/h = 0); tunnel wall (Y/h = 0) highlighted with blue line.

B.5 Background signal profiles from laser flare (no particles present), approaching the acrylic wall at X/h = −1.

B.6 Boundary layer profiles for all four cases far upstream of step (symbols not shown above \( y^+ = 13 \)); Spalding profile shown for comparison.

B.7 Normalized Reynolds stress comparison between data from de Graaff and Eaton [33] at \( Re_\theta = 5200 \) and fluorescent PIV (\( 1.0 \times 10^{-2} \) mol l\(^{-1} \)) at \( Re_\theta = 5900 \). Fluorescent PIV symbols not shown above \( y^+ = 50 \).

B.8 Boundary layer development across the adverse pressure gradient approaching the step; Spalding profile shown for comparison.

B.9 Skin friction coefficients for all PIV cases upstream of the step.
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>VTS geometric parameters corresponding to Figure 2.4, as presented in Pall’s 1969 patent [20].</td>
<td>20</td>
</tr>
<tr>
<td>3.1</td>
<td>VTS array model dimensions corresponding to Figure 5.</td>
<td>52</td>
</tr>
<tr>
<td>4.1</td>
<td>VTS array model dimensions corresponding to Figure 6.</td>
<td>90</td>
</tr>
<tr>
<td>B.1</td>
<td>SBL wind tunnel flow parameters.</td>
<td>133</td>
</tr>
<tr>
<td>B.2</td>
<td>Statistical data for diameters of particles collected by TSI APS.</td>
<td>135</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Standard helicopters are driven by turboshaft engines that require high flow rates of air to sustain internal combustion. In certain environments, near-ground operation of these helicopters can stir up large amounts of foreign particles that are then ingested into the engine. This is a common occurrence with sand and dust; larger helicopters have been known to ingest 2-4 pounds of dirt per minute when close to the ground in sandy areas [1], potentially leading to engine failure or shortened engine lifespans [2]. Other types of foreign particles that may be similarly ingested include volcanic ash, snow/ice, and sea spray. A study by Potts [3] compiled reports of U.S. helicopter engines affected by sand ingestion. Many found that significant compressor blade erosion had occurred, sometimes in as little as 20 hours of operation in dusty environments. At one U.S. Army base, helicopter engine overhauls were required five times as frequently as planned, mostly due to engine erosion. Thus, there has long existed a clear need for particle filtration systems on helicopter engine inlets.

Various forms of engine air particle separators (EAPS) have been implemented on helicopters to address this need. One such device is the vortex tube separator (VTS), which has shown promise for combining high separation efficiency with minimal pressure drop [4]. However, the literature is limited to design patents and studies on the effects of geometric variations on VTS performance. There is a distinct lack of literature on observing and understanding the physical phenomena occurring within VTS systems that drive their performance. Additionally, almost all relevant studies have focused on individual separators, despite the fact that in practice VTSs are generally grouped in arrays of dozens or hundreds of separators on a single manifold with a common surrounding plenum. It is likely that the interactions between multiple separators and the presence of the surrounding plenum generate highly complex fluid and particle dynamical behaviors that significantly impact VTS performance.

The present dissertation describes an experimental investigation of the physical flow phe-
nomena occurring within and downstream of a vortex tube separator array. This research adds to the current understanding of these devices by being the first to study array-specific phenomena in detail. In doing so, it makes additional contributions to the more general fields of cyclone filtration and swirling flows. This work is intended to open the door to subsequent experimental and computational research on inertial particle dynamics in VTS array configurations.

1.1 Structure and Content

Chapter 1: Introduction to the topics, contributions, and achievements of the present dissertation.

Chapter 2: Review of the literature relevant to VTS flows, with emphasis on the gaps addressed by the present dissertation.

Chapter 3: Peer-reviewed research paper undergoing revisions for publication in AIAA Journal entitled, “Mean Flow Characteristics Downstream of a Vortex Tube Separator Array”. Presents key findings from the mean flow relating to interactions between separators and develops a simple mathematical model to explain these findings.

Chapter 4: Future peer-reviewed research paper to be submitted to Experiments in Fluids entitled, “Turbulence and Coherent Motions Downstream of a Vortex Tube Separator Array”. Builds on Chapter 3 by using turbulence statistics and spectral proper orthogonal decomposition (SPOD) to analyze the highly unsteady VTS array flowfield. Identifies unique coherent motions that may impact filtration.

Chapter 5: Summary and conclusions from the present dissertation, including a description of ongoing and future work.

Appendix: Additional contributions to support future computational and experimental research on VTS arrays. Includes information on VTS geometry and boundary conditions, followed by a peer-reviewed research paper published in Measurement Science and Technology entitled, “Fluorescent Particle Image Velocimetry using Atomized Liquid Particles”.

The formatting and content style of Chapters 3 and 4, as well as the Appendix, vary due to the standards of the journals in which they are or will be published.
1.2 Attributions

The research presented in this dissertation was planned and conducted under the guidance of the two co-chairs of the Ph.D. degree committee.

Dr. K. Todd Lowe serves as the primary advisor and committee co-chair for the creation of the present dissertation. He supervised and provided extensive feedback on the planning, data acquisition, data analysis, and writing involved. Additionally, he acquired funding that partially supported this project in partnership with Dr. Ng.

Dr. Wing F. Ng serves as the co-advisor and committee co-chair for the creation of the present dissertation. He provided considerable guidance for the planning, data acquisition, data analysis, and writing involved. Additionally, he acquired funding that partially supported this project in partnership with Dr. Lowe.

Jubel Kurian is a fellow student who provided assistance and is a co-author on the work presented in Chapter 4.

The National Defense Science and Engineering Graduate (NDSEG) Fellowship was awarded to the author of this dissertation, providing the financial means to pursue research relevant to the interests of the U.S. Department of Defense.

1.3 Achievements

The major accomplishments of this dissertation are as follows:

- The first known scientific investigation of the fluid dynamics within and/or around a vortex tube separator array. It is shown that, as predicted, a VTS array flowfield differs significantly from its single-VTS counterpart both in mean flow and fluctuating flow characteristics.

- The identification of a downstream central recirculation zone that is unique to VTS arrays and is not found in single-VTS flow. This is significant because it implies the presence of axial flow gradients that extend upstream into affected vortex tube separators, potentially reducing separation efficiency.
CHAPTER 1. INTRODUCTION

- The development of a new early-stage momentum integral model to predict the onset of recirculation in a VTS array flow. While further refinement and validation is required, the model can be used to show the exclusivity of the central recirculation zone to the VTS array flow under certain conditions. Analysis reveals the mathematical reason for this phenomenon: the disproportionate contribution to angular momentum by VTS outlets that are radially distant from the duct center, which do not exist in single-VTS flows. This finding can theoretically be extended to much larger VTS arrays with many layers of separators, provided the array has a similar shape to the one used here and that separator outlets are all in close proximity to each other.

- The extraction of unique coherent motions from the instantaneous flowfield using spectral proper orthogonal decomposition on a dataset of nearly 100,000 samples. A precessing vortex core is revealed, which has been known to interfere with filtration in other types of cyclone separators. Additionally, a back-and-forth pumping motion is identified at a very low fundamental frequency and its higher harmonics. To the author’s knowledge, this is the first observation of such a structure in a cyclone separator or swirling jet flow. It may also impact filtration due to its lengthy timescales. Both the precessing vortex core and pumping motions may be linked to the central recirculation zone, as they occurred at the center of the duct.

- The enabling of future useful computational and experimental studies of vortex tube separator arrays. Detailed geometry information has been provided, along with measured boundary conditions, to support numerical simulations of the VTS array flow. Additionally, an advancement in measurement technology using fluorescent tracer particles will allow for the simultaneous measurement of the fluid and inertial particles, which may be important in future VTS studies that attempt to link observed fluid dynamics to the particle dynamics.

1.4 List of Publications

This list contains all scientific publications associated with the author to this date, including those whose results are not presented in the current dissertation.
1.4. List of Publications

Peer-Reviewed Journal Publications


- **Acharya, A. S.**, Kurian, J., Lowe, K. T., and Ng, W. F., “Turbulence and Coherent Motions Downstream of a Vortex Tube Separator Array” (to be submitted to *Experiments in Fluids*).

Conference Proceedings


Chapter 2

Review of Literature

2.1 Engine Air Particle Separation

Turboshift particle separating systems generally fall into one of three major categories, as described by Filippone and Bojdo [4]: inlet barrier filtration (IBF), inertial particle separation (IPS), and vortex tube separation. These filter types vary in physical design as well as their principles of operation, though all have demonstrated the ability to separate foreign particles from an engine intake. However, all EAPS systems also incur a performance penalty on their engines due to a pressure drop. In evaluating the effectiveness of an EAPS system, both the particle separation and the performance penalty must be considered.

2.1.1 Inlet Barrier Filters

Inlet barrier filtration involves the use of porous screens to physically block particulate matter from entering the engine. An example of an IBF is provided in the patent by Scimone [5]. The body of an IBF is typically composed of woven fabric folded into a series of pleats and held firm through adherence to wire meshes. Particles in an engine’s intake airstream collide with the screen material – provided they are large enough in diameter – whereas air is allowed through and into the engine.

The dissertation by Bojdo [6], part of a series of several comparative EAPS studies by Bojdo and Filippone, notes that IBFs operate with remarkably high particle separation efficiencies (>99% for Arizona AC Coarse test dust). However, this advantage is offset by serious performance penalties that grow with operation time. Particles separated by the IBF may be embedded into the porous screen, disrupting intake air streamlines and reducing the area of intake streamtubes. This leads to a drop in the pressure differential the engine imposes to ingest surrounding air, forcing the engine to operate at lower power than it otherwise would.
2.1. ENGINE AIR PARTICLE SEPARATION

Indeed, minimizing pressure drop has been a focus of IBF studies in the past [7, 8].

2.1.2 Inertial Particle Separators

Inertial particle separation exploits the tendency of inertial particles to resist following sharply curved fluid streamlines. A typical front-facing IPS, as described by Barone et al. [9], includes a centerbody in the engine intake duct that decreases the duct area, accelerating the flow and increasing the linear momentum of any foreign particles. Once the flow is accelerated, the duct curves radially inwards and an annular splitter separates the flow into two regions. The inner region, known as the “core” or “primary” flow, is mostly free of foreign particles; air streamlines entering this region are turned sharply so as to diverge from the paths of particles, whose inertia carries them in the direction of their prior momentum. The gently-curved outer region, known as the “scavenge” flow, captures these particles and discharges them into the atmosphere while the core flow is directed into the engine.

Only particles above a certain mass will be filtered out by the scavenge flow; smaller particles carry less momentum and are more likely to follow fluid streamlines into the core flow. The size threshold for filtration in an IPS is dependent on many design factors, such as the geometry of the splitter. IPS particle separation efficiencies tend to be less than other types of separators, usually at or below 90% [10]. Bojdo [6] also notes that IPS designs are extremely sensitive to local conditions that are highly dependent on particulate types and engine mass flow requirements, limiting the ability to holistically research IPS performance across a variety of applications.

2.1.3 Vortex Tube Separators

Vortex tube separation expands on the use of foreign particle inertia for filtration. Instead of using linear momentum across a sharp curve, particles are separated from core flow streamlines with centrifugal force in a vortical flow [6]. This vortical flow is generated by sending the flow through a circular duct containing helical vanes that impart angular momentum into the fluid. Once the flow has gained sufficient vorticity, solid particles entrained within it generally experience greater outward centrifugal force than the fluid itself (due to their higher specific gravity). Thus, they gain positive radial velocity and move towards the outer boundary of the circular duct. The duct ends by splitting into two concentric ducts; the
inner one carries the core flow towards the engine while the outer one carries particle-laden scavenge flow away and into the atmosphere.

Figure 2.1 is a simplified schematic of a single vortex tube separator, viewed from the side with internal components visible. Flow enters from the left and is immediately forced through a set of helical vanes, causing it to gain a tangential/swirling velocity component. Downstream of the vanes, the now-vortical flow passes through an open “separation region” to allow foreign particles the time and distance necessary to move to the outer periphery of the duct. Lastly, the concentric exit ducts separate the cleaner core flow from the particle-laden scavenge flow. Core flow (“clean air”) is directed to the engine inlet, and scavenge flow (“dirty air”) is sent to the atmosphere.

Vortex tube separators are part of a larger family of filtration devices known as cyclone separators, all of which make use of vortical (cyclonic) flow to filter out unwanted matter from airstreams. An everyday form of cyclonic separation can be found in bagless vacuum cleaners, which typically have vertical cylindrical collection chambers. Air is directed into the chamber tangentially – along the rounded interior surface of the cylinder – to turn streamlines with the surface and induce vorticity. Inertial particles such as dust and dirt are unable to follow the rotating streamlines and impact the walls of the chamber, losing their momentum and falling to the bottom where they are collected and eventually disposed.

The same concept has been used for filtration of industrial emissions and the engine intakes of earthmoving equipment. In many of these applications, the air within the separator actually reverses its axial direction and exits the separator from the same (upper) side it entered. In

Figure 2.1: Simple schematic of a single vortex tube separator (transparent side view).
2.1. ENGINE AIR PARTICLE SEPARATION

Some applications, as with the vortex tube separator itself, air is injected axially (as opposed to tangentially) and helical vanes are used to alter streamlines and provide some or all of the tangential/swirling velocity required for filtration.

All cyclone separators induce some form of pressure drop on the airflow driven by the primary device, whether that be a vacuum’s fan or a turbine engine. This pressure drop limits the amount of airflow that the device can generate. In the case of an aircraft engine, it is especially important to preserve high flow rates to sustain internal combustion. The vortex tube separator was designed to maximize pressure recovery by allowing the flow to maintain its axial direction throughout the separator (no reversal necessary). Also for pressure recovery reasons, the inlet to a vortex tube separator is in that same axial direction (as opposed to tangential entry) such that the VTS relies entirely on helical vanes for vorticity generation. All of this happens at some cost to particle separation efficiency.

In summary, cyclone separator types are generally distinguished by their use of axial/tangential inlets as well as their use of reversing/non-reversing flow (also called counterflow/uniflow) through their chambers. The three main types of cyclone separators are presented in Figure 2.2, which is adapted from Dziubak et al. [11]. The leftmost schematics are of a tangential counterflow separator, where air is injected along the rounded wall of the chamber and eventually reverses course after filtration, exiting at the top of the separator. The middle

![Figure 2.2](image.jpg)

Figure 2.2: Side-views (top row) and top-views (bottom row) of a tangential counterflow separator (left), an axial counterflow separator (middle), and a vortex tube separator (right). Intake air, exhaust air, general chamber streamlines, and dust pathlines also provided. Adapted from Dziubak et al. [11].
schematics are of an axial counterflow separator, where air is not injected tangentially but instead gains vorticity by traveling through helical vanes before reversing course. The right-most schematics are of a vortex tube separator, where helical vanes are again used but no reversal in airflow direction is necessary. As one might expect, vortex tube separators are sometimes called “uniflow cyclone separators” or, more technically, “axial uniflow cyclone separators” in the literature. It is possible that the various acceptable names for these devices and their internal components have caused confusion in the scientific community, as few “uniflow cyclone separator” studies reference “vortex tube separator” studies, and vice versa.

2.2 VTS Filtration Theory

VTS filtration is a complicated process with many variables and assumptions to consider. This section presents the theory typically used for understanding and predicting VTS performance. The general framework for this theory, including many of the equations presented in this section, can be found across multiple studies \[4, 11, 12, 13, 14\]. It is important to note that this section focuses on individual VTSs – expanding the theory to VTS arrays introduces additional complexities that have not been addressed by the literature to the same extent. Discussion on the array problem is provided in Section 2.5.

Consider a simple VTS filtration scenario: a helicopter equipped with VTSs flies low to the ground in a sandy region such that downwash from its rotors kicks sand into the air. Some amount of the sand enters the streamtube of air being sucked into the helicopter engine, and is carried into the VTS array. Within each of the VTSs, helical vanes generate vortical airstreams and much of the sand is ejected radially outwards due to centrifugal forces before being separated from the core flow and dispersed back into the atmosphere.

2.2.1 Assumptions

In devising a model of VTS performance for such a scenario, some initial assumptions must be made. First, incompressible flow is assumed through the VTS. Helicopter engine mass flow rates vary by vehicle as well as current operation conditions, but are generally far too low to create any compressibility effects in their airstreams. Though a VTS array upstream
2.2. VTS Filtration Theory

of the engine would technically constitute an area reduction and thus a velocity increase in the engine intake stream, this reduction would not be severe enough to deviate from the incompressible regime.

In any particle-laden or multiphase flow it is important to determine the influence of particles, or the dispersed phase, on both the fluid flow and each other. In this analysis it is assumed that foreign particles have no influence on the flow and that particle-particle interactions (collisions) are negligible – also called one-way coupling. This assumption is considered reasonable for a first-order analysis. Note that once centrifugal separation has occurred in a VTS, the concentration of particles at the periphery of the separator will increase, but this analysis will continue to assume that particle-particle interactions are negligible. Even if the concentration increase is significant enough to cross the interaction threshold, the particle-laden flow quickly exits the VTS itself and moves into a plenum known as the scavenge chamber (discussed in Section 2.3.2) where the concentration would again lower.

For a simplified, first-order analysis of VTS behavior, several additional assumptions can be made. The derivations in Sections 2.2.2 through 2.2.4 make use of these assumptions. The assumptions are as follows:

- The particulate is of a single uniform size and is spherical in shape.
- Sand particles are transported axially through the VTS at the same average speed of the fluid.
- Fluid and particles enter the VTS with only axial velocity; no tangential or radial velocity is present until imparted by the VTS itself.
- Sand particle movement falls under the Stokes law regime.
- There is negligible adhering of sand particles to the VTS walls and negligible bouncing of sand particles off of VTS walls and vanes. Note: This is a highly limiting assumption and is only appropriate for a very simplified analysis.
- There is no difference in pressure between the outer periphery of a VTS and the central region.
- There is complete lateral mixing due to turbulence within the VTS.
2.2.2 Force Balance and Equilibrium Radius

It is important to predict the behavior of the sand particles entering the VTS. These particle dynamics are, of course, a result of the aerodynamic forces acting on the particles. A general analysis of these forces can provide useful information such as the radii particles will be ejected to and the size constraints of particle filtration.

Fluid and particles that axially enter the VTS are rapidly imparted with angular momentum by the helical vanes. As described previously, particles gain a positive (outward) radial velocity component due to centrifugal force, and some residual radial velocity will likely remain even downstream of the helical vanes. Eventually, further downstream in the separation region (refer to Figure 2.1), the particles will tend to a rotational steady-state where radial velocities become negligible. In other words, particle path lines will settle into a helical path with unchanging radius as they approach the VTS exit. This unchanging radius is referred to as the equilibrium radius as it results from a balance of the forces acting on the particles.

Consider a single particle that has been ejected to the periphery of a VTS in the separation region, and is now in a steady-state rotational flow due to a balance of forces. These forces are the drag force $F_D$, the buoyant force $F_B$, and the centrifugal force $F_C$ (due to the particle’s continued circular motion). Since a steady state has been achieved, these forces must cancel each other out, as in Equation 2.1.

\[ F_D + F_B + F_C = 0 \] (2.1)

The drag force for such a helicoidal path can be computed using Stokes’ Law for a spherical particle, which assumes a low-Reynolds number flow (of order 1). Drag results from air resistance when the particle motion differs from surrounding fluid motion; in a VTS, the particle’s radial velocity dominates this difference in motion (as the fluid is not centrifuged outwards to the extent that the particle is). This is shown in Equation 2.2, wherein $d_p$ is the geometric diameter of the particle, $\mu$ is the dynamic viscosity of the air, and $V_{R,p}$ is the radial component of the particle’s velocity.

\[ F_D = -3\pi d_p \mu V_{R,p} \] (2.2)

The buoyant force is a result of the density difference between the particle and the sur-
2.2. VTS Filtration Theory

rounding air. It can be found with Equation 2.3, where $\rho_g$ is the air density, $V_{\theta,p}$ is the circumferential component of the particle’s velocity, and $R_{eq}$ is the current (equilibrium) radius.

$$F_B = -\frac{\pi \rho_g d^3 p V_{\theta,p}^2}{6 R_{eq}}$$ \hspace{1cm} (2.3)

The centrifugal force due to the particle’s circular motion is found with a well-known formula. Equation 2.4 presents this and expands the mass term for mathematical convenience. In this equation, $m_p$ is the mass of the particle and $\rho_p$ is the density of the particle.

$$F_C = \frac{m_p V_{\theta,p}^2}{R_{eq}} = \frac{\pi \rho_p d^3 p V_{\theta,p}}{6 R_{eq}}$$ \hspace{1cm} (2.4)

Combining Equations 2.2, 2.3, and 2.4 with Equation 2.1 leads to a result that can be simplified and solved for equilibrium radius $R_{eq}$, as shown in Equation 2.5. Clearly, the radius scales on the square of the particle’s diameter as well as the square of its tangential velocity.

$$R_{eq} = \frac{(\rho_p - \rho_g) d^2 p}{18 \mu} \frac{V_{\theta,p}^2}{V_{R,p}}$$ \hspace{1cm} (2.5)

2.2.3 Filtration Parameters

It is possible to expand on the above derivations and compute some VTS filtration performance parameters. Consider the particle as it moves through the helical vanes before reaching equilibrium. It is convenient to begin by rewriting its circumferential velocity $V_{\theta,p}$ in terms of axial velocity $V_{Z,p}$, which is generally a function of the engine mass flow rate and VTS geometry and is thus simple to determine. Equation 2.6 uses simple mathematical principles to relate tangential velocity to axial velocity using the pitch length of the helical vanes (axial distance across which the vanes complete one full rotation). In this equation, $\omega_p$ is the particle’s angular velocity, $R$ is the current radius (assumed constant for simplicity), $\theta$ is angular distance traveled, $t$ is the time duration of that travel, and $H$ is the helical vane pitch length. Essentially, $\theta$ is taken to be one full vane revolution ($2\pi$ rad) and $t$ is the time of travel across that revolution as enforced by the particle’s axial velocity.
\[ V_{\theta,p} = \omega_p R = \frac{\theta}{I} R = \frac{2\pi V_{Z,p}}{H} R \]  

(2.6)

A force balance can be performed on this particle, as in Section 2.2.2, considering the three primary forces acting on it. Combining this with Equation 2.6 yields Equation 2.7, which has been rearranged to solve for radial velocity \( V_{R,p} \).

\[ V_{R,p} = \frac{(\rho_p - \rho_g)d_p^2}{18\mu} \frac{2\pi V_{Z,p}^2 R}{H^2} \]  

(2.7)

For filtration parameters, the radius of concern is the smallest radius that will be filtered into the scavenge flow – the boundary between the scavenge flow exit and the core flow exit (refer again to Figure 2.1). A particle can be considered unfiltered if it has not yet been transported to or beyond this radius. The radial velocity \( V_{R0,p} \) of a particle at this radius \( R_0 \) could be computed from Equation 2.7. It is now possible to set up a mass balance of the flow in the separation region as it is split into core and scavenge flows. Consider the separation region to have length \( L_s \) and an infinitesimally thin axial “slice” of the region to have length \( dL_s \). Designating \( Q \) as the flow rate of air through the VTS, \( C \) as the concentration of unfiltered sand particles in the air (mass of sand per unit volume of air), and \( dC \) as the change in concentration through the slice due to filtration leads to Equation 8.

\[ Q C = Q(C - dC) - V_{R0,p} C dL \]  

(2.8)

The left-hand side of the above equation represents the total mass flow of sand entering the slice, while the right-hand side represents the unfiltered mass flow of sand exiting the slice minus the filtering rate of sand through the slice; it is clear that the left side must equal the right for conservation of mass to hold. Combining Equations 2.7 and 2.8 and integrating over the separation region length \( L_s \) yields an equation for the unfiltered sand mass flow rate. This can be rearranged into an important filtration parameter for the VTS as a whole: the particle separation efficiency \( \eta_{ps} \), described by Equation 2.9.

\[ \eta_{ps} = 1 - \exp\left(-Q \frac{8\pi d_p^2 L_s}{18\mu R_0^2 H^2}\right) \]  

(2.9)

It can be concluded from Equation 2.9 that VTS filtration performance is better for larger...
2.2. VTS Filtration Theory

sand particles; this is intuitive as larger particles will experience greater centrifugal forces and thus be pushed to the outer periphery of the tube more effectively than smaller particles. It follows that, for a given VTS, there will be some particle diameter $d_{50}$ that achieves 50% filtration. This is a common parameter used in VTS design and can be found by rearranging Equation 2.9 into Equation 2.10.

\[ d_{50} = \sqrt[3]{\frac{18\mu (\ln 2) R_0^2 H^2}{8\pi \rho_p Q L_s}} \]  

(2.10)

2.2.4 Pressure Drop

The presence of a VTS in an engine intake generates a pressure drop that affects the engine’s performance. To quantify this pressure drop, it is first useful to define some velocity terms for the gas moving through the VTS (note: Section 2.2.3 dealt with the velocities of the particles). Designate $V_Z$ as the air’s axial velocity and $V_\theta$ as its circumferential velocity; the magnitude of these velocity components represents the air’s net velocity $V_{mag}$ (assuming no radial velocity for the air, unlike the particles), which can be rewritten by relating the two components as was done for particle velocities in Equation 2.6. The result is Equation 2.11, which can be solved for any radius $R$ within the VTS. An area-weighted average $V_{avg}$ of this velocity magnitude across all radii, from $R = 0$ to the maximum radius $R = R_{max}$ simplifies to Equation 2.12.

\[ V_{mag} = \sqrt{V_Z^2 + V_\theta^2} = V_Z \sqrt{1 + \frac{2\pi R^2}{H}} \]  

(2.11)

\[ V_{avg} = \frac{4}{3} \frac{V_Z \pi}{R_{max}^2 H^2} \left[ \left( \frac{H^2}{4\pi^2} \right)^{\frac{3}{2}} - \left( \frac{H}{4\pi^2} \right)^{\frac{3}{2}} \right] \]  

(2.12)

The pressure loss induced by a VTS can be split into three components: friction losses, dynamic pressure losses, and ram pressure losses (neglecting inertial losses). Friction head loss through a duct is generally calculated with the Darcy-Weisbach relationship [15], expressed in Equation 2.13 in terms of pressure drop $\Delta P_f$, where $f$ is a chosen friction factor, $L$ is the length of the duct, and $D_H$ is the hydraulic diameter of the duct.
\[ \Delta P_f = \frac{\rho g L V_{avg}^2}{2 D_H} \]  

(2.13)

The friction factor \( f \) may be computed in a variety of ways, most of which rely on the Reynolds number (described further in Section 2.6) of the flow through the duct. For example, the well-known Colebrook equation [16] assumes a smooth duct surface and relates the friction factor to the Reynolds number \( Re \), as shown in Equation 2.14. The formula used here for the Reynolds number itself is shown in Equation 2.15.

\[ \frac{1}{\sqrt{f}} = 1.8 \log\left( \frac{Re}{6.9} \right) \]  

(2.14)

\[ Re = \frac{\rho g V_{avg} D_H}{\mu} \]  

(2.15)

The hydraulic diameter \( D_H \) is defined differently for each section of the VTS; referring to Figure 2.1, these sections are: the helical vanes, the separation region, the clean air exit, and the annular scavenge (dirty air) exit. Hydraulic diameter formulae are given as a set in Equation 2.16, where \( N \) is the number of helical vanes and \( R_{clean} \) is the radius of the clean air exit. These can be used in conjunction with Equations 2.13, 2.14, and 2.15 to compute the friction pressure drop through each component: \( \Delta P_{f,vanes}, \Delta P_{f,separation}, \Delta P_{f,clean}, \text{ and } \Delta P_{f,scavenge} \).

\[ D_{H,vanes} = \frac{4\pi R_{max}}{2\pi + 2N} \]
\[ D_{H,separation} = 2R_{max} \]  

(2.16)
\[ D_{H,clean} = 2R_{clean} \]
\[ D_{H,scavenge} = 2R_{max} - 2R_{clean} \]

Dynamic pressure losses relate to the circumferential component of velocity gained by gas molecules moving through the helical vane section. This velocity comprises the portion of the average velocity \( V_{avg} \) that is not attributed to axial motion. As such, the dynamic pressure loss \( \Delta P_d \) is given by Equation 2.17.
2.3 Design of Vortex Tube Separators

\[ \Delta P_d = \frac{\rho g (V_{avg}^2 - V_Z^2)}{2} \]  

(2.17)

Additional pressure loss can arise when the forward flight speed of a helicopter is greater than its VTS’s axial velocity – a ram pressure loss \( \Delta P_r \). This can be represented as a conditional statement as shown in Equation 2.18, where \( U_\infty \) is the helicopter’s forward flight speed.

\[ \Delta P_r = \begin{cases} \frac{1}{2} \rho g (U_\infty - V_Z)^2 & \text{if } U_\infty > V_Z \\ 0 & \text{if } U_\infty \leq V_Z \end{cases} \]  

(2.18)

The total pressure loss through a VTS will then be the sum of the above components, depending on the path of the airstream in question. Equation 2.19 shows the summation for the core flow airstream pressure loss \( \Delta P_{core} \), and Equation 2.20 shows the summation for the scavenge flow airstream pressure loss \( \Delta P_{scavenge} \).

\[ \Delta P_{core} = \Delta P_{f,vanes} + \Delta P_{f,separation} + \Delta P_{f,clean} + \Delta P_d + \Delta P_r \]  

(2.19)

\[ \Delta P_{scavenge} = \Delta P_{f,vanes} + \Delta P_{f,separation} + \Delta P_{f,scavenge} + \Delta P_d + \Delta P_r \]  

(2.20)

2.3 Design of Vortex Tube Separators

A multitude of patents exist for various forms of cyclone separators, though only a handful involve helical vanes and fully axial flow as VTSs do. Some relevant patents were published in the 1990s by Willem J. C. Prinsloo and others at a South African company named Cyclofil™ [17, 18, 19]. These present VTS designs similar to the simple diagrams shown previously in this proposal, along with modified variants that have unique characteristics such as outwards-flaring walls along the entire length of the separator. The 1993 patent [19] is of particular interest as it includes an example of VTSs in an array configuration as well; the separators are arranged in a matrix or Cartesian grid format.

Another series of patents was published decades earlier by David Pall, founder of Pall Corporation™. These patents are notable for their detailed description of VTS geometry and design.
parameters. Because of this, and because Pall Corporation VTS technology continues to be used in modern helicopter applications (such as the Boeing™ CH-47 Chinook and the Eurocopter™ AS332 Super Puma), these designs were selected as the basis for VTS studies in the present dissertation.

2.3.1 The Individual VTS

The first of these patents was filed in 1968 and covers the individual Pall VTS in its simplest form [1]. The patent stresses the need for effective centrifugal particle separation while minimizing pressure loss with fully axial flow (no flow reversal). It first describes a general range of acceptable dimensions for the various VTS components before providing a more specific example. A diagram of the presented VTS, adapted from the patent and modified so that these major components are labeled, is shown in Figure 2.3; this may be used as a reference for the following general summary.

Pall found that keeping tube diameters low resulted in better separation efficiencies and less severe pressure drop; he recommends a tube diameter (in the helical vane section) of less than 2.5 cm (1.0 in) for this reason. He also recommends the combined axial length of the helical vane and separation regions be around or less than 5.0 cm (2.0 in). Pall suggests three to six helical vanes be present with a pitch length of 4.3 to 4.8 cm (1.7 to 1.9 in) so that there is no way to move in a straight line through the VTS without encountering a

Figure 2.3: Diagram of an individual VTS, adapted from Pall’s 1968 patent [1] and with major components labeled.
2.3. Design of Vortex Tube Separators

This is important for extremely large particles with high Stokes numbers which may be less inclined to follow rotational streamlines; they will instead travel axially, strike the vanes, and be physically deflected to the outer periphery of the tube. The hub, as shown in Figure 2.3, is a centerbody that supports the helical vanes; it should be 20-40% of the diameter of the tube in the helical vane section. Pall proposes allowing the hub to protrude upstream of the VTS by about 0.64 cm (0.25 in) to guide the incoming flow into the vanes, and to conclude the downstream end of the hub with a conical tip of half-angle 15-30° to minimize pressure losses.

Additionally, an outward taper of the tube wall in the separation region is said to decrease pressure drop by providing a greater scavenge flow outlet area, but the taper should not exceed 10° or else boundary layer separation may occur. The outward taper also geometrically allows for the filtering of extremely large particles that would otherwise be unable to pass into the scavenge flow. The clean air exit should partially extend upstream into the separation region by 10-25% of the tube diameter. Pall concludes the general summary by stating that abrasion-resistant materials are recommended for the construction of the VTS to combat sand erosion. Nylon and polyurethanes are preferred, but other plastics (such as polypropylene and polycarbonate) and metals (such as stainless steel and nickel alloys) are also appropriate. The helical vanes may be of the same or different material than the outer tube walls.

Pall filed a second patent a year later in 1969 [20] that built on work from the 1968 version, presenting a specific example of a VTS with detailed dimensions. The updated VTS is almost identical to its previous form except for the introduction of a contraction upstream of the helical vane section. Pall states that this contraction was found to decrease pressure drop, which is counterintuitive as duct contractions typically worsen pressure drop. He acknowledges the contradiction and states that the reason for it is unknown. Additionally, the conical downstream tip of the hub is not included or acknowledged in the updated VTS for unknown reasons. However, all other stated features and dimensions are identical to the 1968 version’s detailed example that was provided after the general summary. That information has been compiled and presented as a diagram in Figure 2.4, which is adapted from the patent and modified to include alphabetical dimension labels. Those labels correspond to numbers shown in Table 2.1, which immediately follows the figure. Note the presence of a curved contraction at the upstream (left) end of the VTS. The diagram does not appear to be to scale.
CHAPTER 2. REVIEW OF LITERATURE

Figure 2.4: Diagram of an individual VTS, adapted from Pall’s 1969 patent [20] and with alphabetical labels added for all relevant dimensions (see Table 2.1).

Table 2.1: VTS geometric parameters corresponding to Figure 2.4, as presented in Pall’s 1969 patent [20].

<table>
<thead>
<tr>
<th>Dim.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [cm]</td>
<td>1.720</td>
<td>1.613</td>
<td>0.432</td>
<td>1.168</td>
<td>1.840</td>
<td>0.330</td>
<td>0.246</td>
<td>0.389</td>
<td>2.159</td>
<td>0.726</td>
<td>3.520</td>
</tr>
<tr>
<td>Length [in]</td>
<td>0.677</td>
<td>0.635</td>
<td>0.170</td>
<td>0.460</td>
<td>0.724</td>
<td>0.130</td>
<td>0.097</td>
<td>0.153</td>
<td>0.850</td>
<td>0.286</td>
<td>1.386</td>
</tr>
</tbody>
</table>

According to the patent, a cluster of these VTSs was tested in a flow containing coarse grade test dust (SAE Recommended Practice J-736a). The flow was such that 0.22 $m^3/min$ (7.6 SCFM) was sucked through each VTS. Scavenge flow rate information is not provided, but this topic is discussed in the third Pall patent, which is covered later in this section. As expected, a vortex was created by the helical vanes, which ejected most dust particles to the periphery of each tube. These VTSs were found to have a separation efficiency of 92% while causing a pressure drop of 0.672 kPa (0.097 psi). This can be contrasted to VTSs without the inlet contraction, which created a 10% larger pressure drop of 0.747 kPa (0.108 psi) for the same separation efficiency.

2.3.2 VTS Arrays

A third patent was also filed by Pall in 1968 [1] covering the use of vortex tube separators in an array assembly. This appears to be one of the very few publications of any kind to focus on VTS arrays rather than singular VTSs. Recall that a typical VTS array consists of a large
2.3. Design of Vortex Tube Separators

The plenum, known as the “scavenge chamber”, surrounding dozens or hundreds of VTSs. The inlets and clean air exit of the VTSs are exposed to the atmosphere or engine intake duct, but the scavenge flow leaving the tubes enters the interior of the plenum to prevent it from being ingested by the engine. Early in the patent, the importance of having a powered scavenge flow is highlighted – simply having “dirty air” eject into the plenum (where it remains until cleaned) limits separation efficiency to 80%, according to Pall. Instead, an outlet known as the “scavenge port” may be placed on the chamber walls; if suction flow is generated through this outlet, separation efficiencies are raised and the device becomes self-cleaning as filtered particles are drawn out and eventually dispersed into the atmosphere. The performance of the VTS array is highly sensitive to the nature of this scavenge flow.

Figure 2.5 is adapted from the third patent and modified to include labels used in previous diagrams. The figure shows a side view of a VTS array, with the VTS inlets on top and the clean air exits on the bottom. Most of what is shown is the scavenge chamber, but both ends have been cut away to reveal two VTS cross-sections similar to Figure 4 above. In one of these cross-sections, as with Figure 4, the helical vane region, the separation region, and the clean air exit have been labeled. Small arrows show the scavenge flow escaping from each VTS and moving towards a large outlet in the chamber wall, labeled as the scavenge port. In theory, the vast majority of inertial particles will follow this scavenge flow through the port, after which they are dispersed back into the atmosphere. It is likely that the fluid and particle dynamics occurring within the scavenge chamber are extremely complex, owing to the vortical nature of the scavenge flow and the presence of a great number of solid particles.

Figure 2.5: Side-view diagram of a VTS array, adapted from Pall’s 1968 patent [1] and with cutaways on each side to show individual VTSs within. Modified to include labels for major components.
Figure 2.6: Front-view cross-sectional diagram of a VTS array, adapted from Pall’s 1968 patent [1] and modified to include labels for major components.

boundaries within the chamber.

The patent includes the results of a study showing the effectiveness of scavenge flow, which is measured as a percentage of total inlet flow rate to the VTS array. There is a general increase in VTS array separation efficiency with increasing scavenge flow up to about 8% scavenge flow, after which the curve levels off (92% efficiency). Pall goes on to state that device performance is very sensitive to even slight changes in scavenge flow rates, which is problematic because those flow rates tend to vary across a single VTS array and can be difficult to predict due to flow complexity; some situations even result in negative (backwards) scavenge flow, which has extremely detrimental effects on VTS performance.

Pall also provides a cross-section front view of the VTS array, which has been modified and presented in Figure 2.6. In this figure, the annular circles are cross-sections of VTSs; it appears that Pall chose not to show all such VTSs and represents the remainder with small plus signs. Note the “honeycomb” pattern of VTS placement, in which the tubes are staggered such that none are exactly horizontally aligned with their nearest neighbors on the
2.3. Design of Vortex Tube Separators

right and/or left sides. Another feature of note is the presence of open ducts that travel from the scavenge port down throughout the separator array. These ducts have openings in their walls to allow air to enter them, and are present to provide cleaner paths for scavenge flow to leave the chamber. In this design, the ducts are arranged such that groups of VTSs are never more than three separators across horizontally (perpendicular to the general direction of scavenge flow towards the port).

Actual Pall Corporation™ VTS arrays can be inspected for comparison to these patents. For the purposes of this dissertation, a Pall™ Centrisep™ Air Cleaner used on Hughes™ 369 helicopters was purchased. The Centrisep™ line is Pall’s™ primary line of VTS products, and appears to have several different variations specially fitted to various helicopters. It is assumed that the design principles of the VTS array themselves do not change across the Centrisep™ line; the shape of the scavenge chamber and the number and placement of VTSs may vary, however.

Figure 2.7 shows a front view picture (forward-looking-aft; flow into the page) of the purchased VTS array. Labels are included to show the VTSs, scavenge ducts, and scavenge port, which appear to be arranged in similar fashion to the third Pall patent described previously. Close inspection of the VTSs reveals four helical vanes protruding from hubs in each separator. The “honeycomb” pattern of VTSs is retained, as is the grouping of no more than three VTSs in the direction normal to duct scavenge flow. A notable feature is the horizontal ducts towards the bottom of the array; correspondingly the orientation of the VTS pattern switches to horizontal as well. There are two instances in this region of four VTSs grouped in a column (as opposed to three) for unknown reasons.

Figure 2.8 was taken from an online store page and is included to show the variation in array design across various models within the Centrisep™ line. This particular array was designed for the Bell™ 206 helicopter. Notably, the arrangement of VTSs within the scavenge chamber is very different from the Hughes™ 369 version and the Pall patent itself; the separators form an “arc” around a central point (likely due to the helicopter’s geometry itself), and VTSs are grouped in much larger clusters. Scavenge ducts are still visible, although it appears that the scavenge port is now located in the lower central region of the array, rather than on top as in the Hughes™ 369 version.
Figure 2.7: Front-view (flow into page) picture of a Pall™ Centrisep™ VTS array used for Hughes™ 369 helicopters.

Figure 2.8: Picture of a Centrisep™ VTS array used for Bell™ 206 helicopters.
2.4 VTS Scientific Studies

There have been several scientific papers (theoretical, computational, and experimental) published on vortex tube/axial uniflow cyclone separators, though the collection is far smaller than what exists for reverse-flow or tangential-inlet cyclone separators. This section aims to summarize the contributions of what does exist. It is important to note that almost the entirety of VTS literature known to the author is focused on individual separators. Very little research appears to have been conducted on VTS arrays, which is one of the main motivations for this dissertation as described in Chapter 1.

VTS performance theory has been extensively covered in the previously referenced series of papers published by Filippone and Bojdo from the University of Manchester [4, 6, 8, 12, 13]. These include derivations that are used in this dissertation (Section 2.2) and parametric studies comparing vortex tube separators with the other major forms of turboshaft engine air-particle separation (inlet barrier filters and inertial particle separators). These studies are limited to individual separators.

Some conference proceedings have been published on numerical and experimental investigations of VTSs. Gopalakrishnan and Arul [21] computationally modeled the flow and inertial particle behaviors through a separator in OpenFOAM, varying geometric parameters as well as particle sizes to assess their effects on performance. They found that the general trend of greater separation efficiency with increasing particle size (as expected from the derivations in Section 2.2) is only valid up to a point. Extremely large particles (>60 μm diameter in their case), having significant radial velocity compared to their axial velocity, underwent several collisions with the outer walls of the separator. This pushed their trajectories towards the clean air exit. The authors were able to partially mitigate this issue by increasing the angle of the helical vanes and decreasing the length of the vane section. Another numerical study by Wang and Luan [22] analyzed the pressure drop across a VTS for various primary (total) flow rates and scavenge flow rates as a percentage of primary flow rates. Crumpacker [23] experimentally tested simple VTS geometries in a particle-laden flow, varying the number of helical vanes, and found that four blades produced the lowest pressure drop while preserving separation efficiency.

A handful of researchers have also contributed peer-reviewed scientific publications on VTS-type separators, almost all in the past five years. Huang et al. [24] numerically analyzed
a unflow cyclone separator variant meant for gas-liquid separation with a focus on helical vane geometry. Observed trends were as follows: decreasing the “discharge angle” (essentially adding inwards curvature at the downstream end of the vanes) and increasing the “torsion angle” (essentially the steepness of the helical vanes) both independently grew tangential velocity while maintaining axial velocity, leading to increased separation efficiency but also increased pressure drop, which scaled linearly with both parameters. Deng et al. [25] built off of this work by constructing an AI-based optimization tool for vane geometry. A similar vane-focused study, which included an experimental component, was conducted by Li et al. [26].

A group of Austrian and German researchers headed by Martin Pillei have published three papers on the more traditional VTS design. The first [27] is a brief study in which both CFD and experimental particle image velocimetry (PIV) results show that the shortening of the upstream ends of helical vanes results in detrimental flow detachment within the vane channels. Information on PIV as a measurement technique is provided in Section 4.4. A far more detailed experiment is carried out in the second paper [28]; here, stereoscopic PIV is used to study the swirling flow within the separation region of a VTS. A diagram of this study’s experimental setup is provided in Figure 2.9, and is a good example of the vast differences in VTS nomenclature across various research groups. In this figure, the “swirl generator” is the helical vane section, the “separation chamber” is the separation region, the “vortex finder” is the clean air exit, and the “particle outlet” is the scavenge flow exit.

Figure 2.9: Diagram of PIV experimental setup by Pillei et al. [28] to study gas flow in the separation region of an individual VTS.
2.4. VTS Scientific Studies

It can thus be understood from the figure that the PIV was a gas-focused study (no inertial particles) conducted on a plane normal to the VTS axis and just downstream of the helical vanes. The nondimensional swirl number was computed from velocity data for varying vane angles of attack and hub diameters (DC in the figure), since swirl number may be used as an indication of vortical “strength” and is thus a measure of filtering effectiveness with hypothetical inertial particles. These findings were used in the third paper \cite{29}, in which dust was introduced for measurement of filtration parameters. An ISO dispersion nozzle was used to evenly distribute dust within the intake air stream. The authors were able to confirm the effects of vane angle and hub diameter (and additional design choices, such as vane overlap) on separation efficiency and pressure drop. It was found that certain modifications allowed for a 50% reduction in the minimum filtered particle diameter while only increasing pressure drop by 30%.

Another series of VTS studies has been published by researchers at the Polish Military University of Technology, led by Tadeusz Dziubak. An initial paper \cite{11} focused on the CFD analysis of a particle-laden VTS flow; it goes into great detail about the flow and particle modeling, and involved the 3D scanning of an actual vortex tube separator to accurately reproduce its geometry in software. A sequel paper \cite{30} made use of this simulation method for validation of experimental filtration data on a 3D-printed VTS. The experiment used a dust dispenser to introduce particles into the VTS flow which were caught by downstream filters for measurements of separation efficiency. Initially, CFD model geometric parameters were varied to determine an ideal design, which was then studied at various inlet flow velocities and found to have a peak separation efficiency of 90.2% at 7.5 m/s. The corresponding experiment found similar trends with regards to geometric parameters and inlet flow velocities. An additional study by Dziubak \cite{31} studied the effects of an electric field applied to a VTS; electric fields are sometimes used to boost the performance of cyclone separators.

Ulrich Muschelknautz, a prominent name in cyclone separation research, has also published a series of VTS studies. The first \cite{32} is an experimental study of VTSs with different apparatuses for the discharge of dirty scavenge flow (for example, a window instead of the traditional annular outlet) while highlighting the advantages of the device over reverse-flow cyclone separators. This paper goes into detail about the mechanism for sand injection into the VTS flow, which is an important and challenging topic. It states that sand particles were fed into the flow using a hopper, a vibrating feeder, and an injector. The particle-laden flow was then transported through 2 m of inlet pipe to allow for uniform gas velocity and particle
distribution. For reference, particles used in this study were limestone powders with general diameters on the order of 10s of micrometers. Similar to Dziubak’s study, particles were either separated from the VTS into a larger chamber where they came to rest, or remained with the “clean flow” before being collected on a filter for mass measurements.

The second relevant study by Muschelknautz [33] is notable for being one of the only examples of VTS array investigations known to the author of this dissertation in the literature. Muschelknautz refers to VTS arrays as “multicyclones” and notes that the term can apply to both reverse-flow and uniflow cyclone separators. Some of the primary differences between reverse-flow and uniflow multicyclones are intuitive; reverse-flow separators will achieve higher separation efficiency, while uniflow separators will incur lessened pressure drops (which is why they are chosen for turbine engines, as they require high airflow). Another key difference is that uniflow multicyclones are capable of effective filtration while occupying a smaller physical space than reverse-flow multicyclones, which can be important in space-constrained applications. This study applies the known theory for VTS filtration, treating an array as several individual separators (arranged in a Cartesian grid pattern) and a plenum (which introduces its own pressure drop term). An example of a uniflow multicyclone used in the study is shown in Figure 2.10. The study finds that at smaller scales, uniflow multicyclones are equally efficient as reverse-flow multicyclones. A follow-up publication [34] presents similar information with more mathematical details. It is important to note that the scavenge flow (which Muschelknautz calls “underflow”) is assumed to be nonexistent as a baseline scenario.

2.5 The Array Problem

It is evident from this literature review that little information is available on the fluid and particle dynamics of vortex tube separator arrays. The physical phenomena occurring within and downstream of these arrays is likely complex and heavily influenced by the interactions between multiple vortical streams. Additionally, the geometry of the scavenge chamber as well as the presence of relatively strong scavenge flow further complicates the flowfield. These complexities may have significant impacts on VTS array performance, but are difficult to predict theoretically. This section describes some of the flow phenomena that may be encountered in any investigation of a VTS array.
2.5. The Array Problem

An obvious consequence of the combining of several VTSs into one large device is the generation of many vortices in close proximity to each other. This is most evident downstream of the clean air exits, which will all output highly vortical airstreams. It also occurs within the scavenge chamber itself, to an extent; the scavenge flow emerging from each separator into the chamber will itself be a vortical “donut” (surrounding the outer walls of the clean air exit), though the presence of the scavenge chamber walls and the many VTS bodies within the chamber complicates this. Vortices like these will all tend to interact with each other; vortex-vortex interactions have been the topic of a great deal of research [35]. Since all the VTSs in an array will typically spin airflow in the same direction, these can be described as “co-rotating vortex interactions”.

Figure 2.10: Diagram of a VTS array (“uniflow multicyclone”) used in the study by Muschelknautz [33]; side view cross-section (top) and front view facing inlets (bottom).
Much of the research on vortex interactions focuses on vortex pairs as these have the most widespread applications (such as counter-rotating wing-tip vortices). Consider instead a co-rotating vortex pair. Both computational [36, 37] and experimental [38] studies have observed that such a pair tends to move together and eventually merge into a single vortex. As shown by colored dye visualization in Figure 2.11, the merger process involves severe physical distortions of the vortex cores. Notably, the appearance of trailing vorticity filaments, resembling the spiral arms of a hurricane (Figure 2.11b), is thought to occur due to induced velocities from each vortex. A vorticity “exchange band” also forms between the two cores. Some believe that the vorticity within the filaments is the primary cause for the vortices’ eventual movement towards a common center, where they finally merge [39].

It is likely that some similar behaviors would occur in the case of several interacting co-rotating vortices, as would be present downstream of and (to an extent) within a VTS array. Note, however, that the vane-induced vortices in a VTS flow are expected to be intense (swirl number S > 0.5) compared to those utilized in many vortex interaction studies. Additionally, the literature is limited for cases with several interacting vortices. One topic of research that does involve such a multitude of vortices is arrays of combustion swirlers in turbine engines. These swirlers are used to soundly premix air and fuel for “lean combustion”, which produces less nitrous oxide (NOx) emissions than conventional techniques. Swirling flow is generated with either tangential inlets or guide vanes. An important consideration for such flows is their physical confinement by surrounding walls; differences have been found between low-confinement and high-confinement cases [40]. In one highly-confined case, co-rotating interacting vortical streams were studied as they progressed in the axial direction.

![Figure 2.11: Experimental dye visualizations of two co-rotating vortices: (a) before; (b) during, and; (c) after merger [37].](image)
2.5. The Array Problem

[41, 42]. Velocity vectors within the central regions of the flow (away from the walls) tended to oppose vectors from neighboring vortices and eventually nearly canceled each other out. Velocity vectors near the walls tended to act similarly to vectors from neighboring vortices and eventually conjoined into a “ring” of faster flow that encircled the flow region and clung to the walls. This is illustrated in Figure 2.12, which shows planar velocity vectors in (x-y) planes normal to the flow direction (z) at various points downstream of a co-swirler array in a highly-confined square chamber. Initially, the presence of nine distinct vortices from nine swirlers is clear, but further downstream the vortices begin to interact. At the furthest downstream plane, the flow has evolved into a fast-moving outer vortex that clings to the square walls with relatively slow movement in the central regions.

Figure 2.12: Experimentally measured planar velocity vectors in the flow downstream of a combustion swirler array; 3 mm downstream (top left), 13 mm downstream (top right), and 63 mm downstream (bottom). Adapted from Cai et al. [41, 42].
Another feature found in combustion swirler flows, even those with a single swirler rather than multiple, is the “central recirculation zone” (CRZ), where the axial component of flow velocity slows or reverses. This occurs as a result of significant radial pressure gradients generated by swirling flows, which cause the flow to expand along with a duct expansion and induce an adverse pressure gradient in the evacuated central region \[43\]. The CRZ is particularly sensitive to confinement effects; its strength and size are partially determined by the level of confinement within the chamber containing the vortical flow. It may be accompanied by corner recirculation zones for certain geometries as well. Figure 2.13, adapted from Huang and Yeng \[44\], shows a side-view example of flow structures downstream of a small set of combustion swirlers; the central recirculation zone is clearly visible as a dual-lobe region where streamlines reverse near the tunnel centerline. The dissertation by Fu \[45\] provides several further experimental investigations of flows emerging from swirlers and swirler arrays; CRZs are given special attention. They may be impactful in VTS flows considering they can produce axial flow gradients upstream of even the swirler outlet \[46, 47\]; as described in Section 2.2.3, separation efficiency of a VTS depends on fluid flow rates. This may lead to a scenario where some separators in a VTS array (those upstream of a CRZ) have reduced separation efficiencies relative to other separators.

Central recirculation zones are commonly observed in general swirling flows past sudden expansions. Formation of a CRZ requires that the swirling flow have sufficient swirl intensity, which is typically described as the critical swirl number \[48\]. Some studies have constructed models to predict the critical swirl number for the onset of recirculation, as well as other recirculation quantities \[49, 50, 51\]. Central recirculation is a form of vortex breakdown, and is often accompanied by other vortex breakdown phenomena, such as a vortex core that precesses about an axis \[52, 53\] (also pictured in Figure 2.13). Precessing vortex cores have been linked to reduced separation efficiencies in cyclone separators similar to vortex tube separators \[54, 55\].

The above information suggests that vortex breakdown phenomena such as central recirculation zones and precessing vortex cores play an impactful role in vortex tube separator flows. However, these have never been studied in VTS arrays. The presence of multiple vortical flows and the complex scavenge chamber interactions may either hinder or help the generation of such features. Thus, the current dissertation aims to explore the flowfield downstream of a VTS array model in a wind tunnel.
2.6 VTS Scaling

A final section is presented here on the nondimensional parameters relevant to VTS scaling, as the present work utilizes scaled VTS array models in its experiments. Many wind tunnel models are scaled up or down in size for various logistical reasons, but in doing so the resulting fluid and particle nondimensional parameter differences, if any, must be acknowledged.

The book *Gas Cyclones and Swirl Tubes* by Hoffmann and Stein [56] provides an excellent overview of nondimensional parameters that must be considered for the scaling of cyclone separators and vortex tube separators, which the authors refer to as “swirl tubes”. They begin with the separation efficiency, which is influenced by over a dozen parameters ranging from particle characteristics to gas properties and cyclone geometry. After several assumptions and simplifications similar to those made in this proposal (spherical particles, smooth wall, etc.), the separation efficiency $\eta_s$ is found to depend on only six major parameters: particle diameter $d_p$, particle-gas density difference $\Delta \rho$, gas density $\rho_g$, gas dynamic viscosity $\mu$, a characteristic velocity $V_{ch}$ (often chosen to be an average velocity like $V_{avg}$ in Equation 2.12), and cyclone diameter $D$, as shown in Equation 2.21. Using the Buckingham Pi dimensional analysis technique, these parameters may be represented by the dimensional groups shown in Equation 2.22.
\[ \eta_{ps} = f \left( d_p, \Delta \rho, \rho_g, \mu, V_{ch}, D \right) \]  

\[ \eta_{ps} = f \left( \frac{\mu}{D \rho_g V_{ch}}, \frac{d_p \Delta \rho}{D \rho_g} \right) \]  

The first group is easily recognizable as the inverse of the Reynolds number \( Re \), which translates to a measure of the range of turbulent eddy length scales. The second group can be squared, divided by 18, and multiplied by the Reynolds number and third group to produce the Stokes number \( St \) for a particle in a flow – another nondimensional parameter representing the ratio of particle and flow timescales, which translates to a measure of the tendency of a particle to follow or diverge from fluid streamlines. The formula for the Stokes number is presented in Equation 2.23; this formula assumes low-\( Re \) Stokes flow, but is the standard definition of the Stokes number represented with VTS-relevant variables. Since \( St \) was generated only by manipulating existing dimensional groups, it can itself be considered a nondimensional parameter relevant to the separation efficiency. Additionally, as \( St \) already contains a density ratio term, the third dimensional group in Equation 2.22 is no longer needed. Thus, the separation efficiency’s dimensional groups can be represented as Equation 2.24, assuming similar geometries.

\[ St = \frac{\Delta \rho d_p^2 V_{ch}}{18 \mu D} \]  

\[ \eta_{ps} = f(Re, St) \]  

Consider a prototype (actual) vortex tube separator in comparison with a geometrically similar research model. Equation 2.24 states that, in order to achieve the same separation efficiency with both the prototype and model, the model’s geometry, flow, and particles must combine to match Reynolds number and Stokes number with the prototype. This is simple enough if the model is of the same size as the prototype with identical flow velocities and particle characteristics. However, as with many wind tunnel experiments, it is sometimes desirable to scale the model up or down from the prototype, and this introduces challenges as both \( Re \) and \( St \) depend on the diameter of the separator. While the parameters could still theoretically be matched by changing other variables (such as density), in practice this
2.6. VTS Scaling

is difficult to achieve.

The problem can be reasonably simplified with the understanding that the exact matching of the Reynolds number is not actually critical. Consider a separation efficiency of 50% ($\eta_{ps} = 0.5$); the Stokes number for this efficiency $St_{50}$ will be purely a function of the Reynolds number according to Equation 2.24. Overcamp and Scarlett [57] compiled experimental data from a variety of cyclone studies (shown in Figure 2.14) and found that $St_{50}$ is only strongly dependent on $Re$ when $Re$ is relatively low; at higher $Re$ (which most cyclones operate at), there is less correlation and $St_{50}$ appears to be nearly independent of $Re$. The $St_{50}$ (also called $Stk_{50}$) vs. $Re$ data points for the cyclones they examined are plotted logarithmically in Figure 18 using velocities at the cyclone inlets. This suggests that for a model to retain the separation efficiency of its prototype, it is much more important to match Stokes number than Reynolds number. Additionally, in the field of experimental fluid dynamics (disregarding particle dynamics for the moment), the mismatching of Reynolds numbers between models and prototypes is quite common [58], primarily due to logistical difficulties involving facility size and capabilities. In general, model Reynolds numbers may be as much as an order of magnitude off from prototype Reynolds numbers. While the quantification and minimization of Reynolds number mismatch effects has been the topic of a great deal of work [59], failure to match the Reynolds number has been an acknowledged part of experimental fluids studies since the field’s inception.
Figure 2.14: $St_{50}$ vs. $Re$ using cyclone inlet velocities, experimentally determined for a range of cyclone separators. Adapted from Overcamp and Scarlett [57]
Bibliography


BIBLIOGRAPHY


BIBLIOGRAPHY


Chapter 3

Mean Flow Characteristics
Downstream of a Vortex Tube Separator Array

The contents of this chapter are currently undergoing revisions for publication in the American Institute of Aeronautics and Astronautics (AIAA) Journal.

Permission for re-use of a forthcoming article (estimated publication in 2023) granted by the American Institute of Aeronautics and Astronautics.

Mean Flow Characteristics Downstream of a Vortex Tube Separator Array

Adit S. Acharya *, K. Todd Lowe †, and Wing F. Ng ‡

Virginia Tech, Blacksburg, Virginia, 24061

Vortex tube separator (VTS) arrays are used to filter foreign particles from turboshaft engine intakes. Arrays may consist of hundreds of separators that share a common surrounding plenum, potentially allowing for significant interactions between the devices. However, most VTS studies have been limited to individual separators acting alone. The current study first involves an experimental investigation of the fluid flow emerging from the outlets of a VTS array installed in a wind tunnel. Particle image velocimetry is used to measure the flowfield at planes $0.23D_{VTS}$, $0.58D_{VTS}$, and $1.77D_{VTS}$ downstream of the outlets, where $D_{VTS}$ is the inlet tube diameter of a separator. Results indicate that the emerging vortices quickly merge into a single vortex with high circumferential velocity concentrated near the edges of the duct, and that a central recirculation zone (CRZ) develops. This is in contrast to the flow from a single VTS, which does not have a clear CRZ. Comparisons to similar combustion swirler flows lead to the hypothesis that VTS arrays may uniquely generate fast-developing CRZs that produce strong axial flow gradients near or even within some VTS outlets. Such gradients will alter the filtration performance of affected VTSs, which is highly sensitive to flow rates. To explain and predict the onset of recirculation that is exclusive to the array configuration, the framework of a momentum integral model has been developed and is presented here. Additionally, CAD files of the experimental geometry along with inlet/outlet boundary conditions are being made available for any future computational validation studies of this complex flowfield.

Nomenclature

\[
\begin{align*}
  a_1, a_2 & = \text{vortex core radius at Station 1, at Station 2} \\
  D & = \text{characteristic length} \\
  dt & = \text{PIV double-frame pulse separation} \\
  D_{VTS} & = \text{diameter of VTS inlet tube}
\end{align*}
\]

*National Defense Science and Engineering Graduate Fellow, Department of Aerospace and Ocean Engineering, Student Member AIAA
†Professor, Department of Aerospace and Ocean Engineering, Associate Fellow AIAA
‡Alumni Distinguished Professor, Department of Mechanical Engineering, Fellow AIAA

A version of this manuscript was first presented at the AIAA Aviation Forum in Chicago, IL in June 2022 (paper number: 2022-3260).
I. Introduction

Modern helicopters are powered by turboshaft engines that require high airflow rates to sustain internal combustion. When operated in certain environments, the downwash from their rotors may kick up large amounts of foreign particles which are ingested by the engine. This most commonly occurs with sand and dirt particles; larger helicopters may ingest 2-4 pounds of dirt per minute when flying low over sandy areas [1], which has been directly linked to shortened engine lifespans and even total engine failure [2]. Other types of foreign particles that may be similarly ingested include volcanic ash, snow/ice, and sea spray. Potts [3] compiled reports of U.S. helicopter engines affected by sand ingestion and found that significant compressor blade erosion had occurred in many cases, sometimes in as little as 20 hours of operation in desert environments. Additionally, helicopters at a U.S. army base in Texas required engine overhauls five times as frequently as planned, mostly due to compressor erosion. Thus, there has long existed a clear need for particle filtration systems on helicopter engine inlets.

Three major forms of engine air particle separators (EAPS) have seen heavy use on helicopters, as described by Filippone and Bojdo [4]. Inertial particle separators (IPS) use tight curvatures in
duct geometry to eject large particles away from the flow, and inlet barrier filters (IBF) rely on porous mesh screens to trap particles entering engine inlets. These types of devices have some undesirable characteristics; for example, as per Filippone and Bojdo, IPSs tend to have relatively low separation efficiencies (50% to 85%), and IBFs accumulate trapped particles over time, reducing airflow into the engine. Both devices also create detrimental pressure loss and flow distortion effects.

A third option which mitigates some of these issues is the vortex tube separator (VTS), which uses helical vanes that generate vortical flow upstream of the engine [5]. Foreign particles entrained in this vortical flow experience outward centrifugal forces due to their high specific gravity. Thus, they gain a radial velocity component and migrate to the outer boundary of the circular duct downstream of the vanes. The duct ends with an annular outlet; the inner duct carries the cleaner core flow towards the engine while the outer duct carries particle-laden flow from the periphery away and into the atmosphere.

Figure 1 is a transparent schematic of a single vortex tube separator viewed from the side. Flow enters from the left and immediately passes through a set of helical vanes, generating a tangential/swirling velocity component. Eventually, the now-vortical flow passes through a vane-less “separation region” to allow particles the time and distance necessary to move radially outwards to the boundary of the duct. Lastly, the concentric exit ducts separate the cleaner core flow from the particle-laden periphery flow. Core flow (“clean air”) is directed to the engine inlet, and scavenge flow (“dirty air”) is sent to the atmosphere. Vortex tube separators are part of a larger family of filtration devices known as cyclone separators, all of which make use of cyclonic flow to filter out unwanted matter from various airstreams. An everyday form of cyclonic separation can be found in bagless vacuum cleaners, which rely on the tangential inflow of air along a cylindrical wall to induce vorticity. Dust and dirt carried by the airstream are unable to follow the rotating streamlines and impact the wall, thus losing their momentum and falling into a collection chamber. To distinguish from such cyclonic filters, VTSs are sometimes referred to as (axial) “uniflow cyclone separators”, owing to their non-tangential inlets and lack of airstream reversal.

Some of the only available detailed information on VTS design can be found in a series of patents filed by David Pall in the late 1960s. The first of these [5] describes the ideal VTS as maximizing particle separation efficiency while minimizing pressure drop across the device; indeed, these are the two primary performance parameters of any EAPS. It also provides ranges for various geometrical

![Fig. 1 Simple schematic of a single vortex tube separator (transparent side view).](image-url)
dimensions within the separator. The second patent [6] improves on this work by introducing a contraction at the inlet of the separator, which reduces pressure drop. In these patents, Pall provides a sense of scale; VTSs are small, often less than 2 cm in diameter and 4 cm in length.

Pall’s third patent [1] introduces a major unique and complicating characteristic of vortex tube separators: they are implemented in array configurations, wherein dozens or hundreds of separators are grouped together on a single device. Given their small size, this arrangement is necessary to allow for the high flow rates required by turboshaft engines. The inlets and clean air outlets of each separator are essentially openings in the exterior walls of a large manifold that is mounted on the intake of the engine. It was previously said that “dirty air” from a VTS is directed to the atmosphere; this remains true in a VTS array, but that air is first ejected into the plenum contained within the manifold – the gap between its exterior walls that also houses most of the separator tubes themselves. This region is referred to as the “scavenge chamber”. From there the dirty air is sucked towards an opening (known as the “scavenge port”) that finally leads to the atmosphere.

Figure 2 is adapted from the array patent and modified to include labels consistent with the current study. It shows a top view of a VTS array oriented such that the air flows in the downward direction; two separators within the array are visible through cutaways for clarity, and their previously-discussed features (helical vanes, separation region, and clean air exit) are easily recognizable. A large manifold surrounds and connects the two separators; their inlets (labeled “AIR IN”) and outlets (labeled “CLEAN AIR OUT”) are simply openings in the walls of that manifold. As described above, dirty air that is separated by these VTSs is initially ejected into the scavenge chamber that surrounds the separators. Once in that chamber, the dirty air is drawn (labeled “Scavenge Flow”) towards a scavenge port on the top of the array. Pall notes that the scavenge port’s suction is felt non-uniformly throughout the scavenge chamber due to pressure losses relating to the complex separator geometries. This non-uniformity can be problematic as separator efficiency is highly sensitive to changes in scavenge flow rate. Several examples of actual VTS arrays can be found on Internet stores; Figure 3 shows a front-view image of a Pall Corporation™ Centrisep Air Cleaner intended for use on a Bell Inc.™ 407 helicopter. Each of the black circles is the inlet of a VTS; close inspection reveals a centerbody and four protruding vanes visible in each separator. The VTSs are arranged in a staggered “honeycomb” pattern. It appears that the scavenge port is located at the bottom-center of the pictured array.

Fig. 2  Diagram of a VTS array, with cutouts showing two individual separators within, adapted and modified from Pall’s 1970 patent [1].
There have been theoretical, computational, and experimental scientific papers published on vortex tube/axial uniflow cyclone separators, though the collection is relatively small compared to what exists for other types of cyclone separators. It is important to note that almost the entirety of VTS literature known to the authors is focused on individual separators. Very little research appears to have been conducted on VTS arrays, which is the primary motivation for the current study. In addition, much of the available literature on singular VTSs focuses on the effects of geometric variations on key performance parameters (separation efficiency and pressure drop); there is little discussion of the underlying physical phenomena and flow/particle behaviors within VTSs that influence these.

VTS performance parameters, and their theoretical derivations, were covered extensively in the dissertation by Bojdo [7]. Examples of computational and experimental VTS studies can be found in three series of publications from research groups headed by Martin Pillei, Tadeusz Dziubak, and Ulrich Muschelknautz. The studies by Pillei et al. [8, 9] made use of particle image velocimetry (PIV) on the separation region of transparent vortex tube separators with various vane angles and centerbody diameters; filtration performance was indirectly measured using the nondimensional swirl number of the fluid as an indicator of vortical “strength”. Dziubak et al. [10, 11] incorporated detailed computational fluid dynamics (CFD) on VTSs that were recreated virtually with 3D scanning technology. These simulations were compared with physical experiments on a VTS ingestling particle-laden flow for model validation purposes. Muschelknautz et al. [12] investigated the effectiveness of non-traditional apparatuses for the discharge of dirty air from a VTS (for example, a window in the duct wall instead of the traditional annular outlet), and then published some of the only VTS array studies available in the literature [13, 14]. Referring to VTS arrays as “multicyclones”, these studies mathematically show advantages of axial uniflow cyclone separators over other types of cyclone separators in the “multicyclone” configuration. However, it is
important to note that the scavenge flow (referred to as “underflow” by Muschelknautz et al.) is assumed to be nonexistent as a “worst-case”, baseline scenario.

There is thus a distinct lack of literature on VTS arrays, particularly the intricate fluid and particle dynamics that define their performance. The presence of multiple separators contained within a common scavenge chamber greatly increases the complexity of the problem. The scavenge chamber of an array in operation will contain a chaotic flowfield of toroidal vortices that impinge on solid walls and interact with each other while being drawn to the scavenge port. It is possible that the interactions between VTS flows within the scavenge chamber and at/beyond the clean air outlets may affect the flow within each VTS as well, potentially altering separation efficiency. For example, if a device experiences increased axial flow velocity in its separation region, its separation efficiency may drop as some particles in the process of moving radially outwards will not have enough time or distance to reach the critical radius of filtration.

For these reasons, the current study aims to investigate the fluid flow emerging from the clean air outlets of a VTS array - particle dynamics will be investigated in a future experiment. This study involves three goals:

- Establish a procedure for the experimental measurement of VTS array flows.
- Analyze velocity data from the emerging vortices to identify impactful mean flow phenomena.
- Construct the preliminary framework for a mathematical model that predicts and explains some of these phenomena.

Experimental measurements are also intended to serve future computational validation efforts. Initial results from one measurement plane were first presented by Acharya et al. [15]. The current study extends analysis to two additional upstream planes. Section II provides a detailed account of the facility configuration, VTS array model design, and measurement techniques used. Section III presents experimental results, first addressing their validity and then comparing findings to other types of flows in the literature. Lastly, Section IV describes progress on a momentum integral model that, with further refinement, may be capable of predicting one of the important observed features. It is shown that the VTS array outlet flow quickly develops into a single vortex that clings to the edges of the surrounding duct, and that a strong recirculation zone forms in the center of the flowfield. This central recirculation zone is reminiscent of those found in combustion swirler flows and likely indicates strong axial flow gradients within upstream separators, which could affect filtration performance. It is not found in singular-VTS flows. The momentum integral model is then developed with the goal of reproducing and explaining the recirculation’s exclusive presence in VTS array flow.

II. Experimental Methods

A. Wind Tunnel Facility

VTS array experiments were conducted in the High-Speed Wind Tunnel (HSWT) at Virginia Tech’s Advanced Propulsion and Power Laboratory (APPL). The HSWT is an open-circuit wind tunnel with a test section diameter of 15.24 cm (6.00 in). The upstream end of the tunnel is a large flow conditioning chamber containing mesh screens and aluminum honeycomb to straighten any large-scale eddies that are ingested from the surrounding air. From there, an aluminum bellmouth transitions the flow to the 15.24 cm diameter test section. The body of the tunnel is primarily
composed of PVC, though materials vary in the test section. The test section may be equipped with a variety of measurement instruments, such as a Pitot-static (P-S) probe or a five-hole pressure probe. It can also support laser diagnostics with the use of clear optical walls or windows - in this case a quartz optical test section (OTS) was used. The tunnel expands to a diameter of 30.48 cm (12.00 in) downstream of the test section for compatibility with one of the blowers.

The tunnel flow is driven by two suction blowers, a Hoffman 751 Series centrifugal blower and a Roots-style Panther positive displacement blower by Busch Vacuum Solutions. The blowers can operate independently, which lent itself to VTS experiments; the Hoffman blower was used for the VTS inlet and clean air flow (primary) while the Panther blower was used for the scavenge flow (secondary). A schematic of the HSWT configuration used for this study is provided in Figure 4. At the far left end of the schematic, flow enters the flow conditioner and bellmouth. The bellmouth’s inlet has a diameter of 35.6 cm, which converges exponentially to 15.24 cm at its downstream end over a 15.24 cm axial span. The bellmouth is followed by a 20 cm long open duct. The red region downstream of this duct represents the VTS array model, which is followed by the tunnel test section. The flow diverges from the model; the VTS array’s clean air exits expel flow towards the primary suction blower while the scavenge lines send flow towards the secondary suction blower. Both the primary and secondary blowers are preceded by a secondary inlet through which air enters at a flow rate determined by the position of its corresponding gate valve. When the gate valves are fully closed, all flow enters through the secondary inlet and none passes through the VTS array and test sections. Adjusting the gate valves thus allows for control over primary and scavenge flow rates in the VTS array. The primary blower’s gate valve was located 10 tunnel diameters downstream of the test section in order to prevent any resulting upstream nonuniformities from affecting measurements. Upon testing of this configuration, it was found that very low velocities could be achieved in the test section (< 10 m/s with a VTS array model, described in the following section, placed in the tunnel). Velocities were measured with a Pitot-static probe between the bellmouth and VTS array.

![Fig. 4 Top-view schematic of High-Speed Wind Tunnel as configured for VTS array model experiments (not to scale).](image-url)
B. Scaled VTS Array Model

The lack of established VTS array experimentation literature necessitated a deliberately narrowed scope for this work. It was treated as an introductory study of the complex dynamics of array flows and is intended to be built upon by future studies. While experimentation on a full-size VTS array model with hundreds of separators was initially considered, the model was eventually reduced in size and separator count to ensure compatibility with the HSWT and to allow for future accompanying computational studies (which would be difficult with a great number of separators). The model was designed to act as a smaller version of a larger array: seven VTSs, or a central separator surrounded by six neighbors in a honeycomb pattern. It was believed that this model could be described as a "unit problem", a simplified version of the full VTS array that still represented its key geometric and flow features. These features were determined to be the following:

- Individual VTS model geometric dimensions identical or proportional to real VTSs
- Swirling flow through each VTS model of matching flow angle to real VTSs
- Scavenge separation from each VTS model of matching flow rate to real VTSs (broadly 5-20% of inflow [7]; often 10% or less [1, 13])
- Aerodynamic interactions between a VTS model and its neighboring VTSs that capture key interaction physics such as vortex merging, turbulence generation, mean flow redistribution, and possible unsteady coupling

The following paragraphs describe remaining differences between the VTS model and real VTS arrays and end with an explanation of the preservation of the above features.

To mitigate the "scavenge non-uniformity" issue discussed in Pall’s array patent [1], three evenly-spaced scavenge ports were included on the VTS array model; the total scavenge flow rate was split among them. This was done to eliminate a complicating factor from the flow so that other features could be isolated.

Seven life-size separators, according to the dimensions specified in Pall’s second patent [6], would have occupied only a fraction of the HSWT’s cross-sectional area, creating severe blockage. The separators on the model were thus scaled up by a factor of 2.5 from the patent’s dimensions. The book *Gas Cyclones and Swirl Tubes* by Hoffman and Stein [16] provides a comprehensive overview of the nondimensional parameters that must be considered for the scaling of cyclone separators and vortex tube separators, which those authors refer to as “swirl tubes”. Several assumptions are made, including the sphericity of inertial particles and ideally smooth walls. It is shown that particle separation efficiency scales on both the Reynolds number (ratio of inertial forces to viscous forces) and the Stokes number (ratio of particle timescale to fluid timescale), though dependence on the latter is much stronger. The pressure drop across the device scales on the Reynolds number alone. Matching of these nondimensional parameters for the scaled-up VTS array model would require a proportional decrease in the wind tunnel velocity; in some configurations (as described later in this section), this would have resulted in unreasonably low velocities with relatively high uncertainties. Additionally, the authors believed that the dominance of large-scale vortical phenomena limited the impact of the Reynolds number downstream of the VTS array (where measurements were taken). Thus for the current study, which did not involve any inertial particles, a 2.5x Reynolds number increase was acknowledged and accepted. Any future studies with particles may result in a 2.5x Stokes number increase as well, unless the particle size or other parameters are adjusted accordingly.

Figure 5 is a modified version of the diagram used in Pall’s second patent [6]; all dimensions are labeled for the scaled-up separators used in these experiments. The alphabetical dimension labels correspond to numbers provided in Table 1. Each separator contained four vanes (spaced 90° apart)
Table 1  VTS array model dimensions corresponding to Figure 5.

<table>
<thead>
<tr>
<th>Dim.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [cm]</td>
<td>4.30</td>
<td>4.03</td>
<td>1.08</td>
<td>2.92</td>
<td>4.32</td>
<td>4.40</td>
<td>0.82</td>
<td>5.67</td>
<td>0.62</td>
<td>0.37</td>
<td>5.42</td>
<td>2.39</td>
<td>8.80</td>
<td>14.5</td>
</tr>
<tr>
<td>Length [in]</td>
<td>1.69</td>
<td>1.59</td>
<td>0.43</td>
<td>1.15</td>
<td>1.70</td>
<td>1.73</td>
<td>0.32</td>
<td>2.23</td>
<td>0.24</td>
<td>0.15</td>
<td>2.13</td>
<td>0.94</td>
<td>3.46</td>
<td>5.71</td>
</tr>
</tbody>
</table>

with a pitch length of 8.53 cm (3.36 in) and a tip angle of 58°. The inlet tube diameter of each VTS, \( D_{VTS} \), was 4.30 cm. The clean air outlet radius of each VTS, \( r_1 \), was 2.16 cm.

The model’s scavenge chamber had a width of 15.24 cm, the same as the rest of the wind tunnel test section. Figure 6 shows a front view schematic (forward-looking-aft) of the model; the seven separators, each with four vanes forming a "+" sign shape, are visible. Spacings between the separators and walls and between the separators themselves were acquired (and scaled up) from measurements of a real Pall™ Centrisep array. Clear similarities exist between this experimental setup and multinozzle combustor rigs used in prior propulsion research [17]; indeed, combustion swirler flows will be discussed and compared to the current flow in Section III.

While separator count and scaling differences between the VTS array model and real VTS arrays were present, it was believed that the model represented a "unit problem". Individual separators in the model were designed with dimensions proportional to an actual VTS patent. Primary and scavenge flow rates introduced to this array model (described in detail later in this section) were also proportional to realistic VTS operating conditions, and the swirl vanes in each device generated swirling flow of matching angle to real VTSs. The array model was designed with a staggered pattern of 7 VTSs that matched the pattern found on a real VTS array, with both separator spacing and the angles between separators taken into consideration. This design, along with the existence of a scavenge chamber surrounding all VTSs, allowed for an accurate replication of the aerodynamic interactions between a central VTS and its six neighbors. A notable deviation from real arrays was the highly confined nature of the flow; the scavenge walls and wind tunnel duct tightly surrounded seven separators, whereas in real VTS flows many dozens or hundreds of separators are bounded by these same walls, potentially allowing for more interactions and the reduction of any duct...
confinement effects on the flow. These confinement effects are addressed in Sections III and IV. Hereafter, the VTS array model will be referred to simply as the “VTS array” to avoid confusion with the mathematical flow model to be presented later in the paper.

The array was composed of three major components: a plastic upstream section, a plastic downstream section, and an aluminum housing (see Figure 7). The upstream section formed the front face of the VTS array and the upstream ends of each of the seven separators, including the "inlet" tube containing the helical vanes and separation region (refer to Figure 5). The downstream section formed the rear face of the VTS array and the downstream ends of each separator – the "outlet" tube or the clean air exit. The hollow aluminum housing surrounded all the separators, acting as the walls of the scavenge chamber, and secured the upstream and downstream sections in place. 3D-printing was selected as the fabrication method for the upstream and downstream sections due to their complex geometries. Figure 7 shows this array and also an isometric view of a transparent individual VTS for clarity. In this figure, the helical vane region of one of the separators is labeled “A” (though only the outer wall of the tube is visible in the full array diagrams), and its separation region and clean air exit are labeled “B” and “C”, respectively. As shown in the bottom right diagram, the sections join together by aligning the outlet tubes to sit within their corresponding inlet tubes, just as the clean air exit ("C") of a VTS "sticks" into its separation region ("B") - (see Figure 5, dimension G).

The upstream and downstream sections were bolted onto each end of the hollow aluminum housing, which itself was fabricated with CNC machining and designed for easy installation into the High-Speed Wind Tunnel. Given that the housing acted as the walls of the scavenge chamber, it was necessary to include at least one port for "dirty" air to exit (though no inertial particles were used in this experiment); as described earlier, three ports were used to mitigate scavenge non-uniformity effects. Figure 8 is a diagram of the housing with the three scavenge ports labeled (Port 2 is at the
highest extremity of the chamber, known as top-dead-center or TDC), as well as a diagram of the fully assembled VTS array with the upstream and downstream sections secured into the housing. As initially shown in Figure 4, flexible plastic hosing was attached to each of the three ports to connect them to the secondary blower and enable scavenge flow.

In the 7-VTS configuration, the wind tunnel flow rate was set such that the axial velocity entering each separator (before filtration) was 18.00 m/s - equivalent to 10.03 m/s at the Pitot-static probe located in the open tunnel upstream of the model. Scavenge flow rates were set at 7% (split across the three ports) of the volumetric flow rate through the entire VTS array, or 12.81 L/s. Both the tunnel velocity (Pitot-static probe with manometer) and the scavenge flow rate (variable area flowmeters) were measured by eye from analog devices and were thus prone to some error. From the manometer’s resolution (ticks every 0.01” WC, assuming max error of half a tick), it was determined that the tunnel velocity was actually 10.03 ± 0.10 m/s. Scavenge flow measurements were complicated by apparent unsteadiness; the marker wavered around a central location. The magnitude of these wavers
and the resolution of the flowmeters (ticks every 0.2 SCFM, assuming max error of half a tick) led to a determination that the scavenge flow rate was $12.81 \pm 0.42$ L/s at any instant in time. An additional measurement of static pressure drop across a VTS in the array was made by inserting pressure taps into the wall of a separator; one tap was 1.40 cm downstream of the inlet and another was 1.40 cm upstream of the outlet (as near as possible given the complex geometry). The pressure drop was measured with the same manometer and was found to be $286 \pm 1$ Pa at the above conditions.

Section I established an interest in isolating and identifying features of VTS flow that result from the interactions between separators in the array. To address this, two “cover plates” were 3D-printed for the VTS array. As shown in Figure 9, they attached to the exterior of the upstream and downstream sections, blocking flow from entering the six separators surrounding the central tube. A (smooth-inlet) hole in the center allowed for flow to enter this central tube so that it was the only “active” separator generating the vortical flow necessary for VTS filtration. The scavenge chamber for this singular VTS still contained six other blocked VTSs and thus did not truly represent an isolated individual separator; however, it was believed that effects of separator interactions would still be greatly reduced as no flow was present in the blocked separators. For experiments in this 1-VTS configuration, wind tunnel flow rates were adjusted to maintain the velocity in the singular separator at 18.00 m/s. Owing to the vastly reduced cross-sectional area, this required the upstream open wind tunnel flow to be set to $1.43 \pm 0.10$ m/s. A proportional adjustment to the scavenge flow rate meant a total of $1.83 \pm 0.24$ L/s at any instant in time (the unsteady wavers were less pronounced in this case).

Figure 10 shows two pictures of the fully fabricated and assembled array, in both 7-VTS and 1-VTS configurations. 3D-printing was done by the company Xometry™ using an SLA process with Accura® ClearVue™ material. Machining of the aluminum scavenge chamber was done in-house at the Virginia Tech APPL.
C. Particle Image Velocimetry

This study used particle image velocimetry (PIV) to non-intrusively measure the flowfield downstream of the VTS array’s clean air exits. To conduct PIV, tracer particles are introduced into a fluid flow and illuminated with laser pulses in the measurement plane. Cameras image these illuminated particles and a processing software computes image cross-correlations to ascertain fluid velocities in the measurement plane, with the assumption that tracer particles behave exactly as the fluid does [18]. As one might expect, tracer particles must be small (< 1 μm in diameter for typical gas flows [19]) in order to justify this assumption by effectively following fluid streamlines; they differ significantly from the larger, high Stokes number inertial particles (like sand) that VTSs are designed to filter. PIV has seen extensive use in both laminar and turbulent flows [20], and is an Eulerian methodology; in each image, particles pass through static windows used for analysis. This
study specifically used time-resolved, stereographic PIV: time-resolved because of a high image acquisition/laser pulse rate (suitable for instantaneous data from highly turbulent high-frequency unsteady flows, the kind which VTS flow is expected to be) and stereographic because two cameras were used to acquire three-component velocity data.

Three PIV measurement planes were used, all normal to the axial wind tunnel flow, to allow for observation of the flow’s development with distance. They were located $0.23D_{VTS}$ (1.00 cm, 0.39 in), $0.58D_{VTS}$ (2.45 cm, 1.00 in), and $1.77D_{VTS}$ (7.62 cm, 3.00 in) downstream of the VTS outlets, and are referred to as Planes A, B, and C respectively. The $1.77D_{VTS}$ location (Plane A) was chosen to match the minimum downstream distance of a United Sensor™ Model DA-125 5-hole Cobra probe, which was traversed horizontally across the centerline of the tunnel to provide velocity data points for comparison with the PIV measurements. Data were obtained from the probe by use of an Esterline™ NetScanner Model 98RK pressure scanner; mean values were computed from 100 data points at each traverse location. According to manufacturer specifications, the static accuracy of the pressure scanner channels resulted in an uncertainty of $\pm 17.2$ Pa ($\pm 0.003$ psi).

At the PIV measurement planes, a Photonics Industries™ Nd:YAG dual cavity laser generated a 532 nm laser sheet at 15 mJ per pulse. For the primary measurements, the sheet was 0.64 cm (0.25 in) thick to allow for two captures of most particles (minimizing out-of-plane losses). Two Phantom v2512 cameras, equipped with 100 mm focal length lenses and Scheimpflug adapters, acquired images at 6.248 kHz. To verify repeatability and expose any lower-frequency motions, images were also acquired at 0.780 kHz and 1.562 kHz, but in this study all data shown is for the 6.248 kHz runs as no significant differences were found. Cameras were positioned 53.3 cm axially downstream of each measurement plane and 43.2 cm laterally from the center of the tunnel (on each side of the test section), forming an angle of $39^\circ$ from the plane (due to geometric constraints, this was the closest achievable angle to the ideal $45^\circ$) and capturing nearly the full tunnel cross-section. Double-frame images were acquired with a $dt$ (pulse separation) of 35 $\mu$s.

A Colt 4 seeder generated Fluid A tracer particles, both products of Concept Smoke Systems™, near the wind tunnel inlet. Fluid A particles were analyzed with a TSI™ 3321 Aerodynamic Particle Sizer, which found that 90% of particles had an aerodynamic diameter of less than 1.197 $\mu$m; an aerodynamic particle diameter is defined as the diameter of a sphere of water that settles in air at the same velocity as the analyzed particle. For the flow through the array separators, this 1.197 $\mu$m diameter translates to a maximum Stokes number of $2.57 \times 10^{-3}$ for the flow integral timescale $T_0$ (taking the separator diameter to be the integral length scale). A rough estimate of the Kolmogorov timescale $T_\eta$ can be found by approximating each VTS outlet flow as a round jet; prior studies have reported on peak turbulence dissipation rates $\epsilon$ for these flows [21], which can be used in the relation $T_\eta \equiv (v_g/\epsilon)^{1/2}$ provided by Pope [22] (where $v_g$ is the kinematic viscosity of air). This results in a Kolmogorov timescale on the order of $5.24 \times 10^{-5}$s and a Kolmogorov-based Stokes number on the order of 0.1. Raffel et al. [23] state that a Stokes number of 0.1 or less typically yields acceptable tracer particle accuracy. Figure 11 is a simple side-view schematic of the three PIV measurement planes, each shown as a vertical green line downstream of the VTS array. Figure 12 is a picture of the PIV setup for Plane C with major components labeled; note that the flow is from right to left as the tunnel could not be accessed from the other side. The laser sheet can be seen emanating downwards from its sheet-forming optics (D) and passing through the quartz test section (C) downstream of the array (E).

The DaVis 10 software by LaVision™ was used to coordinate all instruments, record high-speed images, and compute velocity data. 10,000 images were collected and processed for each of the
Fig. 11  Side-view schematic of HSWT test section, including VTS array and PIV measurement planes A, B, and C.

Fig. 12  Picture of PIV setup to measure flow downstream of VTS array.

six data sets presented in this study: three for the 7-VTS case, and three for the 1-VTS case. All data was treated with the time domain filter method [24] to mitigate the effects of laser flare on the
quartz boundaries of the test section. Images were first processed by two passes with 64x64 pixel interrogation windows, and then by four passes with 16x16 pixel interrogation windows (spatial resolution of 2.67 mm or 0.06$D_{VTS}$). All windows had 50% overlap. A median filter [25] with a 5x5 stencil was applied in post-processing to remove spurious vectors with a residual value greater than 2.0; removed vectors were replaced with interpolated data. Instantaneous velocity measurements were further treated through analysis of fluctuating (mean-subtracted) velocity histograms at each point; velocity ranges with instance counts totaling less than 2% of the most common range (typically 0 m/s) were eliminated. This was done to further reduce the detrimental effects of laser flare, some of which remained despite the time filter subtraction.

Random uncertainties from the PIV data were quantified to ensure that the data was statistically reliable. The standard formula for random uncertainty $\delta$ of a mean quantity $\bar{a}$ for a 95% confidence interval is shown in Equation (1).

$$\delta(\bar{a}) = \frac{2\sqrt{\sigma^2}}{\sqrt{N}}$$  (1)

When using time-resolved data, it is necessary to compute an effective number of samples that replaces $N$ in Equation (1) if $N_{eff} < N$. This is because the high frequency of image acquisition may exceed the eddy turnover frequency. The number of effective samples can be computed with Equation (2).

$$N_{eff} = \frac{T_0}{2\mathcal{T}_I}$$  (2)

The integral time scale $\mathcal{T}_I$ for the flow at the measurement plane is equivalent to the integral of the autocorrelation coefficient of velocity over time. The center-point of the duct was selected as the point of interest for this, and integral convergence of the axial velocity autocorrelation coefficient was achieved at a value of 0.0021 s for the 7-VTS case and 0.0015 s for the 1-VTS case. This translated to an $N_{eff}$ of 381 samples for the 7-VTS case and 533 samples for the 1-VTS case. Resulting uncertainties were used to generate 95% confidence error bars for mean velocity data shown in Section III.

### III. Experimental Results and Discussion

This section presents measured mean velocities downstream of the VTS outlets. First, data is shown for Plane C across the centerline of the duct to directly compare PIV and 5-hole probe (5HP) results for further uncertainty analysis. Then, a series of contour maps is provided to describe the full flowfield across all three planes. This is followed by a review of literature relating to the observed features. Section IV continues the effort to explain these observations.

All quantitative data in this study were converted to a cylindrical coordinate system due to the circular test section. Figure 13 is a diagram describing the orientation from which data are presented. It is a back view of the VTS array, looking upstream into the clean air exits (aft-looking-forward). A polar coordinate system is provided, with the third z-axis pointing downstream out of the page. The centerline of the duct, used in the following subsection, is defined in this figure as well. Note that the measurement planes were all downstream of the VTS outlets.
A. Centerline Data

Figure 14 shows the mean velocity components ($V_R$, $V_\theta$, and $V_Z$) across the duct centerline for Plane C (1.77$D_{VTS}$ downstream of outlets) as measured by both the 5-hole probe and particle image velocimetry. The centerline comprised 83 data points for the 5HP and 104 data points for the PIV. Error bars for the PIV data were generated using the method described at the end of Section II, and are shown for every fifth point in this figure. The $x$-axis is presented as radial position $r$ normalized on the wind tunnel duct radius $r_3$ (denoted as such for consistency with the geometry in Section IV). While this figure shows some discrepancies between 5HP and PIV radial velocities ($V_R$) at negative radius positions, the two datasets are remarkably consistent given the complexity of this highly three-dimensional flowfield, with velocity differences between 0.1 and 0.6 m/s, or 1.1% and 6.4% of the bulk through-flow velocity downstream of the VTS outlets (after scavenge separation). Circumferential velocity ($V_\theta$) trends are shown to be in good agreement across most of the centerline, especially at negative radius positions, where velocity differences ranged from 0.0% to 8.4% of through-flow velocity. From $r/r_3$ of around 0.0 to 0.4, the 5-hole probe recorded lower velocities than PIV, though trends align once more above $r/r_3$ of 0.4. Axial velocities ($V_Z$) show fair agreement for the entire centerline except very near the edges of the duct, with velocity differences ranging between 0.1% and 8.9% for $r/r_3$ of ±0.7. Possible sources of the discrepancies observed here include: slight misalignment between the PIV measurement plane and 5-hole probe traversing plane, detrimental tunnel vibration effects on PIV imaging, and slight flow rate differences due to these experiments not happening in immediate succession. The overall consistency of the independently acquired datasets establishes the repeatability of the flow case while also giving additional insight to actual uncertainties that could be used when quantitatively comparing the data for computational validation structures. Practice indicates that a posteriori uncertainties in validation experiments are always greater than those predicted from a priori analyses of instrumentation uncertainty.

Some physical conclusions can also be reached from this centerline data, and they are presented here to set up the ensuing subsections. Figure 15 shows the mean velocity components and random uncertainty error bars from PIV for both the 7-VTS and 1-VTS case at Plane C; all data shown hereafter is from the PIV experiment. Note that the $y$-axis scale is different for the 7-VTS and
Fig. 14  Mean velocity data across duct centerline at Plane C \((1.77D_{VTs})\) for both 5-hole probe and PIV experiments. 95% confidence interval error bars shown for every fifth PIV data point.

1-VTS case to allow for clear observation of 1-VTS features; subsequent data is presented in non-dimensional fashion with identical scaling. Analysis of the 7-VTS case reveals approximate symmetry of circumferential and axial velocity components about the central point. Axial velocity peaks around a normalized radius of 0.7 on each side of the central point, with much slower flow in the center region itself. This indicates the possibility of a recirculation zone in the center of the duct, a phenomenon that is further discussed later in this section. Circumferential velocity peaks at the extreme edges of the tunnel, suggesting strong counter-clockwise swirling flow in this region (note that the VTs also generated counter-clockwise swirling flow from this perspective). Circumferential velocity drops sharply outside of the edge regions, going so far as to become weakly negative (clockwise swirling flow) in the approximate range of -0.1 to -0.5 normalized radius. The radial velocity component appears less symmetric and is of low intensity throughout.

Significantly different flow is observed in the 1-VTS case; note the lack of apparent symmetry. A distinguishable feature of this flow is that circumferential velocity peaks remain on either side of the central point, suggesting some amount of bulk counter-clockwise swirling flow. The peak at a normalized radius of around 0.3 rapidly drops to negative velocity values at the central point, indicating that the vortex core of this swirling flow drifted to the left - vectors that point counter-clockwise on one side of the duct center will point clockwise on the other side. This drift, in addition to the asymmetric nature of the flowfield, points to the conclusion that duct confinement effects are a significant factor in this experimental setup. The 7-VTS flow, upon emerging from its outlets, occupies a large share of the duct’s cross-sectional area and is thus heavily constrained by...
Fig. 15  Mean PIV velocity data across duct centerline at Plane C ($1.77D_{VTS}$) with 95% confidence interval error bars; 7-VTS case (left), and 1-VTS case (right).

the walls of the duct. This may contribute to the symmetric nature of its downstream flowfield. The 1-VTS flow occupies a much smaller share of the duct’s area and is thus less constrained - it appears that other effects or perturbations significantly influence the outlet flow in this case, allowing the emerging vortex to drift and warp. These confinement effects are discussed further in the ensuing subsections.

B. Planar Data

Heatmaps of mean planar velocities $V_{planar}$ across all three measurement planes are shown for the 7-VTS case in Figure 16, and for the 1-VTS case in Figure 17. Planar velocity is defined here as the magnitude of radial and circumferential velocity components. Data is normalized on the theoretical velocity magnitude $V_{mag}$ through each VTS; assuming no radial velocity, this was computed to be 33.87 m/s. The radial axis is represented by rings with white axis labels, normalized on the test section duct radius $r_3$. Colorbar scaling is kept consistent across all six of the plots in these two figures to allow for direct quantitative comparison. Additionally, planar flow vectors are shown to emphasize the swirling nature of local and bulk flow. Recall that the presented data is for PIV at a 6.248 kHz acquisition rate; the 0.780 kHz and 1.562 kHz runs produced mean flowfields with no major differences from these in both configurations.

Figure 16 reveals an initially complex planar flowfield that develops into a simpler bulk swirling flow. At Plane A, pockets of intense planar velocities are found near the edge of the duct around circumferential positions of $45^\circ$, $135^\circ$, $225^\circ$, and $315^\circ$. Irregular regions of very low planar velocity dot the central regions of the duct. The overlaid vectors reveal multiple small vortical structures in the mean flow, including one around the center point (which appears to be expanding radially) and two that are visible around a normalized radius of 0.5, between circumferential positions of $45^\circ$ and $135^\circ$. These structures are likely examples of individual swirling VTS outlet flows that have been captured at this plane. They lie within a larger vortical pattern of strong counterclockwise vectors that grips the edge of the duct. At Plane B, many of the complex flow patterns in the center of the duct have been eliminated, leaving only some weaker small vortices that again are likely associated
Fig. 16  Mean planar velocity heatmaps and vectors for the 7-VTS configuration; Plane A (left), Plane B (middle), and Plane C (right).

Fig. 17  Mean planar velocity heatmaps and vectors for the 1-VTS configuration; Plane A (left), Plane B (middle), and Plane C (right).

with individual VTS outlet flows. Notably, the vortex that surrounded the center point (central VTS outlet flow) is nowhere to be found. The stronger vortical flow near the edges of the duct remains in place.

By the time the flow reaches Plane C, there is negligible planar velocity throughout most of the analyzed area. All that remains is the vortex at the extreme outer radii of the duct, which has preserved considerable strength. It appears that the flow features observed along the centerline in the previous subsection extend to the entire duct at Plane C - in other words, circumferential uniformity. Close inspection no longer reveals any features that may be attributed to the vortical flows emerging from individual VTSs upstream of the measurement plane; clearly, significant flowfield development and vortex interactions occur rapidly beyond the outlets. Analysis of several instantaneous velocity samples also did not produce any features that could be considered direct evidence of individual outlet airstreams, though those sample flow fields differed significantly from the mean data, pointing to the highly unsteady nature of this flow.

These plots show that the six non-central VTS vortices, constrained by the duct, apparently merge into a single vortex that is concentrated at the edges of the duct. The central VTS vortex is effectively eliminated or rapidly spread out due to the oppositely-swirling flow from all surrounding vortices. This merging behavior has been observed in studies of similar flows emerging from combustion swirler arrays [26, 27], wherein a duct-confined group of vortices fuses into one because
their interior (near-center) velocities mostly cancel each other out while their exterior (near-wall) velocities do not. It is notable that in the current study, merger occurs so quickly that no remnants of individual vortices are observed just 1.77 VTS diameters downstream of the outlets.

As one would expect, the 1-VTS case in Figure 17 shows swirling flow around a single point rather than multiple. Data at Plane A indicates a well-defined and centralized vortex that has quickly spread to occupy the entire duct within $0.23D_{VTS}$ of the outlets. Planar velocities do not reach the same maximum values as in the 7-VTS case, as there are no neighboring vortices to combine or conflict with planar flow paths. A single small pocket of very low planar velocity is found as the center of the duct, about which the larger vortex churns. Little changes at Plane B save for a slight decrease in general planar velocities, especially at higher radii. Interestingly, at Plane C the planar flow is not circumferentially uniform, which was expected from the centerline data. A general (though severely weakened) counter-clockwise vortical trend is still visible, but the center or core of this vortex is no longer at the center-point of the duct, a result that was hinted at by the centerline data. The vortical stream appears to have shifted laterally between Planes B and C. As discussed previously, this may be a result of the lessened confinement in the 1-VTS case, allowing factors other than the duct walls to significantly influence the flow (though it is difficult to identify these factors with the current data). This lack of confinement may also explain why the vortical flow at this plane appears "lopsided", with slightly higher planar velocities in the upper regions of the duct.
Fig. 20  Mean radial velocity data for the 7-VTS configuration with upstream VTS outlet locations overlaid; Plane A (left), Plane B (middle), and Plane C (right).

Fig. 21  Mean radial velocity data for the 1-VTS configuration with upstream VTS outlet location overlaid; Plane A (left), Plane B (middle), and Plane C (right).

(θ = 30° to 200°) than below it (all other θ). In any case, much of the vorticity apparent at Planes A and B appears to have dissipated by Plane C.

Heatmaps of only the circumferential velocity $V_\theta$ are presented for the 7-VTS case in Figure 18 and for the 1-VTS case in Figure 19. Instead of vectors, a diagram of the upstream VTS outlets is overlaid on these plots. Note that the colorbar scales have been extended to include some negative values. It is immediately observed that the circumferential component is dominant within the planar flow as the heatmaps are very similar to their planar magnitude counterparts. In the 7-VTS configuration, Plane A data reveals a ring of negative $V_\theta$ centered approximately around a normalized radius of 0.5. It is surrounded by a ring of positive $V_\theta$ (the outer vortex discussed above). Note that the six outer separators appear to straddle the two rings. This is a result of the individual swirling flows from each VTS outlet passing through Plane A; the outlets each produce a region of clockwise swirling flow paired with a region of counter-clockwise swirling flow as seen from the origin. In the center of the duct, a lobe of positive $V_\theta$ is visible, indicating the counter-clockwise swirling flow emerging from the central VTS outlet. This lobe is fully positive as it is centered on the origin. These oppositely-signed regions are a key part of the momentum integral model presented in Section IV. Many of these features are observed at Plane B (though the central lobe is greatly diminished). The presence of contributions from individual separators in these data is notable, as previous work at only Plane C [15] was not able to capture these.

65
Radial velocity $V_R$ data is presented in Figure 20 for the 7-VTS case and Figure 21 for the 1-VTS case. Note the lowered colorbar scale. As with the circumferential velocity, Plane A shows evidence of individual swirling flows emanating from each of the separators. In this case, the non-central outlets of the 7-VTS case straddle lobe pairs of positive and negative $V_R$ at Plane A. The central outlet appears to be associated purely with positive $V_R$, indicating the radially expanding flow that was seen in the planar magnitude data in Figure 16. This region of expansion is not observed to the same extent in the 1-VTS case until Plane B. In both configurations, the distinct lobes diminish in intensity with distance downstream. While the vortical outlet flows clearly interact rapidly upon exiting the array, at Plane A (and Plane B, to an extent) there remain enough features to isolate pieces of the flowfield specific to individual separators.

Figures 22 (7-VTS) and 23 (1-VTS) present axial velocity data in the same format. A distinct pattern is immediately observed in the 7-VTS case at all planes: high axial velocities in a ring around the center, and much lower (near-zero) axial velocities in the center itself. At Plane C, like the planar velocity magnitude, this appears to be a circumferentially uniform extension of the centerline data presented previously. Each VTS outlet expels a stream of vortical flow with significant axial velocity - the six non-central flows spread and merge to form the observed ring of high axial velocity at Plane A. In contrast, there is no clear evidence of the central VTS stream at any location. Consider that typical swirling flow is known to generate significant radial pressure gradients, which causes the
flow to quickly expand and results in the generation of positive axial pressure gradients around the center [28]. This is known as a central recirculation zone (CRZ) as it can involve the stoppage or even reversal of axial flow along a centerline. It is considered a form of vortex breakdown, wherein vortical fluid streams depart drastically from their upstream behavior and begin to migrate, swell, or break apart [29]. A general representation of a strong CRZ in a swirling flow with a sudden duct expansion is provided in Figure 24, where the axial component of flow streamlines is represented by blue arrows. The vortical fluid initially travels downstream axially, but the expansion of the duct allows it to migrate radially outwards, leaving a region of low pressure in the duct’s center. Fluid is then pulled into this region, reversing the flow’s axial streamlines and forming a recirculation zone (outlined roughly by the orange dashed line). A CRZ appears to be present in the 7-VTS data, implying that the central VTS flow rapidly expands and joins the ring of high axial velocities upstream of the measurement plane. This rapid expansion is confirmed by the planar and radial velocity data shown earlier. Most of the central VTS flow’s kinetic energy in the axial direction is redirected to the radial direction, as shown by the vectors in Figure 16 and the central region of high $V_R$ in Figure 20. A hypothetical depiction of this process is given in Figure 25, in the same style as Figure 24.

1-VTS data does not show signs of a central recirculation zone - rather a single well-defined region of high axial flow is shown to expand and weaken slightly between Planes A and B. By Plane C the axial velocity is low throughout the duct. Close inspection reveals that multiple weak lobes of positive and negative axial velocity are present, mainly in the region defined by $45^\circ < \theta < 270^\circ$. These lobes may be evidence of other forms of vortex breakdown. According to the review by Lucca-Negro and O’Doherty [30], turbulent vortex flows may undergo "spiral-type" or "bubble-type" breakdown; the latter is marked by the emergence of an oblong envelope of recirculating fluid. This envelope has been found to contain multiple recirculation zones in some past experiments [31], leading to the possibility that the observed flowfield is undergoing an asymmetric form of bubble-type breakdown. This may also explain the apparent lateral shift in the vortex core shown by planar velocity data. In

![Fig. 24 Simple schematic of a strong central recirculation zone in a swirling flow with a sudden duct expansion. Axial flow streamlines are shown as blue arrows, circumferential flow streamlines are shown as gray arrows (inlet only), and the recirculation zone is bounded by an orange dashed line.](image-url)
any case, such behavior is weak and not present until Plane C.

It is notable that a distinct central recirculation zone is present in the 7-VTS flow, but not in its 1-VTS counterpart. Vortical flows require a certain level of swirl intensity to induce strong breakdown and recirculation [32] - this is known as the critical swirl. All VTSs in the current study had the same internal (local) swirl intensity, so it appears that the combination of seven vortices in the array case was necessary to surpass the critical swirl and produce the unique features one may expect to find in a vortical expanding flow. The 1-VTS case, on the other hand, apparently fails to reach its critical state, behaving more like a standard round jet at Planes A and B. This is demonstrated in Figure 26, which plots axial velocity $V_Z$ normalized on the centerline jet velocity $V_ZC$ at each of the two planes against radial position normalized on the jet half-width $r_{half}$. As per Chapter 5 of Pope’s book [22], a round jet’s mean velocity profile is expected to be self-similar, collapsing into a single curve when plotted in this manner. Indeed, the 1-VTS data appears as a self-similar round jet for $r/r_{half} \leq 1.5$, implying it has not achieved the critical swirl necessary to begin rapid vortex breakdown and recirculation. The following subsections provide more information on the causes and behaviors of central recirculation zones. In Section IV, a mathematical explanation is given for the 7-VTS case reaching a supercritical state while the 1-VTS remains subcritical.

Before continuing, the authors wish to briefly bring attention to the symmetric placement of the multiple scavenge ports. As stated earlier, this was done to minimize the effects of scavenge flow non-uniformities across the VTS array, which have been observed by Pall [1] in real arrays. In such an array, more scavenge flow is extracted from separators closer to the scavenge port than those farther away. Applying this concept to the mean flow results in the current study, one would expect some slight differences in outlet axial velocities across the measurement plane if the model contained
only one strong scavenge port. Any unsteady flow phenomena within the existing model’s scavenge chamber may be more difficult to extend to a one-port model conceptually. Such phenomena will be discussed in a sequel study. Certainly motivation exists for future experimental work using a one-port VTS array model to quantify any scavenge non-uniformity effects on the observed flowfield.

C. Central Recirculation Zone Literature

In this subsection, the authors aim to address three questions about the observed 7-VTS recirculation zone using the available literature. These are:
- What is the nature of the recirculation zone?
- What is the effect of duct confinement on recirculation?
- Why is this important for VTS flow physics?

1. What is the nature of the recirculation zone?

The 7-VTS case is marked by a central recirculation zone which forms rapidly, with nearly stagnant central flow observed at most just $0.23D_{VTS}$ downstream of the outlets. CRZs are most commonly found and studied downstream of combustion swirlers (used in jet propulsion). In such
flows, CRZs are considered desirable as they contribute to flame stabilization and the mixing of combustion products. The dissertation by Fu [33] describes the nature of these swirlers and a series of experiments conducted to study their downstream aerodynamics - resulting contour maps and vector fields reveal the presence of significant CRZs in many flow configurations. CRZs display a strong dependence on the swirl number, another nondimensional parameter used to characterize the strength of a swirling flow. The swirl number $S_w$ is defined as the ratio of the axial flux of angular momentum to the axial flux of axial momentum. Fu experimentally studied the flow downstream of combustion swirlers with swirl numbers ranging from 0.48 to 1.23 (varying vane tip angle), after an expansion into a duct 2.6 times the radius of the swirler. At lower swirl numbers (less swirl strength), reduced axial pressure gradients allowed for the swirler outlet flow to continue without any noticeable recirculation. Between swirl numbers of 0.69 and 0.83, however, a distinct central recirculation zone formed. This CRZ was found to increase in size and strength as swirl number increased. Thus the critical swirl number was in that range.

While the swirl numbers in Fu’s combustion swirlers cannot directly be compared to VTSs, some similarities do exist between the two flows. For example, the combustion swirlers contained centerbodies and helical vanes. In his dissertation, Fu employed a simplified formula for the swirl number, shown in Equation 3, based on the radius of the swirler $R_2$, the radius of the centerbody $R_1$, and the vane tip angle $\beta_t$. This was derived with the understanding that $V_\theta = V_Z \cdot \tan(\beta_t) \cdot r / R_2$. Applying this to the current study’s VTS flow yields a localized swirl number (in each VTS) of 0.85. The flow is thus intensely swirling, but barely exceeds the range of possible critical swirl numbers that Fu found and cannot be confidently deemed “supercritical”. The critical swirl number of each VTS likely differs from the swirlers due to geometric differences (the centerbody does not occupy the full VTS length, and the scavenge exit is a unique feature) and a different expansion ratio (discussed further in the next subsection). Given that the 1-VTS flow did not produce recirculation, the critical swirl number was clearly not surpassed. In any case, the 7-VTS flow saw a single recirculation zone rather than one associated with each VTS, suggesting that a global measure of swirl (across all outlets) may be more appropriate.

$$S_w = \frac{G_{\theta Z}}{G_{ZZ} R_2} = \frac{2\pi \cdot \int_{R_1}^{R_2} \rho_g \cdot V_\theta \cdot V_Z \cdot r^2 \, dr}{2\pi \cdot R_2 \cdot \int_{R_1}^{R_2} \rho_g \cdot V_Z^2 \cdot r \, dr} = \frac{R_2^2 + R_1^2}{2R_2^2} \cdot \tan(\beta_t) \quad (3)$$

It is worth noting that some studies have been conducted on combustion swirler arrays (arranged in a grid pattern). Fu’s dissertation showcases multi-swirler arrays wherein central recirculation zones are not distinctly visible. Other multi-swirler studies [26, 27] have observed weak CRZs in the center of the downstream duct. Velocity data from these studies, including the recirculation zones, were compared to measurements of flame structure in a reacting flow downstream of the multinozzle combustor first discussed in Section II [34]. It is likely that CRZs in the multi-swirler case are highly dependent on additional factors, such as duct confinement and swirler spacing, which makes a comprehensive review and comparison to VTS flows challenging.

2. What is the effect of duct confinement on recirculation?

It has been stated previously in this paper that the confinement of the HSWT duct walls on the VTS array flow may have influenced the flow development. A real array may have a much greater
distance between any group of seven VTSs and the duct wall. Can a central recirculation zone still be expected to form in such a flow? The dissertation by Fu [33] studied CRZs with various duct confinement levels for a combustion swirler with a swirl number of 1.00. These levels were defined by expansion ratios (by radius) of 1.30 to 3.26, with an additional case completely free of any local confinement. For reference, the expansion ratio of a single VTS into the HSWT duct in the current study was 3.52. Fu found that highly confined flows (low expansion ratio) featured a small but strong CRZ in the center of the duct, occupying less than half of the duct’s area. In contrast, less confined flows featured slightly weaker CRZs that grew very large, occupying over two-thirds of the duct area. In these cases, swirling jets emerged from the combustion swirler at steep angles, rapidly spreading the flow radially and allowing for adverse axial pressure gradients to form in large portions of the central regions. The unconfined case saw a recirculation zone so large that it occupied the entire width of the measurement region.

These findings suggest that the CRZ observed in the current study may persist even if the duct was much larger, albeit with significant growth in size and loss in strength. Note, however, that a real VTS array would also contain many other vortex tube separators occupying this enlarged space. It is possible that a similar result would ensue as the emerging vortices develop based on their proximity to the duct wall, especially given the global nature of the recirculation zone. This topic will be revisited at the end of Section IV.

3. Why is this important for VTS flow physics?

Though the central recirculation zone in the 7-VTS case was observed just downstream of the VTS array, there are potential implications of this to VTS flow physics and operation. Consider that separators leading into CRZs will experience strong axial velocity gradients in and around their outlets. The extent of these gradients in combustion swirlers has been demonstrated by Rojatkar et al. [35, 36], who used computational fluid dynamics to study axial flow development. Contour maps show negative (reverse) axial flow occurring upstream of the swirler exits in most cases - that is to say, the recirculation zone extends into the swirler itself! This is of little concern in combustion applications, but is potentially very impactful in VTS flows. It is possible that, given how rapidly recirculation is shown to develop, the reduced or reversed axial flow zones associated with CRZs extend into the vortex tube separators themselves. This could significantly affect VTS filtration, which depends on specific primary and scavenge flow rates to achieve desired separation efficiencies.

IV. Momentum Integral Model

Two important questions remain:
- What is the physical reason for the occurrence of a central recirculation zone in the 7-VTS case, but not the 1-VTS case?
- How can the findings of this paper be extended to larger/general VTS array flows?

To answer these, the authors have constructed the framework of a mathematical model for central recirculation downstream of vortex tube separators. The model involves the use of mass and momentum integral conservation laws, given velocity profiles at two stations. It is primarily inspired by the work of Hallett [37], who first devised such a model for the onset of recirculation in singular swirling jets undergoing sudden expansion. This was followed by more detailed models [38, 39] that computed useful recirculation quantities, such as recirculating mass flow rate. The current study
focuses on the simple onset of recirculation as a beginning effort. The newly constructed model extends the single swirling jet to multiple swirling jets, as in a VTS array flow, and the authors use it to examine effects on the onset of recirculation as well as the underlying cause of observed phenomena.

A. Mathematical Construction

First, a model is constructed for the 1-VTS flow, which is a simple adaption of Hallett’s method for a single swirling jet. Figure 27 shows a half cross-section of the single vortex tube separator outlet expanding into the HSWT duct. The control volume of analysis is contained between Stations 1 and 2, where Station 1 is a plane at the VTS outlet and Station 2 is a plane at the downstream location where recirculation would theoretically begin. The flow is assumed to be axisymmetric about the dotted black centerline at the bottom of the figure. Profiles of axial velocity $V_Z$ and circumferential velocity $V_\theta$ are provided at each station, with the thin blue lines marking zero. Radial velocity $V_R$ is assumed to be negligible in this analysis; while radial expansion of the flow was observed at the PIV planes shown in Section III, it theoretically would not begin until immediately downstream of the VTS outlet plane.

The assumed profiles at Station 1 are that of a Rankine vortex; within a defined vortex core (marked by radius $a_1$), $V_\theta$ decreases linearly towards a centerline value of 0, while outside of the core it decreases as $1/r$ (never quite reaching zero due to upstream transport of angular momentum by corner recirculation zones, as discussed by Hallett [37]). The peak circumferential velocity, like any Rankine vortex, is determined by the circulation $\Gamma$ (to be solved for) within the swirling flow. $V_Z$ is treated as a flat jet velocity that drops to 0 outside of the VTS outlet radius, marked here as $r_1$. However, the model allows for a linear increase in axial velocity within the vortex core through the adjustment of an input parameter $\lambda$. At Station 2, $V_\theta$ again decreases linearly within a downstream vortex core of radius $a_2$, but remains flat at some velocity $V_\theta_2$ (to be solved for) outside of the core. $V_Z$ is approximated as a parabola that begins at some velocity $V_Z_2$ (to be solved for) at the duct radius $r_3$ and reaches exactly 0 at the centerline - the onset of recirculation, such that any more swirl would bring about negative $V_Z$ at this point.

Fig. 27 Cross-section of 1-VTS outlet and downstream duct, where the dashed black line marks the duct centerline. $V_Z$ (red) and $V_\theta$ (green) profiles presented at Stations 1 and 2; blue line marks 0 velocity.
Piecewise functions describing the Station 1 profiles for 1-VTS flow are provided in Equations 4 and 5. The Station 2 profiles are subsequently described by Equations 6 and 7.

1. \[ V_Z = \begin{cases} V_{Z1} [\lambda - (\lambda - 1)] \frac{r}{a_1}, & 0 \leq r \leq a_1 \\ V_{Z1}, & a_1 < r \leq r_1 \\ 0, & r_1 < r \leq r_3 \end{cases} \] \hspace{1cm} (4)

2. \[ V_\theta = \begin{cases} \frac{r_2}{a_1}, & 0 \leq r \leq a_1 \\ \frac{r}{r_2}, & a_1 < r \leq r_3 \end{cases} \] \hspace{1cm} (5)

1. \[ V_Z = \begin{cases} V_{Z2} \left( \frac{r}{r_3} \right)^2, & 0 \leq r \leq r_3 \end{cases} \] \hspace{1cm} (6)

2. \[ V_\theta = \begin{cases} V_{\theta2} \left( \frac{r}{a_2} \right), & 0 \leq r \leq a_2 \\ V_{\theta2}, & a_2 < r \leq r_3 \end{cases} \] \hspace{1cm} (7)

Extending the model to the 7-VTS case required significant modifications to the Station 1 profiles. It is important to note that the axisymmetric assumption remained in place for the 7-VTS case. The flow at the outlet plane of the VTS array was not technically axisymmetric, but rapid mixing (and possibly upstream convection of angular momentum) was observed in PIV experiments that created a similar outcome. For instance, consider Plane A’s \( V_Z \) profile at \( \theta = 0^\circ \) across all radii. If this is extended circumferentially without any changes, as would be true in an axisymmetric flow, the resulting mass flow rate is nearly identical (0.2% difference) to the integrated mass flow rate calculated from all points in Plane A. While Plane A did not coincide exactly with the VTS outlet plane, its close proximity leads the authors to believe that the axisymmetric assumption was justified for a preliminary attempt at a momentum integral model to ensure simplicity. The new velocity profiles are shown in Figure 28, along with additional geometrical dimensions such as the spacing between the VTSs \( (r_{s1}) \) and the spacing between the outer VTS and the duct wall \( (r_{s2}) \). The non-central outlets are represented by an additional Rankine vortex and axial jet. As these outlets are not along the centerline, the full vortex is shown, rather than only half as with the central VTS. Because circumferential velocity is computed with reference to the centerline, the non-central VTS flow appears as a region of inner negative \( V_\theta \) paired with an opposite region of outer positive \( V_\theta \) (see Figure 18, where non-central VTSs are shown to produce fairly axisymmetric bands of negative and positive \( V_\theta \)). For simplicity, a discontinuity was introduced in the circumferential velocity between the two VTS outlets, in the region where both flows decay as the inverse of distance from their vortex axis, but with opposite signs. The 7-VTS Station 1 velocity profiles are described by Equations 8 and 9. Station 2 was kept the same as the 1-VTS case, as according to the PIV results a single large vortex and recirculation zone can be expected.
This model utilized the governing conservation laws of fluid mechanics in their integral forms. These three equations - conservation of mass, conservation of angular momentum, and conservation of axial momentum - are given in Equations 10-12. These have been simplified assuming an inviscid, axisymmetric flow. They do not account for the effects of turbulent stresses.

\[ \int_0^{r_3} V_Z r \, dr = \text{constant} \]  \hspace{1cm} (10)

\[ \int_0^{r_3} V_Z V_\theta r^2 \, dr = \text{constant} \]  \hspace{1cm} (11)
\[ \int_{0}^{r_3} V_Z^2 r \, dr + \int_{0}^{r_3} \frac{P}{\rho} r \, dr = \text{constant} \quad (12) \]

The pressure term \( P \) in Equation 12 can be expanded using the radial momentum conservation equation (radial velocity being negligible), as shown in Equation 13. The Bernoulli Equation for flow along the central stagnation streamline is given in Equation 14, replacing all unknowns in the pressure distribution with known quantities. Thus a system has been constructed containing three unknowns \((V_Z, V_{\theta}, \Gamma)\) that are solved with three equations (Eq. 10-12).

\[ P = P_0 + \rho g \int_{0}^{r} \frac{V_{\theta}^2}{r} \, dr \quad (13) \]

\[ P_{02} - P_{01} = \rho_g \lambda^2 \frac{V_{Z1}^2}{2} \quad (14) \]

Given the choice of velocity profiles, the quantity \( \Gamma \) can be considered \( \Gamma_{cr} \): the circulation in each VTS necessary to induce a central recirculation zone in the duct, or the critical circulation. It can be plugged into Equations 5 and 9 to determine the corresponding circumferential velocity \( V_{\theta} \) in each VTS. A critical swirl number \( S_{w, cr} \) can then be computed at Station 1 using Equation 15 for any desired radius of analysis \( R \).

\[ S_{w, cr} = \frac{\int_{0}^{R} V_Z V_{\theta} r^2 \, dr}{R \int_{0}^{R} V_Z^2 r \, dr} \quad (15) \]

Previously-cited studies on recirculation zones in combustion swirler flows and general swirling flows have mostly computed what the current authors refer to as a local swirl number - one that measures the swirl intensity within the initial jet, before expansion, which may eventually create recirculation in a larger downstream duct. Similarly, Hallett’s version of the critical swirl number [37] is localized, as he sets \( R \) in Equation 15 to \( r_1 \), the radius of the swirling jet prior to expansion. In the current study, however, it was observed that multiple swirling jets (VTS outlet flows) form a single central recirculation zone. As this was a clearly a global phenomenon resulting from the effects of several combined separator outlet flows, the authors elected to compute a global swirl number - one that took into account the full duct radius at Station 1. In other words, \( R \) in Equation 15 was set to \( r_3 \), the radius of the HSWT test section. This was done in both the 1-VTS and 7-VTS cases for consistency.

The newly-constructed momentum integral model was run using VTS geometry as shown by Figures 5, 6, 27, and 28; \( r_1 = 0.0216 \, m, \ r_{s1} = r_1/3.429, \ r_{s2} = r_1/4.235, \ r_2 = 2r_1 + r_{s1}, \) and \( r_3 = r_2 + r_1 + r_{s2} \). The baseline axial jet velocity was computed by subtracting 7\% from the known inlet volumetric flow rate of each VTS (removal of scavenge flow); \( V_{Z1} = 16.6 \, m/s \). The parameters \( \lambda \) and \( a_1 \) were treated as variable inputs because no detailed data measuring the vortex core within each VTS were available. Downstream vortex core radius \( a_2 \) was set assuming growth proportional to the duct expansion, which Hallett [37] found to be a reasonable assumption; \( a_2/r_3 = a_1/r_1 \). In any case, model outputs were found to have only weak dependence on \( a_2 \).
B. Model Results and Discussion

The model determined global critical swirl number for a range of \( \lambda \) and \( a_1 \) inputs and found that across most conditions, \( S_{w_{cr}} \) was significantly higher for the 7-VTS case than the 1-VTS case. This is shown in Figure 29, which presents critical swirl profiles for the ranges \( 0.8 \leq \lambda \leq 1.0 \) and \( 0.2 \leq a_1/r_1 \leq 1.0 \). However, the global swirl number itself for the 7-VTS was also expected to be higher than its 1-VTS counterpart. To demonstrate this, an integrated global swirl number was computed from \( V_\theta \) and \( V_Z \) data across PIV Plane A, \( 0.23 D_{VTS} \) or \( 0.46 r_1 \) downstream of Station 1 (see Figures 18, 19, 22, and 23). It was found that \( S_w = 0.48 \) for the 7-VTS case and \( S_w = 0.15 \) for the 1-VTS case. Note that the global swirl number was likely underrepresented in the 7-VTS case due to small areas of intensely swirling flow within the duct being cut off by the edges of the field of view.

These computed values are overlaid onto the Figure 29 curves as horizontal lines for reference. This figure thus serves to demonstrate the plausibility of 7-VTS global swirl number exceeding its critical swirl number while 1-VTS does not. For example, if no axial velocity differences are present in the VTS vortex cores (\( \lambda = 1.0 \)) and if the vortex cores occupy more than 75% of each VTS (\( a_1/r_1 > 0.75 \)), the model finds that the 7-VTS flow surpasses its critical swirl number (supercritical state) while the 1-VTS flow remains just below its own critical swirl number (subcritical state). In other words, only the 7-VTS flow sees a central recirculation zone, as was observed in the PIV experiment. The reader should note that this does not serve as a validation of the model, given the lack of actual measured \( \lambda \) and \( a_1 \) values and the use of comparison data that is not located exactly at Station 1. It is instead presented merely to showcase that the model is capable of reproducing the observed results under what the authors consider to be reasonable input conditions. Additionally, it opens the door to some further discussion about the mathematical and physical cause of recirculation that is exclusive to the 7-VTS flow.

![Fig. 29 Critical global swirl number at Station 1 to induce recirculation for 7-VTS and 1-VTS cases. PIV-computed global swirl numbers at PIV Plane A overlaid; solid black line (7-VTS) and dashed black line (1-VTS).](image-url)
Consider what drives a swirl number mathematically; being the angular momentum flux divided by the axial momentum flux (both in the axial direction), it would require increased angular momentum flux or decreased axial momentum flux to rise in value. The 7-VTS case, as just shown, produces a high global swirl number despite the presence of a large region of negative swirl for \( r_1 + \frac{r_2}{2} < r < r_2 \). This is because angular momentum flux scales on the square of radius (see Equation 15), meaning the highly positive swirl region at the extreme edges of the duct \((r > r_2)\) contains very high angular momentum - more than enough to overcome the deficiency introduced by the negative region. Thus, the outer (non-central) VTSs contribute disproportionately to positive angular momentum flux. The accompanying rise in axial momentum flux from these VTSs, which would otherwise serve to prevent a rise in swirl number, is limited in impact because axial momentum only scales linearly with radius. Physically speaking, one can simply note the ring of strongly positive \( V_\theta \) that grips the outer edge of the duct in Figure 18; this swirling flow occurs quite far from the duct centerline, inherently raising its angular momentum. Thus, swirl number is much higher for the 7-VTS than the 1-VTS case, which has no such swirl at its outer radii. It is then unsurprising that 7-VTS flow may exceed its critical swirl number for recirculation while 1-VTS flow does not.

This concept may be extended to VTS arrays larger than the simple 7-separator version used here, provided the geometry is close to symmetric and that separators are generally in close proximity to each other. Consider a large array, similarly shaped to the model used in the current study, but with many more layers of outer (co-swirling) separators surrounding the central VTS. It is likely that, under the correct conditions, the same global phenomenon would occur - a single large recirculation zone forms in the center of the downstream duct. This is because, as in the current study, each outer separator would produce both positive and negative swirl from the perspective of the centerline, but the positive swirl region would be located at higher radii and thus contain higher angular momentum than its negative counterpart, driving up the global swirl number.

The authors believe the momentum integral model presented here to be a promising first step towards the prediction of recirculation in VTS array flows and general flows involving multiple swirling jets. A formal validation of its accuracy is necessary to proceed. Reasonable accuracy may require improvements to the assumed velocity profiles at Stations 1 and 2, and would also be aided by an extension of the model into another spatial dimension (removal of the axisymmetric assumption). Once validated, the model may serve as a design tool for VTS arrays, multi-swirler combustors, and any other flows in which control over the generation of a central recirculation zone is desirable.

V. Conclusions

Particle image velocimetry experiments were conducted to study the fluid flow emerging from the clean air outlets of a vortex tube separator array model containing seven separators - most of the current literature focuses instead on singular separators. Measurement planes were located 0.23\( D_{VTS} \), 0.53\( D_{VTS} \), and 1.77\( D_{VTS} \) downstream of the outlets. PIV measurements found that the vortices emerging from the array quickly merged into a larger vortex with high circumferential velocity concentrated at the duct edges, while a region of slowed or reversed axial flow occupied the center of the duct. When all but the central VTS were blocked off (simulating single-VTS flow), a vastly different flowfield emerged - one that had not surpassed the critical swirl number necessary for recirculation and instead resembled more of a typical round jet. The central recirculation zone observed in the 7-VTS flow was compared to similar features often found downstream of combustion...
swirlers. It was hypothesized that the recirculation began upstream of even the $0.23D_{VTS}$ plane, potentially implying strong axial flow gradients near or even within the outlet of the central VTS - something that could affect filtration performance.

A momentum integral model of the flow was developed to predict and explain the onset of recirculation that is exclusive to the VTS array flow. While the model requires further adjustment and validation, it was able to show the plausibility of 7-VTS flow exceeding its critical swirl number while 1-VTS flow does not. The root cause of this is the vastly increased global swirl number that 7-VTS flow experiences due to swirl located at its outer radii, which disproportionately contributes to higher angular momentum.

This study will be followed by a sequel that includes turbulence statistics and modal decomposition of the fluctuating data, as the flowfield was found to be highly unsteady. The authors also intend to make available the mean and instantaneous data, as well as wall pressure and inlet condition measurements, for future computational validation efforts. Eventually, experiments will be conducted with inertial particles entrained in the flow to observe particle dynamics and relate observed behaviors to previously-recorded fluid phenomena.

Acknowledgments

This work was supported by the Office of Naval Research through grant N00014-21-1-2633, program manager Dr. Steven Martens. Author Adit S. Acharya is supported by a National Defense Science and Engineering Graduate (NDSEG) Fellowship. The authors are grateful to the Naval Air Systems Command (NAVAIR) and Pall Corporation for their insights and feedback on this project.

References


Chapter 4

Turbulence and Coherent Motions Downstream of a Vortex Tube Separator Array

The contents of this chapter will be submitted to *Experiments in Fluids*. 
Turbulence and Coherent Motions
Downstream of a Vortex Tube Separator
Array

Adit S. Acharya¹, Jubel Kurian¹, K. Todd Lowe¹ and Wing F. Ng¹

¹Advanced Propulsion and Power Laboratory, Virginia Tech,
Blacksburg, Virginia, USA.

Corresponding author: aacharya@vt.edu;

Abstract

Vortex tube separator (VTS) arrays filter harmful particles from turboshaft engine intakes with centrifugal forces. These arrays typically contain dozens or hundreds of separators, enabling significant aerodynamic interactions. Despite this, most researchers in the past have studied individual VTSs acting alone. The present study is part of a series that aims to expand the literature to include VTS array flows. In prior work, it was shown experimentally that VTS arrays may uniquely generate central recirculation zones that are not seen when only the central separator is active. Here, another configuration is added: a single non-central separator. Turbulence profiles across the duct centerline downstream of the VTS clean air outlets reveal unexpectedly low anisotropy, indicating the VTSs are effective fluid mixers. Spectral proper orthogonal decomposition is also conducted on the highly unsteady 7-VTS flowfield. High-energy harmonic behavior is observed at very low frequencies, which are shown to consist of back-and-forth pumping motions in the center of the duct. This appears to be unique to the VTS array flow shown here, as it is not reported in similar studies that extract coherent motions from swirling flows. A high-energy precession motion is also found at slightly higher frequencies - this has been observed in cyclone separators before, though oriented differently. Precessing structures at certain timescales have been shown to reduce separation efficiency. This study will be followed by one that examines the behavior of inertial particles through the same VTS array, tying observations to the fluid phenomena presented here and in prior work.
1 Introduction

Helicopter rotors may produce a powerful downwash that impinges on the ground when operated at low altitude. In sandy, snowy, ashy, or watery environments, this can kick up large amounts of foreign particles which may then be ingested into the helicopter’s turboshaft engine. For example, low-flying larger helicopters have been found to ingest as much as four pounds of dirt per minute [1]. Such conditions can shorten engine lifespans and, in extreme cases, cause sudden failure [2]. A report by Potts [3] recorded instances of U.S. helicopter engines damaged by sand ingestion; significant compressor blade erosion was found in many. There is thus great motivation for the filtration of particles from engine intake airstreams.

Devices that accomplish this filtration are known as engine air particle separators (EAPS), and their performance is evaluated using both their particle separation efficiency and the pressure drop they incur on the intake airstream. EAPSs generally fall into one of three major categories, as described by Filippone and Bojdo [4]: inlet barrier filters, inertial particle separators, and vortex tube separators (VTS). Inlet barrier filters make use of porous screens to physically block particulates from entering an engine; while they can achieve very high separation efficiencies, performance penalties due to pressure drop are significant and grow over time until the screen is cleaned of particle blockage. Inertial particle separators introduce a sharp turn in intake geometry that causes massive foreign particles to diverge from core flow streamlines due to inertia; while pressure drop remains constant with time, separation efficiencies are typically low (below 90%) [5].

Some of the performance issues of these devices are mitigated in vortex tube separators, which expand on the use of foreign particle inertia for filtration. Instead of exploiting the linear momentum of particles across a sharp curve (as in inertial particle separators), VTSs remove particles from a vortical core flow using centrifugal forces [6]. Vorticity is generated by a series of helical vanes at the inlet of the device. Foreign particles then experience large centrifugal forces due to their high specific gravity, and are displaced radially towards the periphery of the duct. The device ends with an annular exit which collects particle-free air from the center of the duct, while particle-laden air from the periphery is independently ejected to the atmosphere. By eliminating loss-inducing features such as particulate blockage and duct turns/reversals, VTSs incur relatively low pressure drops while maintaining impressive separation efficiencies (over 95%) [7].

Figure 1 is a simple schematic of an individual transparent VTS viewed from the side such that the flow axis is horizontal across the page. When flow enters at the inlet (left-hand side), it immediately passes through a set of vanes that deflect it into helical motion with both axial and circumferential/swirling velocity components. This vortex continues after the vanes end in an open section known as the separation region, where foreign particles are given the time and space necessary to move radially outwards. A concentric pair of exits can be seen at the downstream end (right-hand side), where core flow (“clean
air”) is separated from scavenge flow (“dirty air”). The loss of some air to the scavenge (typically around or less than 10% of total volumetric flow rate [1, 8]) limits the performance of a VTS, though not as severely as in other EAPSs.

Vortex tube separators belong to a large family of filtration devices known as cyclone separators, which all make use of vortical flow for the separation of unwanted particles from airstreams in a variety of applications. Cyclone separators are used to protect the engines on earthmoving equipment operating in dusty environments [7], for pollution control in construction sites [9], and for general industrial filtration [10]. The common bagless vacuum cleaner is another simple example of a cyclone separator; the tangential inflow of air along the cylindrical wall of the collection chamber induces vortical flow wherein inertial particles are unable to turn and strike the wall. The distinctions between these types of cyclones and the vortex tube separator lie in the generation of vorticity and the direction of airflow. Some cyclones, like the vacuum, rely on tangential inlets to turn the flow. Many also fully reverse the direction of the flow to maximize separation efficiency; however, the resulting increase in pressure drop is unacceptably high for aerospace applications. Thus the VTS can be considered an “axial uniflow cyclone separator” because of its axial inlet and constant flow direction.

Most publicly available information on the design of vortex tube separators comes from patents. A notable series of such patents was filed by David Pall in the 1960s and 1970s. In his first patent [7], Pall describes the general concept of his vortex tube separator and provides the geometric dimensions that he found to achieve peak performance (maximized separation efficiency and minimized pressure loss). A sequel patent [11] introduced minor alterations, such as a contraction at the separator inlet, to further improve performance. The VTS described in this second patent is used as the basis for VTS geometry in the current study. Figure 2 is adapted from the patent and modified to include labels consistent with the language used above. The inlet tube diameter in the vane section and inlet tube length are provided to give a sense of scale.

There exists a major complicating factor in the practical implementation of VTSs on aircraft: they are grouped into array configurations, wherein dozens
or hundreds of separators share a common manifold. This arrangement is necessary to allow for high flow rates given the small size of each VTS. Pall’s third patent [1] describes the design of a separator array. The manifold is essentially a large box containing all VTSs such that the inlets and clean air outlets of each separator are simply openings in the upstream and downstream walls of the manifold, respectively. The “dirty air” from each VTS is first ejected into the manifold-contained space between each separator (known as the “scavenge chamber”), after which externally-applied suction draws it towards one or more openings in the side of the manifold (known as “scavenge ports”).

A side view of Pall’s VTS array is shown in Figure 3, modified again to include language consistent with the current study. Cutaways in the diagram reveal two individual VTSs oriented such that the core flow axis is vertical. Particle-laden air enters at the separator inlets (“AIR IN”), which are holes in the front face of the array. Flow then moves through the previously-discussed features (helical vanes, separation region, clean air exit), which are labeled for clarity. Filtered air exits at the separator outlets (“CLEAN AIR OUT”) while dirty air is directed into the scavenge chamber, filling the gaps between separators and chamber walls. As shown in the diagram, this air is directed by suction (“Scavenge Flow”) towards a scavenge port that then ejects it into the atmosphere. An example of a modern-day Pall Corporation™ Centrisep Air Cleaner is provided in Figure 4. The black circles are all inlets to individual separators; the centerbody and vanes are visible in each upon close inspection. The VTSs are arranged in a staggered “honeycomb” pattern, which was also shown in Pall’s patent. Many are grouped in columns with widths of three separators; the gaps between columns act as passageways for scavenge air to reach the scavenge port, according to the patent. The scavenge port for this array appears to be located on the bottom face of the manifold.

While a large collection of scientific papers exists on cyclone separators in general, only a small percentage of them are dedicated to vortex tube/axial uniflow cyclone separators specifically. Of what does exist, almost the entirety known to the authors has focused on individual separators. That is to say, very little research appears to have been conducted on VTS arrays. Additionally, much of the existing VTS literature specifically studies the performance...
effects of geometric variations in separators, as opposed to an exploration of the underlying physical phenomena and flow/particle dynamics that influence them. These factors serve as the motivation for the current study.

Several theoretical studies on VTS performance have been published in a series of papers by Filippone and Bojdo from the University of Manchester [4, 6, 12]. These include derivations of performance parameters and parametric studies comparing VTSs with other EAPSs. Computational and experimental VTS studies have been conducted by research groups led by Martin Pillei, Tadeusz Dziubak, and Ulrich Muschelknautz. Pillei et al. [13, 14] experimentally measured swirl intensity in the separation region of several different VTSs. The studies by Dziubak et al. [15, 16] utilized CFD simulations of VTSs that were recreated virtually by 3D scanning real separators. These simulations were compared with particle-laden flow experiments for model validation purposes.

Muschelknautz, a prominent name in cyclone separation research, first published a study on the effectiveness of unconventional scavenge flow outlets from
an individual VTS (for example, a window of small area rather than concentric ducts) [17]. His group then conducted some of the only VTS array studies known to the current authors [8, 18]. Referring to these devices as “multicyclones”, Muschelknautz et al. theoretically derived the advantages of vortex tube separators over other types of cyclone separators in array configurations, as are necessary in aerospace applications where high flow rates are required through limited areas. Note that this research assumed that the scavenge flow (or “underflow”) was nonexistent as a worst-case scenario. While an underflow is required for helicopter VTSs in order to allow for self-cleaning, prevent re-entrainment of particles, and raise separation efficiencies, the mathematical framework introduced by Muschelknautz will undoubtedly prove useful as array flows are further studied.

Beyond this, there is a distinct lack of literature on VTS arrays, particularly relating to the intricate fluid and particle dynamics that influence their performance. The VTS array problem is far more complex than that of an individual separator; the common scavenge chamber and proximity of VTSs to each other allow for aerodynamic interactions to occur between separators. Within the scavenge chamber, there likely exists a chaotic flowfield of toroidal vortices that interact and impinge on the solid walls while moving towards the scavenge port(s). Should any of these interactions affect the scavenge output of a VTS, perhaps unsteadily, the separation efficiency of that VTS may be altered; separation efficiency is dependent on axial flow rate, among other things, as shown by Filippone [4]. Additionally, given the low speed of VTS flows, it is possible that downstream interactions between clean air outlet flows could produce upstream effects within the VTS array that would not be present in a single VTS system.

For these reasons, the present study experimentally investigates the air flow emerging from the clean air outlets of a vortex tube separator array model, with the expectation that the observed flowfield will reveal physical phenomena unique to VTS array flows. Flows with inertial particles will be examined in a future effort; the authors believe it is important to first understand and explain the flow physics involved. This is a sequel study to Acharya et al. [19], which focused on the mean flow characteristics downstream of a VTS array. In that work, the authors observed a central recirculation zone forming exclusively downstream of arrays - and not in single-separator flows - that was the result of increased angular momentum contributions from outer (non-central) separators in the array.

The current study returns to the same flow (with an additional VTS configuration), this time with a focus on the unsteady features. This involved the re-taking of velocity data in a manner suitable for turbulence and instantaneous flow analysis. Some results were first presented in Acharya et al. [20]. Section 2 of the current study describes the experimental facility, test article, and measurement methodology. An overview of the spectral proper orthogonal decomposition technique is also provided. Section 3 presents the results:
an analysis of turbulence profiles is followed by a description of select high-energy spectral proper orthogonal decomposition modes that reveal coherent structures in the flowfield. It is shown that VTS flows contain only low anisotropy, and that the 7-VTS flowfield contains harmonic back-and-forth pumping motions as well as a precessing vortex structure that may impact performance.

2 Experimental Methods

2.1 Wind Tunnel Facility

Experimental work was conducted at Virginia Tech’s Advanced Propulsion and Power Laboratory (APPL) in the High-Speed Wind Tunnel (HSWT), an open-circuit wind tunnel powered by two blowers. The primary blower, a Hoffman™ 751 Series centrifugal blower, was used to drive core flow from the clean air exits of the VTS array model (which itself is described later). The secondary blower, a Roots-style Panther positive displacement blower by Busch Vacuum Solutions™, was used to drive scavenge flow from the scavenge ports of the model. The HSWT itself begins with a large flow conditioner containing aluminum honeycomb and mesh screen to eliminate large-scale fluctuations from the ingested air. From there, an aluminum bellmouth transitions the flow exponentially from a diameter of 35.60 cm at its inlet to 15.24 cm at its outlet over a 15.24 cm axial span. This outlet diameter is maintained through the test section of the HSWT.

The test section can be equipped with a variety of measurement instruments. For the current study, a Pitot-static probe was placed in the short 20.00 cm section of open tunnel downstream of the bellmouth and upstream of the VTS array model to ascertain the tunnel flow velocity. Downstream of the VTS array model, a quartz optical test section (OTS) was used to enable laser diagnostics on the flow emerging from the model’s clean air exits. Details on those measurements are provided later in this section.

Figure 5 is a schematic of the HSWT configuration used for the current study. As described previously, it shows air entering the tunnel through a flow conditioner box before a bellmouth reduces the diameter. At the VTS array model, colored red, the flow paths diverge. “Clean air” (though recall that no inertial particles were used in this work) continues through the OTS towards the primary blower while “dirty air” is separated and passes through three smaller scavenge lines towards a plenum upstream of the secondary blower. The flow rate in each of these lines is monitored by an analog flowmeter. While neither blower is capable of direct flow rate control, both were equipped with secondary inlets downstream of gate valves - as these valves were turned towards the SHUT position, more flow entered the tunnel from the secondary inlet than the main inlet (flow conditioner), reducing the flow rate through the test section. This allowed for the recreation of realistic VTS operating conditions, taken in this study to mean 18 m/s through each separator with scavenge flow set to 7% of the total volumetric flow rate. The primary blower
gate valve was placed 10 tunnel diameters downstream of the test section to prevent upstream nonuniformities from impacting measurements.

2.2 VTS Array Model

The lack of prior VTS array experimentation meant that this study was the first of its kind, and thus the scope was deliberately narrowed. The work is treated as an introductory exploration of VTS array flows and is intended to be built upon in the future. Additionally, the authors and their collaborators intend to pursue computational studies of the same geometry, which would become difficult with a great number of vortex tube separators. As a result, the VTS array model was designed to represent a section of a larger array, with seven separators arranged in a symmetric honeycomb pattern - or in other words, a central separator surrounded by six equally-spaced outer separators. The same model was used in the previous work [19] and is described there in detail. It was believed that this configuration represented a “unit problem” that simplified the VTS array flow as much as possible while retaining key physical features that make arrays unique and worthy of study. As stated in the previous work, these features were determined to be the following:

- Individual VTS model geometric dimensions identical or proportional to real VTSs
- Swirling flow through each VTS model of matching flow angle to real VTSs
- Scavenge separation from each VTS model of matching flow rate to real VTSs (generally 5-10% of inflow)
- Aerodynamic interactions between a VTS model and its neighboring VTSs that capture key interaction physics such as vortex merging, turbulence generation, mean flow redistribution, and possible unsteady coupling

Some of the differences that do exist between the VTS array model and real arrays lie in the nondimensional parameters due to scaling. Seven life-size separators, as defined in Pall’s second patent [11], would have only occupied a small percentage of the HSWT’s cross-sectional area, resulting in total blockage
across the remaining area. Scaling the separators up by a factor of 2.5 maximized their size within the HSWT, minimizing blockage. In *Gas Cyclones and Swirl Tubes* [21], Hoffman and Stein detail the critical nondimensional parameters for cyclone and vortex tube separators, referring to the latter as “swirl tubes”. After making several assumptions, such as the existence of smooth walls and spherical inertial particles, it is shown that particle separation efficiency scales on the Reynolds number and the Stokes number. Dependence is much stronger on the latter; as shown by Overcampf and Scarlett [22], Stokes number for a partially filtered particle size becomes largely independent of Reynolds number outside of very low Reynolds numbers. The pressure drop across a VTS is shown by Hoffman and Stein to depend only on the Reynolds number. Because the Reynolds number includes a linear diameter term, the scaled-up VTS model had a 2.5x Reynolds number increase over its life-size counterpart; this difference impacted the pressure drop. No inertial particles were used, but any future studies involving them will experience a 2.5x Stokes number increase (and thus an impact on separation efficiency) unless the particle size or other parameters are adjusted accordingly. The matching of these nondimensional parameters through the reduction of velocity was deemed impractical, as in certain cases it would have led to unacceptably high velocity uncertainties.

As shown in previous publications [19, 20], Figure 6 shows a modified version of the diagram used in Figure 2, now with all dimensions labeled for the scaled-up separators used in the current study. The alphabetical dimension labels correspond to numbers provided in Table 1. Each separator contained four vanes (spaced 90° apart) with a pitch length of 8.53 cm (3.36 in) and a tip angle of 58°. The inlet tube diameter of each VTS, $D_{VTS}$, was 4.30 cm.

![Fig. 6 Diagram of singular VTS (adapted and modified from [11]), with labels corresponding to Table 1.](image)

**Table 1** VTS array model dimensions corresponding to Figure 6.

<table>
<thead>
<tr>
<th>Dim.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [cm]</td>
<td>4.30</td>
<td>4.03</td>
<td>1.08</td>
<td>2.92</td>
<td>4.32</td>
<td>4.40</td>
<td>0.82</td>
<td>5.67</td>
<td>0.62</td>
<td>0.37</td>
<td>5.42</td>
<td>2.39</td>
<td>8.80</td>
<td>14.5</td>
</tr>
<tr>
<td>Length [in]</td>
<td>1.69</td>
<td>1.59</td>
<td>0.43</td>
<td>1.15</td>
<td>1.70</td>
<td>1.73</td>
<td>0.32</td>
<td>2.23</td>
<td>0.24</td>
<td>0.15</td>
<td>2.13</td>
<td>0.94</td>
<td>3.46</td>
<td>5.71</td>
</tr>
</tbody>
</table>
Details of the design of the larger array model were provided in the previous publications [19, 20], and are summarized here. The model contained seven of the separators described above. In Figure 7, the array model is shown from a forward-looking-aft perspective wherein each separator’s inlet contains four “+” shaped vanes. These separators were part of a larger manifold whose outer walls defined a scavenge chamber of width 15.24 cm. Spacings between the separators were acquired and scaled up from a real Pall™ Centrisep VTS array.

![Diagram of VTS array model](image)

**Fig. 7** Diagram of VTS array model from a forward-looking-aft orientation. The seven separators are arranged in a staggered pattern, as on real VTS arrays.

Figure 8 depicts the part of the assembly of the VTS array model, which was in total composed of three major components: an upstream section, a downstream section, and a cylindrical housing (not shown in this figure). The upstream and downstream sections were 3D printed by an SLA process with Accura™ ClearVue material, while the cylindrical housing was machined out of aluminum. In the figure below, an isometric view of a singular VTS is first shown, with the previously-described sections (helical vanes, separation region, clean air exit) respectively labeled A, B, and C. The next diagram, on the bottom left, shows that the upstream section formed the front face of the manifold, wherein openings were the inlets of each separator. The downstream section formed the rear face of the manifold wherein openings were the clean air exits of each separator. Sections A, B, and C are labeled in these sections. As shown in the bottom right diagram, the upstream and downstream sections could be brought together (with C sections of each separator protruding into B sections - see Figure 6, dimension G) to form seven complete vortex tube separators.

The cylindrical housing formed the walls of the scavenge chamber and, as shown in Figure 9, contained three equally-spaced scavenge ports. This design was selected to avoid any scavenge-based nonuniformity effects, which Pall observed in his array patent [1]. The upstream and downstream sections
described above were bolted onto each end of the housing to complete the VTS array model, as shown on the right hand side of Figure 9.

As the authors aimed to identify phenomena unique to VTS arrays, it was desirable to compare the 7-VTS array configuration described above to a
singular VTS. This was achieved with a set of “cover plates” that were attached onto the faces of the upstream and downstream sections. This plate blocked the inlets and outlets of six of the seven separators in the array, creating a 1-VTS configuration. HSWT flow rates were adjusted accordingly to maintain the velocity and scavenge flow ratio for the 1-VTS configuration as identical to the array configuration. The original study on mean flow characteristics [19] used a single set of cover plates which left the central separator unblocked, eventually finding that duct confinement and proximity to the duct walls may have had first order effects on VTS outlet flows. To better understand these effects, the current study added a second set of cover plates which left a non-central separator unblocked. Figure 10 shows the VTS array with both of these cover plate sets attached.

The HSWT flow rate for the 7-VTS configuration was set to $10.03 \pm 0.10$ m/s as measured by the Pitot-static probe in the open tunnel section upstream of the VTS array model (uncertainty determined from analog manometer tick marks, assuming max error of half a tick). Due to a reduction in total cross-sectional area, this increased to a nominal inlet velocity of 18.00 m/s for each VTS. As noted earlier, the scavenge flow rate was set to be 7% of the total volumetric flow rate through the array, which translated to $12.81 \pm 0.42$ L/s split across the three scavenge ports. The uncertainty of this flow rate was partially the result of significant low-frequency unsteadiness in the scavenge flow that manifested as wavering in the analog flowmeters’ markers. The remaining uncertainty was computed from the tick marks of the flowmeter, assuming a maximum error of half a tick. In 1-VTS configurations, all flow rates were adjusted to maintain the velocity in the unblocked separator at 18.00 m/s. Thus the wind tunnel velocity was $1.43 \pm 0.10$ m/s and the total scavenge flow rate was $1.83 \pm 0.24$ L/s.

![Diagram of VTS array model in 1-VTS configuration through use of cover plates; 1-VTS central configuration (left), and 1-VTS non-central configuration (right).](image)

**Fig. 10** Diagram of VTS array model in 1-VTS configuration through use of cover plates; 1-VTS central configuration (left), and 1-VTS non-central configuration (right).
2.3 Particle Image Velocimetry

This study made use of particle image velocimetry (PIV) to non-intrusively measure the flowfield downstream of the VTS array model’s clean air exits. The PIV setup was first described in detail by Acharya et al. [20]. PIV involves the introduction of tiny tracer particles to a fluid flow - small enough that they can be considered effectively massless and thus perfectly follow fluid streamlines [23]. These particles are then illuminated by a laser sheet that forms the measurement plane. Cameras image these illuminated particles and a PIV processing software ascertains fluid velocities from image cross-correlations. Typical gas flows require tracer particles of less than 1 µm diameter to justify the assumption of particle pathlines matching fluid streamlines exactly [24]; these particles differ significantly from the larger, high Stokes number inertial particles that VTS arrays are designed to filter. Particle image velocimetry has seen extensive use in both laminar and turbulent flows [25], and is an Eulerian methodology because in each image, particles pass through static windows used for analysis. This study specifically used time-resolved, stereographic PIV: time-resolved because of a high image acquisition/laser pulse rate (suitable for instantaneous data from highly turbulent high-frequency unsteady flows) and stereographic because two cameras were used to acquire three-component velocity data.

The PIV measurement plane in the current study was located 1.00 cm (0.39 in) downstream of the clean air outlets, which was the minimum distance possible in the HSWT - a small opaque connecting piece existed between the VTS array model and the optical test section. Normalized on the VTS inlet diameter $D_{VTS} = 4.30$ cm, this plane was 0.23$D_{VTS}$ downstream of the outlets. This plane was referred to as “Plane A” in the original work [19] - the current study focuses on it exclusively as the authors wished to capture unsteady phenomena at a location where individual VTS outlet flows were still somewhat identifiable. A simple side-view schematic of the HSWT test section and PIV plane location is provided in Figure 11. Illumination was provided by a Photronics Industries™ Nd:YAG dual cavity 532 nm laser (15 mJ per pulse), converted to a sheet with thickness 0.64 cm (0.25 in) by lenses to cover the entire duct cross-section and minimize out-of-plane tracer particle losses. Image acquisition was performed by two Phantom™ v2512 cameras equipped with 100 mm focal length lenses. The cameras were located 53.3 cm downstream of the measurement plane and 43.2 cm laterally from the tunnel centerline, making a 39° angle from the plane and capturing a field of view of nearly the entire test section area. The acquired images were double-frame with a pulse separation of 35 µs.

Fluid A tracer particles were generated by a Colt 4 seeder (both of which are products of Concept Smoke Systems™) for the PIV experiment. Measurements by a TSI™ 3321 Aerodynamic Particle Sizer found that 90% of these particles had an aerodynamic diameter of less than 1.197 µm - aerodynamic diameter being the diameter of a sphere of water with the same settling velocity as the measured particle. This diameter translates to a maximum Stokes number
of $2.57 \times 10^{-3}$ using the flow integral timescale $T_0$ where the integral length scale is taken to be the VTS diameter. VTS outlet flows were approximated as round jets for the estimation of the Kolmogorov timescale. Peak dissipation rates $\epsilon$ for such flows, as found by Darisse et al. [26], were used in the relation $T_\eta \equiv (\nu_g/\epsilon)^{1/2}$ provided in Chapter 6 of the book by Pope [27], where $\nu_g$ is the kinematic viscosity of air. The resulting Kolmogorov timescale was of order $5.24 \times 10^{-5}$ s, leading to a maximum Kolmogorov-based Stokes number of order 0.1. According to Raffel et al. [28], Stokes numbers of 0.1 or less are generally considered to indicate satisfactory tracer particle behavior.

Coordination of all instruments, recording of high-speed images, and computations of velocity data were performed by the LaVision™ DaVis 10 software. All data were treated with the time domain filter method [29] to minimize the effects of laser flare on the reflective boundaries of the test section, and to eliminate static background features. Images were first processed by two passes with 64x64 pixel interrogation windows, and then by four passes with 16x16 pixel interrogation windows (spatial resolution of 2.67 mm or $0.06D_{VTS}$), each window having 50% overlap with its neighbors. A 5x5 stencil median filter [30] was applied in post-processing to remove spurious vectors with residual values greater than 2.0; removed vectors were replaced with interpolated data. Further treatment of instantaneous velocity measurements was performed through analysis of fluctuating (mean-subtracted) velocity histograms at each point; velocity ranges with instance counts totaling less than 2% of the most common velocity range (typically 0 m/s) were eliminated.

As stated previously, three VTS array model configurations were used in the current study: 7-VTS, 1-VTS central unblocked, and 1-VTS non-central unblocked. For each case, 30,000 double-frame images were taken at an acquisition rate of 780 Hz for the purposes of computing mean velocities and turbulence statistics. This relatively low acquisition rate was selected to allow for more “effective samples”, which naturally decrease at high frequencies if
the eddy turnover frequency is exceeded, thus doing little to mitigate random uncertainties. The authors also wished to conduct a spectral orthogonal proper decomposition (described in the next subsection) on the 7-VTS flow. A larger additional dataset of 96,000 double-frame images was captured at a much higher acquisition rate of 6248 Hz to enable this analysis, which otherwise typically has high uncertainties. The higher acquisition rate allowed for the inclusion of any high-frequency motions in the decomposition, while the larger number of samples enabled a greater number of realizations of any low-frequency motions.

2.4 Spectral Proper Orthogonal Decomposition

The 96,000 image high-frequency dataset was used for spectral proper orthogonal decomposition (SPOD), an analysis method that extracts coherent motions and structures from fluctuating flowfields. These motions are presented as a series of modes, each of which contributes some varying amount of energy to the flow’s total energy. High-energy modes are thus considered to represent motions that have a strong impact on the overall flowfield. Detailed descriptions of the SPOD process are provided by Towne et al. [31] and Schmidt and Colonius [32]; the latter provides a link to an open-source MATLAB code that was used for SPOD computations in the current study. A summary of the SPOD methodology is presented in this section.

SPOD is an extension of traditional proper orthogonal decomposition (POD), which is applied to zero-mean stochastic processes such as the fluctuating velocity of a flow at a point over time. The stochastic process (represented as a function) is assumed to belong to Hilbert space wherein its inner products are well-defined everywhere. POD seeks a deterministic “basis function” that best represents (or, in other words, is most closely aligned with) the stochastic process in question. The concept of alignment in the POD sense is visually demonstrated using vectors in Chapter 3 of the thesis by Spencer [33]. Mathematically, the alignment is represented by the normalized expected value of the stochastic function’s projection onto the basis function. This is shown mathematically in Equation 1, where \( \lambda_P \) is a measure of the “alignment”, \( q(x, t) \) is the stochastic function (which varies with position \( x \) and time \( t \)), and \( \phi(x) \) is the basis function (which varies only with position). The goal of POD is thus to select an optimum basis function \( \phi(x) \) that maximizes the quantity \( \lambda_P \).

\[
\lambda_P = \frac{E\{\langle q(x, t), \phi(x) \rangle^2 \}}{\langle \phi(x), \phi(x) \rangle}
\]

(1)

As shown by Towne et al., the optimum basis function also satisfies an eigenvalue problem (hence the selection of \( \lambda \) to represent the alignment quantity) which is shown in Equation 2. Here, \( \Omega \) is the spatial domain of the flow, \( C(x, x') \) is the two-point correlation tensor between positions \( x \) and \( x' \), and \( W(x') \) is a Hermitian weighting tensor.
\[ \int_{\Omega} C(x, x') W(x') \phi(x') \, dx' = \lambda P \phi(x) \quad (2) \]

For each mode \( \phi(x) \), the eigenvalue that satisfies Equation 2 indicates the energy captured. Thus modes are typically arranged such that their eigenvalues, or energy contributions, are in order from highest to lowest. Corresponding eigenvectors are orthogonal and provide a complete mathematical basis for the stochastic function \( q \) being analyzed. As a result, summing all modes together reconstructs the stochastic function (the flowfield), as shown in Equation 3, where the time coefficient \( a(t) = \langle q(x, t), \phi(x) \rangle \). The actual computation of POD modes can occur through a variety of mathematical methods, as explained in Spencer’s thesis [33]. Of these, one of the most common is the singular value decomposition.

\[ q(x, t) = \sum_{j=1}^{\infty} a_j(t) \phi_j(x) \quad (3) \]

As shown in the above equations, POD results in a single set of position-dependent modes for any time-varying flowfield. Spectral proper orthogonal decomposition extends POD basis functions to depend on time \( t \) as well as position \( x \). The SPOD eigenvalue quantity \( \lambda_S \) is then modified to use spatiotemporal modes \( \phi(x, t) \), as shown in Equation 4. However, a problem arises due to the statistically stationary nature of turbulent flows: they persist indefinitely and thus have infinite energy in the space-time norm. This dismantles the useful properties of the eigenvalues made use of by the original POD method. To work around this, the eigenvalue problem is reconstructed in the spectral (frequency-dependent) domain using the cross-spectral density tensor \( S(x, x', f) \), which is the Fourier transform of the previously-used correlation tensor \( C \) (which in SPOD depends on time delay \( \tau \) in addition to two spatial points). The cross-spectral density tensor is defined in Equation 5.

\[ \lambda_S = \frac{E\{\langle q(x, t), \phi(x, t) \rangle^2\}}{\langle \phi(x, t), \phi(x, t) \rangle} \quad (4) \]

\[ S(x, x', f) = \int_{-\infty}^{\infty} C(x, x', \tau) e^{-i2\pi f \tau} \, d\tau \quad (5) \]

The resulting updated spectral eigenvalue problem is presented in Equation 6, where \( \psi \) represents the frequency-dependent SPOD modes. Modes that satisfy the problem again allow for the reconstruction of the frequency-dependent stochastic process \( \hat{q} \) using the summation expressed in Equation 7. The unique challenge of SPOD is thus the generation of a cross-spectral density tensor \( S(x, x', f') \), which can be done with the Welch periodogram method as described by Schmidt and Colonius [32]. Unlike standard POD, SPOD usefully provides a set of position-dependent modes for each frequency of velocity fluctuation (up to the Nyquist frequency). This allows for the identification of low-frequency coherent motions independently from that of higher-frequency motions.
\[
\int_{\Omega} S(x, x', f') W(x') \psi(x', f') \, dx' = \lambda S(f') \psi(x, f')
\] (6)

\[
\hat{q}(x, f) = \sum_{j=1}^{\infty} a_j(f) \psi_j(x, f)
\] (7)

3 Results and Discussion

Flow data is presented in a cylindrical coordinate system because the HSWT duct was circular. Figure 12 is a diagram showing a back view of the VTS array model (aft-looking-forward) with a depiction of the radial \( r \) axis (which is positive moving away from the center point) and the cylindrical \( \theta \) axis (which is positive in the counterclockwise direction). The axial \( z \) axis points downstream, out of the page. A green dashed line indicates the horizontal centerline of the duct, along which some data will be presented later in this section. Note again that measurements were actually taken at a plane 1.00 cm, or 0.23\( D_{VTS} \), downstream of the outlets. All velocity data is normalized on the theoretical velocity magnitude \( V_{mag} \) through the inlet tube of each VTS. \( V_{mag} \) here is the magnitude of the axial and circumferential velocity components, assuming no radial velocity of the fluid, and was found to be 33.87 m/s. Recall that mean flow and turbulence PIV data (used in Sections 3.1-3.3) were computed with 30,000 samples at 780 Hz, while SPOD data (shown in Sections 3.4-3.5) were computed with 96,000 samples at 6248 Hz.

Fig. 12  Polar coordinate system used for velocity data, aft-looking-forward into the VTS outlets.

3.1 Mean Velocity Data

Figures 13-16 show heatmaps of mean velocity components as measured by PIV. In each figure, the leftmost plot shows data from the 7-VTS configuration, the middle plot from the 1-VTS central configuration (henceforth referred to as “1C-VTS”), and the rightmost plot from the 1-VTS non-central configuration (henceforth referred to as “1NC-VTS”). The radial axis is represented by rings
with white axis labels, normalized on the test section duct radius. 7-VTS and 1C-VTS velocity maps appear nearly identical to previously-shown data in Acharya et al. [19] that were taken at a higher acquisition rate and with less samples, suggesting that there are no significant high-frequency mean flow features that were missed at 780 Hz. They are shown here for direct comparison with 1NC-VTS data.

Mean planar velocity magnitudes, defined here to be the magnitude of the radial and circumferential components, are shown in Figure 13, which additionally includes planar velocity vectors. As described in the previous work [19], 7-VTS planar velocities reveal a strong counterclockwise vortical flow near the edges of the duct, peaking in strength around circumferential positions of 45°, 135°, 225°, and 315°. Vortical flow from the central VTS is also clearly apparent in the center of the duct, though it is also undergoing radial expansion. The 1C-VTS flow is much simpler, with a single well-defined vortex churning about the center of the duct. The swirling flow emerging from the sole VTS appears to have already expanded enough to fill the duct by just 0.23DVTS downstream of the outlet, though it is possible that some of this is the result of the upstream transport of angular momentum by corner recirculation [34, 35]. In the 1NC-VTS case, some amount of swirl can be observed about the VTS outlet location (which is centered at the 0° mark). However, the vortex has not occupied the entire duct in a well-defined manner as the 1C-VTS vortex did. Planar velocities are mostly low, especially far away from the outlet.

Figures 14 and 15 are heatmaps of the radial velocity VR and circumferential velocity Vθ, respectively. Diagrams of the VTS outlets are overlaid on these plots - though recall that the outlets are in reality located 0.23DVTS upstream of the measurement plane. Note the difference in scales between the two figures, which indicates that circumferential motions contribute significantly more to overall planar velocity than radial motions. As shown in Figure 14, each outer separator outlet straddles lobes of positive and negative VR, which indicates swirling flow that is directed radially outward on one side of each outlet and radially inward on the other. This is especially evident in the 1NC-VTS case, highlighting the swirling nature of the outlet flow with more

![Fig. 13 Mean planar velocity heatmap and vectors at the plane 0.23DVTS downstream of VTS outlets; 7-VTS configuration (left), 1-VTS central configuration (center), and 1-VTS non-central configuration (right).]
clarity than the planar magnitude. A similar straddling of positive and negative $V_\theta$ can be found in Figure 15, though these regions appear as layered rings rather than lobes in the 7-VTS case. Again, this points to swirling flow that is directed counterclockwise on one side of each outlet and clockwise on the other (from the perspective of the origin at the duct center point). The 1C-VTS case sees generally positive $V_\theta$ throughout the duct, owing to the expanded swirling flow seen previously. In the 1NC-VTS configuration, some amount of distinctly positive circumferential velocity is visible trailing away from the lone outlet, but much of the rest of the duct is featureless.

Figure 16 shows mean axial velocity data. The 7-VTS configuration contains a ring of high axial velocities around the same radius as the outer (non-central) separators. It is likely that this represents the high-velocity outlet flows from these separators, possibly after some amount of “smearing” in the counterclockwise direction due to the swirling flow components, forming a connected ring rather than individual lobes. Notably, there is no clear evidence of the outlet flow from the central separator. The axial component is nearly stagnant just 0.23$D_{VTS}$ downstream of the central outlet. This appears to be a central recirculation zone (CRZ), a well-known feature found in intensely swirling flows that undergo sudden expansion. CRZs were discussed extensively in the previous work [19], and will be revisited with regards to the current
study in Section 3.2. The 1C-VTS case contains no visible central recirculation, instead appearing to resemble a typical round jet flow in the center of the duct. Some pockets of negative axial velocity are discernible near the duct walls, which may be evidence of the corner recirculation that was previously theorized to bring about the upstream transport of angular momentum. In the 1NC-VTS configuration, a similar singular jet-style flowfield appears, but with some striking differences. The jet appears “smeared” in the counterclockwise direction, possibly undergoing the same transformation that each outer separator experienced in the 7-VTS flow. The jet is also more concentrated - smaller in area, but with higher $V_Z$, possibly a result of constraints from the nearby wall. Less spreading has occurred than in the 1C-VTS case.

### 3.2 Central Recirculation and Swirl Intensity

A swirling flow with sufficient swirl intensity will undergo rapid and strong vortex breakdown when allowed to expand. Radial pressure gradients centrifuge the flow outwards, evacuating the central regions of the duct and generating an adverse axial pressure gradient as fluid from further downstream is swept upstream to fill the void [36] - a central recirculation zone. The swirl intensity necessary for this behavior is known as the critical swirl [37]; a flow that has not reached this state (subcritical) will not take on the features unique to strongly swirling flows, such as the CRZ. A detailed description of CRZs, their implications on VTS flows, and the reason for the generation of one by the 7-VTS configuration but not the 1C-VTS configuration were provided in Acharya et al. [19]. The current subsection will briefly summarize those contributions, and then extend them to the 1NC-VTS configuration.

While no literature known to the authors explores the effects of central recirculation on vortex tube separators, findings from other CRZ-based studies (such as those on combustion swirlers and swirling jets past sudden expansions) have been extended to VTS applications due to their many similarities. Some combustion swirler studies are particularly noteworthy for their use of helical vanes and a centerbody, much like the present VTS devices. For example, the dissertation by Fu [38] reports experimental measurements downstream of a
vaned combustion swirler while varying swirl intensity. The swirl intensity is described, as in many other studies, by the nondimensional swirl number $Sw$ as defined by Equation 8 for an axisymmetric flow with radius of analysis $R$. It is the ratio of angular momentum flux to axial momentum flux (both in the axial direction).

\[
Sw = \frac{\int_0^R V_Z V_\theta r^2 dr}{R \int_0^R V_Z^2 r \, dr}
\]

Fu defined the swirl number locally (the radius of analysis $R$ being the radius of the singular swirler before expansion) and found the critical swirl number to be between 0.69 and 0.83 for an expansion ratio (by radius) of 2.6. Above this swirl number, the flow was supercritical and a distinct central recirculation zone formed. To compute $Sw$, Fu used several assumptions and derived a simplified version of Equation 8 based simply on the radius of the swirler, the radius of the centerbody, and the helical vane tip angle. Applying this same calculation to the VTS flows in the current study, a local swirl number of 0.85 is achieved in the inlet tube of each VTS. However, geometric differences exist between combustion swirlers and vortex tube separators - VTS centerbodies occupy only a fraction of the device length, and the scavenge exit complicates the flow. Additionally, the current study’s expansion ratio was 3.52, and Fu also demonstrated that duct confinement plays a significant role in CRZ generation. Evidently, all of this drives the local critical swirl number above the actual outlet flow swirl number, given that the 1-VTS flows did not produce any visible central recirculation.

Notably, a single large CRZ formed for the 7-VTS case, suggesting that the recirculation was a global phenomenon. Because each VTS in every case had the same local swirl number, the CRZ must have resulted from the flow in the duct as a whole, rather than from the swirl intensity in each individual VTS. To demonstrate this, in the previous work [19] the authors constructed a preliminary version of a momentum integral model that could predict the critical swirl number for VTS array flows. This was based on a study by Hallett [35] that did the same for a single swirling jet - the current authors extended this analysis to multiple swirling jets using an axisymmetric assumption. Critical global swirl numbers - using the entire duct radius $r_3$ as the radius of analysis $R$ - were generated for a variety of input conditions. While it was found that the critical swirl was higher for the 7-VTS case than for the 1-VTS case, it was noted that global swirl numbers themselves are inherently higher for the 7-VTS case than for the 1-VTS case. The reason for this is the exponential dependence of the angular momentum on radius, as shown in the numerator of Equation 8. Outer (non-central) VTS outlets produced identical swirling flows to the central VTS outlet, but at a larger radius from the duct center. While they generated both negative and positive swirl (see Figure 15), the positive swirl was at the outermost radius, which allowed it to contribute disproportionately to angular momentum, driving the swirl number to be higher. The momentum integral model was used to demonstrate the plausibility of
the observed scenario: 7-VTS flow being supercritical while 1C-VTS flow was subcritical.

This begs the question: what about the 1NC-VTS case? The non-central separator is radially distant from the center of the duct, so must naturally generate high angular momentum from a global perspective. Yet no central recirculation zone was generated. This can be explained by the momentum integral model’s assumption of axisymmetric flow, which was reasonable in the 7-VTS case when six non-central separators covered the vast majority of the outer radii of the duct. For 1NC-VTS flow, however, the high angular momentum is concentrated within a small arc of the outer radii, and is allowed to quickly diffuse without any interactions or merging with nearby similar flows. This drives the global swirl number downward to a subcritical state. A more complex model allowing for analysis in the circumferential $\theta$ direction would be required to generate a reasonable critical swirl number for the 1NC-VTS case.

The presence of a central recirculation zone - or lack thereof - may be impactful to VTS filtration capabilities. Computational studies on combustion swirler CRZs by Rojatkar et al. [39, 40] show that recirculation zones can stretch upstream into the swirlers themselves. At the least, it can be understood that CRZs are bounded by axial velocity gradients which transition from regions of downstream axial flow to upstream reversed flow. The observation of stagnant flow just $0.23D_{VTS}$ downstream of a VTS outlet in the 7-VTS configuration likewise suggests that axial flow gradients are present upstream of the plane and within the separator itself. Recall from Section 1 that VTS separation efficiency depends partially on flow rate. Thus it is likely that VTS arrays experience localized differences in separation efficiency for certain separators. With the potential importance of VTS CRZs established, the authors now move to analyze the unsteady aspects of this complicated flowfield.

### 3.3 Turbulence Statistics

PIV results indicate that the flow at the measurement plane is highly unsteady - the mean flowfield differed significantly from instantaneous snapshots. This is unsurprising considering the many aerodynamic interactions occurring within and downstream of the array, as well as the high Reynolds numbers involved ($Re_{VTS} = 52,000$ for the inlet of each separator). Some useful information from these unsteady fluctuations can be captured through the use of turbulence statistics, which are presented in this subsection. The state of turbulence in a VTS flow may help paint a picture of its capabilities as a mixer, as well as any potential challenges with regards to future numerical simulations. It has been noted, for instance, that accurate simulations of turbulent swirling flows past sudden expansions are difficult to achieve [41–43]. These flows have been observed as highly anisotropic in the near-field [44], meaning they see velocity fluctuations and turbulent momentum transfer that are not uniform in all directions (the choice of coordinate system impacts the Reynolds stresses that define this transfer). The current study thus analyzes the Reynolds stresses
and turbulence state at the measurement plane using the same 780 Hz data as in Section 3.1.

Consider first the Reynolds stress profiles of the swirling jets in the studies cited above. Wang et al. [41] plotted Reynolds stresses at several axial locations using both computational and experimental data. For their supercritical swirl cases, at 0.25 jet diameters downstream of the outlet, axial normal stresses were found to peak on either side of the duct center - an effect of the central recirculation zone. The other stress components behaved differently, plateauing for some distance from the duct center. Similar results were reported by Xia et al. [43] for a supercritical swirling jet at an axial location of 0.2 jet diameters: two axial normal stress peaks surround the duct center, while the circumferential normal stress takes on a more complicated three-peak structure. Returning to combustion swirlers, Fu [38] showed that subcritical flows display three axial normal stress peaks, which morph into two peaks as the swirl passes its critical point. The other stress components look different in the near-field, and Fu notes the anisotropy of the flow.

Using the current study’s data in all three VTS configurations, normal Reynolds stresses \( \overline{v_R'v_R'}, \overline{v_\theta'v_\theta'}, \text{ and } \overline{v_Z'v_Z'} \) are shown in Figure 17, while shear Reynolds stresses \( \overline{v_R'v_\theta'}, \overline{v_R'v_Z'}, \text{ and } \overline{v_\theta'v_Z'} \) are shown in Figure 18. Both are plotted across the centerline of the duct (as defined in Figure 12), which was chosen to simplify data visualization while retaining important flow features. Note that the y-axis has been shifted downward in the shear stress plot, though the scale remains the same. The random statistical uncertainties for these covariance data have been quantified and appear on the plots as 95% confidence interval error bars. Quantification accounted for the eddy turnover time, which reduced the amount of effective samples. Recall that the measurement plane was located 0.23D_{VTS} downstream of the outlets. Several interesting features are immediately observed from these figures:

1. The three normal stress components are strikingly similar for all three VTS configurations. All components follow the same general trend in each case. One of the few distinct differences lies in the 7-VTS axial stresses being noticeably higher in value than the other components throughout. 1-VTS axial stresses are higher than their radial and circumferential counterparts at times, though not consistently.

2. The 7-VTS normal stresses all follow a pattern of two peaks surrounding the central point, which was observed in axial stresses in the previously-cited literature for supercritical swirl and ascribed to the central recirculation zone.

3. The 1C-VTS normal stresses instead contain one high peak in the very center of the duct, aligning with the outlet port of its configuration. This peak clearly exceeds the turbulent kinetic energy (TKE) - half the sum of normal stresses - of the 7-VTS configuration at the same point. Fu [38] indeed notes that subcritical combustion swirler flows tend to produce higher turbulence than their supercritical counterparts.
4. The 1NC-VTS normal stresses form a similar one-peak shape at the location of its outlet port, but at much lower values. This is likely related to the “smearing” found in the mean flow; much of the turbulence has also migrated slightly counterclockwise and away from the centerline.

5. All shear stresses in all cases are fairly low in magnitude throughout the duct. Some noticeable features are observed - for example, the 7-VTS radial-circumferential stresses again follow a two-peak pattern.

Some of these findings were unexpected given the results of previous studies. The nature of the normal stresses point to vortex tube separators being more effective fluid mixers than typical swirling jets and combustion swirlers. Only the axial normal stresses in the 7-VTS case prove similar to known data from supercritical swirling flows, suggesting once again that the flow must be analyzed from a global perspective wherein outer separators contribute greatly to angular momentum, driving the flow past its critical swirl. The extension

\[ \text{Fig. 17 Normal Reynolds stresses across duct centerline for 7-VTS, 1C-VTS, and 1NC-VTS configurations; radial stresses (top), circumferential stresses (middle), and axial stresses (bottom). 95\% confidence interval error bars shown for every third data point.} \]
Fig. 18 Shear Reynolds stresses across duct centerline for 7-VTS, 1C-VTS, and 1NC-VTS configurations; radial-circumferential stresses (top), radial-axial stresses (middle), and circumferential-axial stresses (bottom). 95% confidence interval error bars shown for every third data point.

The quantification of anisotropy allows for further conclusions and a determination of the “state” of turbulence in the flow. A method involving the invariants of the anisotropy tensor was first derived by Lumley and Newman [45] and is explained concisely in Chapter 11 of *Turbulent Flows* by Pope [27]. The normalized anisotropy tensor $b_{ij}$ is defined using tensor notation in Equation 9, where $v'$ indicates a general fluctuating velocity while $\delta_{ij}$ is the Kronecker delta. The overline bar indicates a mean quantity. Essentially, the anisotropy tensor is constructed by normalizing the Reynolds stress tensor by twice the TKE (where $TKE = \frac{1}{2}v'_k v'_k$ or half the sum of the normal Reynolds stresses) and then subtracting $1/3$ from its diagonal.
As with any tensor, there are three principal invariants for the normalized anisotropy tensor $b_{ij}$. However, its trace is always zero, effectively reducing the useful invariants to the remaining two, $II_b$ and $III_b$. The state of anisotropy in a turbulent flow can thus be characterized by these two invariants. As shown by Pope [27], it is convenient to express them as the quantities $\eta$ and $\xi$, which are defined in Equations 10 and 11 respectively.

$$6\eta^2 = -2II_b = b_{ii}^2$$  \hspace{1cm} (10)$$

$$6\xi^3 = 3III_b = b_{ii}^3$$  \hspace{1cm} (11)$$

These quantities are suited to graphical representation. When plotted against each other, all physically realizable values are required to fall within a narrow strip known as the Lumley “triangle” or anisotropy-invariant map. The state of turbulence - isotropic versus anisotropic, and if the latter, the kind of anisotropy - can be determined from the location of data points on the Lumley triangle. The sides of this strip are defined by the equations $\eta = \xi$, $\eta = -\xi$, and $\eta = (\frac{1}{2\eta^2} + 2\xi^3)^{0.5}$. True isotropy is indicated by invariant quantities at the origin: $\eta$ and $\xi$ both equaling zero. As such, the greater value that $\eta$ has, the more anisotropic the turbulence is. Invariant quantities that cling to the straight sides of the triangle are considered to indicate a state of axisymmetric turbulence; if on the bottom right ($\eta = \xi$), one component of turbulence dominates over the others (one large eigenvalue of the anisotropy tensor), and if on the bottom left ($\eta = -\xi$), one component of turbulence is much smaller than the others (one small eigenvalue). Invariant quantities floating in the middle of the triangle are considered to indicate general 3-dimensional anisotropic turbulence. These and other states are described in Table 11.1 of the book by Pope [27].

A Lumley triangle is presented in Figure 19 for the same centerline data shown previously as Reynolds stresses. An immediate observation is that all $\eta$ values, while not quite zero, are low (around or below $1/12$). This confirms that, in all three VTS configurations, the turbulence only has low anisotropy, as evidenced by the similarity between the normal Reynolds stress components. The vast majority of data points cling to either the bottom right ($\eta = \xi$) or bottom left ($\eta = -\xi$) sides of the triangle, signifying axisymmetric turbulence with either one or two dominant components. Some points, primarily for the 1-VTS configurations, are closer to the center of the triangle, which indicates generally three-dimensional anisotropic turbulence.

Xia et al. [43] present Lumley triangles of anisotropic invariants for highly swirling flow with $Sw = 1.16$ at a Reynolds number of 60,000. At a normalized location of 0.2 diameters downstream of a sudden expansion, invariants are shown to cling mostly to both the axisymmetric edges of the triangle, like the VTS data here. Quantities skew heavily to the $\eta = \xi$ side. Notably, there is far more anisotropy in the swirling jet flow, with $\eta$ values reaching as high as $1/6$, ...
twice as much as the maximum observed in the VTS flow (though recall that swirl strength was also higher). Xia et al. examine the bimodal distribution of invariant quantities, and explain their tendency to “switch” from one form of axisymmetry to the other as originating in the relative location of each point to the jet shear layer. $\xi$ was positive in the center of the shear layer, but negative towards the edges of the shear layer.

In the current study, the vast majority of 7-VTS invariants are found to have positive $\xi$, indicating that one component dominates the axisymmetric turbulence. As noted earlier, this is the axial component, which has higher normal Reynolds stress values than other components across most of the centerline. The few locations dominated by two components (negative $\xi$) are found near the edges or between the VTS outlet port locations. The 1-VTS data appears more complex on the invariant map, with a much heavier mix of positive and negative $\xi$ points as well as several locations that do not see axisymmetric turbulence. A trend is observed in both 1-VTS cases: the very center of the outlet port contains positive $\xi$ values, while the edges of the outlet port contain negative $\xi$ values. Far away from the singular outlet port, the invariants generally have positive $\xi$, though exceptions do exist.

This subsection characterized the state of turbulence in a VTS flow, showing it to be surprisingly low-anisotropy, though dominated by axial stresses in some regions. Stress profiles show that turbulence peaks at the center of 1-VTS outlets, but away from the 7-VTS central outlet, further highlighting the differences between these flows. These differences, as in the mean flow, arise from the global swirl intensity. In the following subsection, coherent motions will be extracted for further analysis of the unsteady 7-VTS flowfield.
3.4 SPOD Results

Using the Welch periodogram method, spectral proper orthogonal decomposition was performed on 96,000 high-frequency (6248 Hz) PIV samples for the 7-VTS configuration. The goal of this analysis was to identify any fluctuating motions that were not discernible in the mean flow due to its highly unsteady nature and the presence of the central recirculation zone. Before studying the SPOD data itself, it is important to first understand the distribution of energy across the various frequencies and modes. Recall from Section 2.4 that SPOD eigenvalues $\lambda_S$ measure the energy contributions of their corresponding modes to the overall flowfield. They are thus ranked from greatest to least so that the first eigenvalue represents the highest-energy mode. SPOD generates a set of energy-ranked modes for each frequency up to the Nyquist frequency (half the acquisition rate). In this study, frequency $f$ has been nondimensionalized into the Strouhal number $Str = f D_{VTS} / V_{thru}$, where $V_{thru}$ is the computed through-flow (axial velocity) in each VTS based on bulk flow rate after scavenging separation (16.74 m/s). A visualization of SPOD mode contributions across all frequencies is presented in Figure 20, where frequency bins have a width of approximately 0.76 Hz or $Str = 1.9 \times 10^{-3}$. The three graphs within this figure depict the energy contributions from the total flowfield (red), the sum of the three highest eigenvalues (green), and the heighest eigenvalue alone (magenta) for the three velocity components. Higher modes containing less energy are also shown in gray. Note that both axes are logarithmic. This figure was constructed in the style of Nekkanti and Schmidt [46].

A general trend is apparent: modes at lower Strouhal number have higher energy. A notable exception to this is the sharp spike around $Str = 1.5 \times 10^{-1}$ experienced by $V_\theta$ and, to a lesser extent, $V_Z$. It is most prevalent in the first mode, which will be analyzed in detail at this frequency later in this section. At the lowest Strouhal numbers, especially below about $Str = 4.0 \times 10^{-2}$, the first mode’s contributions to the total energy are significantly higher than any other mode (in all three components). In this range, the data appear to show some harmonic behavior as indicated by the “knees” at $Str = 9.0 \times 10^{-3}$ and small spikes that follow at $Str = 1.8 \times 10^{-2}$ and $Str = 2.6 \times 10^{-2}$. These are close to multiples of what appears to be a fundamental frequency ($Str = 9.0 \times 10^{-3}$), with slight discrepancies likely being the result of frequency binning. As with the higher-frequency spike, the first mode at these Strouhal numbers will also be investigated in the current section.

Another useful visualization is provided in Figure 21: a heatmap of the energy content $\lambda^{(i)} / \sum_i \lambda^{(i)}$ of each mode $i$ across all analyzed Strouhal numbers (shown only for the axial component of velocity fluctuations). This figure emphasizes the significance of the first mode in comparison to other modes, especially at lower frequencies. The dashed orange line indicates number of modes required to capture 50% of the total energy content; at the lowest frequencies, the first mode accomplishes this on its own. A solid orange line indicating the 90% cumulative energy mode is also shown.
SPOD modes are inherently periodic, which allows for their representation as time-dependent cyclical motions. They can be captured at any phase $\zeta$ within the period associated with their frequency bin. Figure 22 depicts four equally-spaced phases of the first mode at a bin centered on $Str = 1.5 \times 10^{-1}$, or the frequency of the sharp energy spike observed in Figure 20. Contours depict...
the axial velocity mode: red denotes positive values and blue denotes negative values. These are normalized on their maximum value for clear visualization. The planar modes are represented by overlaid vectors. Similarly to the mean velocity plots in Section 3.1, radial position values have been normalized on the duct radius.

The $Str = 1.5 \times 10^{-1}$ mode is dominated by a pair of oppositely-signed axial lobes that rotate about the center point of the duct, with vectors indicating broad sweeping motions and some amount of bulk swirl. These lobe pairs are confined mostly within a normalized radius of 0.5. Rotating modes are commonly observed in swirling flows, and are typically referred to as “vortex precession” [47], which is a type of time-dependent instability wherein a vortex core is displaced and begins to orbit its initial axis. It is worth noting, however, that traditional vortex precession found in combustion swirlers [48], cyclone separators [49], and general swirling flows [50] involves the unsteady rotation of an axial vortex core about the central axis of a duct. In the current study, the precessing structure does not appear to be an axial vortex core; rather, it is the precession of regions of positive and negative axial velocity. This can be interpreted as the rotation of a spanwise vortex whose vorticity vector points radially outward with time-varying circumferential position $\theta$. Such a vortex would indeed appear in the spanwise measurement plane as a region of out-of-the-page flow paired with a region of into-the-page flow. The axis of rotation for the precession itself, which is different than the vortex’s vorticity vector, points in the axial $z$ direction. This precession motion is discussed further in Section 3.5.

Figure 23 depicts the first mode at $Str = 9.8 \times 10^{-3}$, or what appeared to be the fundamental frequency of the harmonic modes observed at the lowest Strouhal numbers in Figure 20. This is the frequency associated with the “knee” seen in that figure. This mode has one distinct feature: a single axial velocity lobe at the center of the duct that, over the course of its period, alternates between highly negative and highly positive values. The lobe is mostly contained within a normalized radius of about 0.3; only weak pockets are found beyond this point. Notably, the switch from highly negative to highly positive is rapid, occurring almost entirely between $\zeta = \pi/2$ and $\pi$. Planar vectors indicate that this mode contains bulk swirling flow that is centered at the origin - there is no evidence here of the multiple vortices or individual contributions from non-central separators seen in the mean flow. Counterclockwise swirling planar flow appears to converge towards the origin when the axial lobe is positive. In contrast, it diverges in clockwise fashion away from the origin at opposite phases when the axial mode is negative.

The swirling nature of this mode and its central location suggest that the observed motion is associated with the outlet flow from the central vortex tube separator. This periodic behavior occurs within the central recirculation zone, which could also be described as having an approximate boundary at normalized radii of 0.3 to 0.4 at the measurement plane. The axial component appears to depict a coherent “pumping” motion that may be interpreted as
actual back-and-forth motions due to the mean velocity in the CRZ being close to zero. Given the significant energy contribution of the first mode at this Strouhal number, the observed pumping mode is likely a significant part of the local flowfield that appears as merely stagnant in the mean flow.

The first mode at $Str = 1.8 \times 10^{-2}$ is shown in Figure 24. This frequency bin contained the first tonal spike beyond the knee observed in Figure 20 and represents the second harmonic of the fundamental frequency. It is immediately clear that the same style of back-and-forth central pumping motions occurs at this frequency. The strength of the central lobes at $\zeta = 0$ and $\pi$ is significantly lower than at their counterparts $\zeta = \pi/2$ and $3\pi/2$, but this is simply a consequence of the periodic motions shifting in phase (phases of analysis remained unchanged). This means that the $\zeta = 0$ and $\pi$ phases now capture part of the transition between highly positive and highly negative central lobe values. At $\zeta = \pi/2$ and $3\pi/2$, the central lobe extends slightly asymmetrically in the range of circumferential positions from $110^\circ$ to $215^\circ$, but otherwise it is similar to the lobe observed at $Str = 9.8 \times 10^{-3}$. Planar vectors also follow the same general converging/diverging swirl pattern seen at the fundamental frequency.

This is shown once again in Figure 25, which contains the first mode for $Str = 2.6 \times 10^{-2}$, the bin of the second tonal spike and third harmonic of
the fundamental frequency. A nearly identical pumping motion is observed in the center of the duct, with small but very intense positive and negative lobes appearing at \( \zeta = 0 \) and \( \pi \). The remaining phases again appear to capture the transition of the lobe from positive to negative, showing this time that the lobe spreads out and breaks apart slightly as its sign switches. Still, the overall motion is preserved.

### 3.5 Coherent Motion Discussion

Section 3.4 showed that the VTS array flow was primarily composed of harmonic back-and-forth pumping motions at very low frequencies, in addition to a unique precession motion. All of these observed coherent motions were concentrated in the central regions of the duct, raising the possibility of some association with the central recirculation zone that was observed in the mean flow.

Prior studies involving coherent motion extraction in swirling jet or combustion swirler flows have reported strong precessing features. For example, a research group led by Maarten Vanierschot studied annular swirling jets [47, 51] and detected helical vortex breakdown structures that precessed at
about $Str = 2.7 \times 10^{-1}$. They were identified by a spike in velocity power spectral density (PSD) that surpassed the PSD at all other frequencies. Similar behavior has been reported in singular swirl tubes which were like vortex tube separators but driven by tangential inlets rather than helical vanes; Brar and Derksen [49] computationally found planar precession of an axial vortex core at $5.1 \times 10^{-1}$, noting that in other types of cyclone separators, precession frequency appeared to have some dependency on the Reynolds number. Hoekstra [52] also detected this precession in experimental measurements of a tangential inlet swirl tube.

While the precessing structure found in the current study had a different orientation than those found in the cited publications, the presence of such a structure may have implications in ideal VTS array design. The difference in orientation is likely a result of the interactions between VTS outlet flows, which drive up the global swirl number as discussed previously. Yazdabadi et al. [53] point out that, in a reverse flow cyclone separator, precessing vortex cores (PVCs) may contact separator walls and can reduce separation efficiency. They also note the possibility that a PVC resonates with other instabilities; large systems of cyclone separators produce low-frequency, high-amplitude oscillations that can interact with PVCs, generating large pressure fluctuations.
and resulting in undesirable noise or even overstressing of plumbing systems. Brar and Derksen [49] state that precessing vortex phenomena in cyclone separators, including tangential swirl tubes, enhance particle dispersion and can reduce separation efficiency. They are particularly problematic when particle relaxation timescales interfere with precession timescales. Consider a spherical particle that experiences inertial forces and Stokes drag forces. Its relaxation timescale $T_p$ can then be approximated by Equation 12 [54], where $m_p$ is the particle mass, $r_p$ is the particle radius, and $\mu_g$ is the dynamic viscosity of air.

$$T_p = \frac{m_p}{6\pi r_p \mu_g}$$

As a rough example, a dust particle with a density of 2500 kg/m$^3$ (reasonable for materials such as quartz dust) and a radius of 25 $\mu$m would have a relaxation timescale of 0.019 seconds. This translates to a Strouhal number in the current study’s VTS flow of $1.3 \times 10^{-1}$, which is quite close to the measured precession Strouhal number of $1.5 \times 10^{-1}$. Of course, various fluid mechanisms not accounted for in Equation 12 may influence this value, but so too would a variation in density and size - VTSs may ingest and attempt to filter all manners of particles. The example shown here is meant simply to
showcase the plausibility of the PVC timescale nearing or exceeding the particle relaxation timescale, which according to Brar and Derksen may indicate increased probability of interference in the filtration process.

Studies that have extracted significant motions from swirling jet or cyclone separator flows [47–53] have focused mostly on PVCs. The current authors have found no references to the back-and-forth pumping motions that were also described in Section 3.4, even in those studies that analyzed extremely low frequency regimes. Thus it is believed that these motions are unique to the VTS array flow measured in the current study, either as a result of vortical outlet flow interactions or more intricate mechanisms within the complex scavenge chamber flow. One possible link is the low-frequency oscillations observed in the scavenge flow lines, as discussed in Section 2.2. While erratic, visible wavers in the analog flowmeter could be described as occurring at a frequency under 10 Hz (for reference, the fundamental frequency of pumping was around 4 Hz when dimensionalized). Perhaps these oscillations are transferred into the central VTS outlet flow. Further investigation will be necessary to determine a cause for these intriguing pumping motions, which may interfere with separation efficiency in the central separator thanks again to their uniquely high timescales and energy.

4 Conclusions

A vortex tube separator (VTS) array model was experimentally studied in a wind tunnel without inertial particles. Mean flow measurements downstream of its clean air outlets had in the past revealed swirling flow phenomena, such a central recirculation zone (CRZ), that were unique to the array configuration and did not occur when only the single central separator was active. In the present study, further time-resolved, stereographic particle image velocimetry results were taken to add a non-central single separator configuration to the compiled data and to analyze unsteady flow phenomena.

Non-central 1-VTS mean flow results showed that a CRZ was again not present in the flow, providing more evidence for the authors’ theory that the global swirl intensity in the duct as a whole exclusively creates recirculation in the 7-VTS configuration. The flow instead resembled a round jet like the central 1-VTS flow, but a more concentrated one that had been “smeared” in the counterclockwise direction because of proximity to the constraining duct wall and global counterclockwise swirl.

Turbulence profiles were analyzed across the duct centerline in all three configurations: 7-VTS, central 1-VTS, and non-central 1-VTS. Axial normal Reynolds stresses displayed expected trends for these flows, with profile shapes depending on the global swirl intensity relative to the critical swirl (presence or lack of a CRZ). Surprisingly, the other normal Reynolds stress profiles appeared quite similar in shape to the axial component, only differing slightly in values. Further analysis of the turbulence state using the Lumley triangle
revealed low-anisotropy flows in all three configurations, indicating that vortex tube separators are excellent fluid mixers. This was unexpected because most studies on swirling jets past sudden expansions have reported highly anisotropic turbulence.

Spectral proper orthogonal decomposition was also conducted on the 7-VTS flow to extract coherent structures relating to its complex phenomena, such as the CRZ. Of the first modes, four frequencies (nondimensionalized into Strouhal numbers) of interest were isolated due to their high energy contributions: a fundamental frequency $Str = 9.0 \times 10^{-3}$, its apparent second and third harmonics $Str = 1.8 \times 10^{-2}$ and $2.6 \times 10^{-2}$, and another separate frequency $Str = 1.5 \times 10^{-1}$. The three harmonic modes were found to indicate coherent back-and-forth pumping motions in the very center of the duct at extremely low frequencies. This type of motion appears unique to the current study’s VTS array flow, as the authors were unable to find it referenced in other studies of swirling flows. It is possibly a feature of the CRZ that is produced uniquely by the interactions between outlet flows, or may be linked to similarly low-frequency oscillations observed in the VTS scavenge flow, which directs “dirty air” away and into the atmosphere. The fourth and highest frequency of interest was revealed to be a precession motion that rotated over time. Precessing vortex cores are common in swirling flows, though the orientation of the structure in the VTS array flow was uniquely non-axial - possibly again the result of the more complex vortex interactions than what are found in typical swirling flows. Given that precessing motions have been linked to reduced separation efficiencies in cyclone separators, especially at timescales that are near or above particle relaxation timescales, this finding may be impactful to VTS design.

Additional measurements investigating the scavenge chamber flow may be useful to learn more about the causes and implications of the coherent motions observed here. The authors also plan to continue this research by introducing inertial particles to the flow, studying how separation efficiency and particle dynamics differ across the VTS array, and tying any observations to the fluid dynamics findings presented in the current study and previous work.

References


Turbulence and Coherent Motions Downstream of a VTS Array


Chapter 5

Conclusions and Outlook

5.1 Conclusions

Vortex tube separators are used to effectively filter foreign particles from turboshaft engine intakes. The existing body of scientific literature on VTSs focuses mostly on singular separators, giving almost no attention to VTS arrays despite the array configuration being necessary for practical implementation on helicopters. Motivated by this, the research presented in this dissertation investigated the fluid flow downstream of a vortex tube separator array. Its goal was to identify and explain any flow phenomena specific to the array configuration. The research was split into two categories: mean flow and unsteady flow.

The first study included in this dissertation focused on the mean flowfield. Particle image velocimetry measurements were taken downstream of a VTS array model (7-VTS) placed in a wind tunnel. Data was also acquired for a second configuration that blocked all but one separator, imitating a single VTS flow (1-VTS). Mean velocities revealed a 7-VTS flowfield containing several vortices that rapidly interacted as they moved downstream. High circumferential velocities gripped the circular edge of the duct, while a central recirculation zone developed in the axial component, already distinctly visible just 0.23 VTS diameters downstream of the outlets. This phenomenon did not occur in the 1-VTS flow despite an unchanged local swirl intensity in each separator. A momentum integral model was derived to predict the critical swirl number to induce recirculation for each configuration. The model showed that, under reasonable conditions, it was indeed possible for 7-VTS flow to be supercritical while 1-VTS flow remained subcritical. The reason for this could be found by using a global perspective accounting for the entire duct and all VTS outlet flows. Outer (non-central) separators generated both positive and negative angular momentum if the origin was considered to be the duct center point, but the positive momentum was generated at higher radii. As angular momentum depends exponentially on radius, each non-central
5.2. Outlook

A separator produced a net positive contribution to global angular momentum, driving up the swirl number in the 7-VTS configuration. The finding is expected to remain true for larger VTS arrays than the one studied here - arrays with more separators, but a similar overall shape. So long as all separators are co-swirling, each non-central separator will contribute positively to global angular momentum.

The second study extended analysis into the instantaneous and fluctuating velocity realm; the VTS flow as a whole was found to be highly unsteady. Further PIV measurements showed unexpectedly low-anisotropy turbulence generated by all VTSs, even in 1-VTS configurations. This was in contrast to high-anisotropy turbulence found in other intensely swirling flows, indicating the effectiveness of VTSs as fluid mixers. Spectral proper orthogonal decomposition was then conducted on a large dataset immediately downstream of the 7-VTS outlet plane to extract any coherent structures in the flow. A precessing vortex core was found in the center of the duct at a Strouhal number of $1.5 \times 10^{-1}$. Precessing vortex cores have been observed in swirling flows and other (singular) cyclone separators before, though typically oriented differently. In cyclone separators, they are associated with a reduction in separation efficiency. An additional high-energy structure was found: a back-and-forth pumping motion in the center of the duct at the very low Strouhal number of $9.8 \times 10^{-3}$ and two of its higher harmonics. To the author’s knowledge, this motion has not been observed in any previous swirling flow or cyclone separator. Its origin remains unclear, though it may be linked to low-frequency oscillations observed in the scavenge flow. Both structures may be associated with the central recirculation zone, as they were found roughly within its boundaries. In any case, given their lengthy timescales, they could both be expected to impact the separation efficiency of associated upstream separators.

5.2 Outlook

This dissertation is an early exploration of VTS array physics, and it is hoped that many future studies may build upon its findings. An obvious next step is to analyze inertial particle dynamics in the same VTS array model. Measurements of local separation efficiency in the individual separators of the array - highlighting any potential differences - would be useful. Additional investigations into the dynamics of unfiltered particles exiting the VTS outlets may provide some explanation for efficiency observations. Perhaps these particle
dynamics could be linked to the complex flow phenomena noted in the present dissertation. A preliminary effort to achieve these goals is currently in the planning stages and will begin in the near future with the author’s assistance.

As always, experimental measurements are only part of the picture - numerical simulations will play a valuable role in the future of VTS array research as well. A major challenge with VTS array experiments is the complex geometry involved, which prevents easy optical or probe-based measurements within the scavenge chamber itself. Given that the scavenge chamber is likely the source of many array-specific fluid and particle behaviors of interest, this limitation is severe. Numerical simulations must be conducted to reveal the inner workings of the scavenge chamber.

This dissertation includes some added efforts to aid in the two steps listed above - particle dynamics measurements and numerical simulations - in the appendices. CAD geometry of the VTS array model will be made available alongside the publications shown in Chapters 3 and 4. Additionally, some boundary condition measurements were taken upstream and downstream of the array. These are provided in Appendix A to assist any future CFD studies. Lastly, the author developed a novel method of fluorescent tracer particle generation that is presented as a peer-reviewed publication in Appendix B. It is expected that the easy and inexpensive generation of fluorescent tracer particles will enable simultaneous fluid and inertial particle measurements, should they ever be needed in a future VTS array study.

With time, the author hopes that many details of the fluid and particle dynamics can be revealed to the scientific and engineering community. These may be used to improve the design of vortex tube separator arrays in order to increase the lifespan and safety of helicopters operating in particle-laden environments.
Appendices
Appendix A

Efforts to Support Numerical Simulations

Going forward, numerical simulations of VTS arrays will be desirable, as experimental measurement techniques are limited by the complex geometries involved. To enable and support such simulations of the experimental setup used in the author’s work, the following additional information is provided:

- Computer-aided design (CAD) files of the VTS array model will be published alongside the paper shown in Chapter 3.
- Velocity measurements upstream of the VTS array which may serve as CFD inlet boundary conditions.
- Velocity and pressure measurements downstream of the VTS array which may serve as experimental validation and CFD outlet boundary conditions.

The locations of measurements presented in this section are shown in Figure A.1.

A United Sensor™ Model DA-125 5-hole Cobra probe was traversed (1/8” increments) across the horizontal centerline of the duct 17.78 cm upstream of the VTS inlets (7-VTS configuration). As in Chapter 3, pressure data were acquired through an Esterline™ NetScanner Model 98RK pressure scanner, which had an uncertainty of ±17.2 Pa (±0.003 psi) according to manufacturer specifications for the 5 psi range module. 100 samples were averaged at each location, which was enough to achieve statistical convergence. Resulting velocities are presented in Figure A.2 as a function of radial position $r$ normalized on duct radius $r_3$. This is shown from an aft-looking-forward perspective (looking upstream from the VTS inlets) to stay consistent with previously-presented data. Radial ($V_R$), circumferential ($V_\theta$), and axial ($V_Z$) velocity components are plotted.
Nominally, the velocity would have been 10.03 m/s solely in the axial direction. The measured results are similar to these nominal values, though some small discrepancies are apparent. $V_Z$ appears to decrease very slightly as $r/r_3$ increases. This may be the result of minor shifts in condition in the suction blowers or the atmosphere over the course of the measurements, which took nearly an hour to complete. $V_\theta$ has a very low non-zero value throughout the duct, which is likely tied to measurement errors, but would otherwise indicate some small positive swirl. $V_R$, as expected, is negligible everywhere.

For comparison, 5-hole probe data from 7.62 cm downstream of the VTS array outlets is also provided in Figure A.3. This was first presented in Chapter 3, where it is discussed in detail.

A wall tap was also inserted 54.61 cm downstream of the VTS outlets. This allowed for the measurement of static pressure in a region where it was expected to be constant across the duct cross-section. The Model 98RK scanner measured 995.6 ±17.2 Pa gauge pressure at this location. Notably, a small change was observed over time, possibly providing some evidence for the blower or atmospheric condition shifts noted earlier in this section.
Figure A.2: Velocity components across the centerline of the duct 17.78 cm upstream of VTS inlets, as measured by the 5-hole probe.
Figure A.3: Velocity components across the centerline of the duct 7.62 cm downstream of VTS outlets, as measured by the 5-hole probe.
Appendix B

Fluorescent Particle Image Velocimetry using Atomized Liquid Particles

The contents of this chapter were published in *Measurement Science and Technology* in 2022. They describe the development of a novel laser-based measurement technique that enables simultaneous velocimetry of both fluid and inertial particles in a vortex tube separator flow. Fluorescent tracer particles may be imaged separately from inertial particles in the same flow with the use of a high-pass filter.

As stated in Section 5.2, the present dissertation is intended to be succeeded by research focusing on inertial particle dynamics in a VTS array flow and establishing links to the known fluid dynamics.

Fluorescent particle image velocimetry using atomized liquid particles

Adit S Acharya*, K Todd Lowe and Wing F Ng

Advanced Propulsion and Power Laboratory, Virginia Tech, Blacksburg, VA, United States of America

E-mail: aacharya@vt.edu

Received 23 September 2021, revised 2 February 2022
Accepted for publication 7 February 2022
Published 3 March 2022

Abstract
Aerosolized fluorescent particles of Kiton Red 620 dye in a water/glycol fluid are generated using a Venturi-type atomizer and shown to provide effective flow seeding for fluorescent particle image velocimetry (PIV), which can mitigate the detrimental effects of laser reflections from surfaces. Ninety two percent of particles by number concentration were found to be <1 µm in diameter, an acceptable size threshold for gas-flow PIV purposes. A PIV application was conducted in a wind tunnel (freestream velocity $U_\infty = 27 \text{ m s}^{-1}$), using the particles for measurement of the boundary layer flow approaching a forward-facing step (approach boundary layer momentum thickness Reynolds number of $Re_\theta = 5930$). Particles were generated from solutions with dye molar concentrations of $2.5 \times 10^{-3}$ and $1.0 \times 10^{-2} \text{ mol l}^{-1}$, and PIV images were obtained for both elastic Mie scattering and filtered, Stokes-shifted fluorescent light. Raw images indicate that the fluorescence yield of the $1.0 \times 10^{-2} \text{ mol l}^{-1}$ solution provides PIV images with high contrast, even in the near-surface regions where Mie scattering image contrast is highly affected by surface reflections. Boundary layer profiles are processed in the region of adverse pressure gradient leading up to the forward-facing step, where the fluorescent PIV was found to perform comparably to the most optimized Mie scattering PIV; both approaches obtained data as near to the wall as 30 µm, or two viscous wall units in our flow of interest. These results indicate that the new seeding method holds promise for near-surface measurement applications with more complicated three-dimensional geometries, where it is impossible to arrange PIV cameras to reject surface-scattered light.

Keywords: particle image velocimetry, fluorescent, liquid

(Some figures may appear in color only in the online journal)

1. Introduction
Particle image velocimetry (PIV), which involves the optical measurement of light-scattering tracer particles, has become a ubiquitous flow diagnostic technique over the past few decades. In PIV, a fluid flow of interest is seeded with small particles [1] which have negligible inertia compared to drag forces (i.e. a low Stokes number) and thus effectively follow fluid streamlines. The particles are then illuminated with laser light of wavelength $\lambda$, which they scatter elastically at the same wavelength (i.e. Mie scattering, in the case of spherical particles). The motion of these particles is recorded with a rapid succession of photographs, after which the fluid velocity is obtained in numerous small windows by image cross-correlation. PIV has seen extensive use in both laminar and turbulent flows [2].

A frequent challenge for PIV experimentalists is the occurrence of surface laser reflection, or ‘flare’, in flows around models [3], flows involving free surfaces [4], and studies of near-wall regions in general [5]. Flare is detrimental to PIV correlations because it decreases the image contrast and signal-to-noise ratio in the vicinity of surfaces. Light that is scattered by surfaces can be far more intense than particle light...
scattering, potentially leading to saturation of sensor pixels and the loss of flow vectors [6]. Paterna et al [3] also note the possibility of camera sensor damage from intense flare, although this is less of a concern with modern complementary metal-oxide-semiconductor (CMOS) cameras [7].

Attempts to reduce laser flare often involve modifications to surfaces themselves, such as a coat of black paint [8], an anodized black treatment [9], or clear surfaces that match the fluid’s index of refraction [10]. The comparative study of materials and surface treatments by Paterna et al [3] concluded that a coating of fluorescent paint was the most effective method of reducing flare in air-based experiments; refraction index matching is more optimal, but no material can match the refractive index of air. The fluorescent paint technique relies on laser-induced fluorescence, the emission of light that is red-shifted relative to any absorbed laser light. This alteration of wavelength is also known as the Stokes shift [11] (as opposed to much weaker, blue-shifted fluorescence, termed anti-Stokes shift). Surfaces covered with fluorescent paint emit Stokes-shifted light that can be blocked from the camera sensor with a band-pass filter to limit their impact on PIV measurements; Mie-scattered light at the laser wavelength from tracer particles is passed and collected.

Inversely, laser flare reduction may be accomplished with the use of fluorescent tracer particles; their Stokes-shifted light can be collected through a long-pass filter that blocks surface reflections at the laser’s wavelength. Fluorescent tracer particles have seen previous use for simultaneous velocity and temperature measurements [12, 13], though these studies still relied on Mie-scattered light for velocimetry purposes. Fluorescent-light PIV has been used in water-based experiments [14, 15], but is more challenging for gas flows, which require smaller particles and careful consideration of particle inhalation hazards [16]. For example, the study by Chennaoui et al [6] successfully demonstrated flare reduction with fluorescent PIV in air, but made use of hazardous materials that warranted protective measures.

A more recent study by Petrosky et al [17] demonstrated PIV with fluorescent dye-doped particles, with the goal of avoiding hazardous substances. Kiton Red 620 (KR620) dye was selected for its low toxicity, having even been used in food coloring applications [18]. The KR620 dye was used to dope polystyrene latex microspheres, which are commonly used as PIV tracer particles [19]. The ensuing experiments successfully allowed for accurate PIV measurements near the surface of a flat plate, where conventional PIV techniques were shown to be severely hampered by flare. This result was notable for its combined use of safe materials and tracer particles small enough to be suitable for gas flows; as noted by Petrosky et al, the intensity of fluorescent light from particles is typically two to three orders of magnitude lower than Mie scattering intensity, and this difference is exacerbated for small particles.

Notably, most examples of fluorescent PIV up to this point have involved the use of solid tracer particles. While effective, solid particles bring about a variety of undesirable challenges. The generation of dye-doped particles can be cumbersome, involving an emulsion polymerization process [20] or the grounding and dispersal of solidified resin [4]. These processes can be lengthy and expensive, requiring special facilities and materials. While researchers may order dye-doped particles for delivery, doing so forces the selection of a limited set of dye concentrations to which an experiment must be constrained—dye concentration impacts fluorescence yield and thus affects PIV results. In the current study, the authors expand on the work of Petrosky et al [17], exploring a novel method of liquid fluorescent tracer particle generation and injection that is relatively simple and inexpensive when compared to the aforementioned solid particle techniques. The particles are first shown to be of acceptable size for PIV purposes. Then, they are used in a PIV experiment in the boundary layer of a wind tunnel approaching a forward-facing step. Both fluorescent and Mie PIV are conducted and comparisons are made between their wall boundary layer profiles and skin friction coefficient results, showing the ability of the fluorescent PIV to perform comparably to the most optimized Mie-PIV case. This method of fluorescent particle generation was first presented by Acharya et al [21].

2. Experimental methods

The liquid fluorescent tracer particles were generated with a device the authors previously developed for the seeding of high-pressure nozzle flows [22]. This method, depicted conceptually in figure 1, involved two main components: the nozzle itself and a separate liquid reservoir. The reservoir was connected to the throat of a Venturi contraction upstream of the nozzle. When both the nozzle and reservoir were supplied with the same total pressure, the static pressure drop at the Venturi throat created suction, drawing the reservoir’s liquid into the nozzle tubing. Once in the tubing, strong shear forces atomized the liquid into fine particles. The device was found to generate a dense spray of particles across a range of total pressures and using different seed liquids: water and di-ethyl-hexyl-sebacat (DEHS) oil. Note in figure 1 the inclusion of a needle valve between the liquid reservoir and Venturi throat; this was added after the initial study to aid with mass flow rate control.

While the original intent of the device was for laser-based velocimetry and visualization of the nozzle plume itself, the authors saw potential in using the dense spray for PIV on external areas of interest, or even for the seeding of wind tunnels. Additionally, it was thought that a solution of fluorescent dye in a suitable liquid would be atomized in the same way as the seed liquids in the original study, creating fluorescent tracer particles for PIV. Kiton Red 620 dye was chosen for its safety and previous success in the study by Petrosky et al [17]. The dye was dissolved in a non-toxic, proprietary water/glycol solution (i-fog Fluid, Martin Lighting) used for long-lasting fog generation. Two separate dye concentrations were used: $1 \times 10^{-2}$ and $2.5 \times 10^{-3}$ mol l$^{-1}$.

The conducted experiments aimed to assess the suitability of the generated fluorescent particles for PIV and to demonstrate the potential advantages of such a method for near-wall measurements in complex settings where standard flare mitigation techniques are difficult to implement. First, a TSI 3321 aerodynamic particle sizer (APS) was used to extract...
and analyze particles from the seeded nozzle’s plume. This device determines aerodynamic size distributions of ingested particles over a diameter range of 0.5–20 µm. The Venturi device was supplied with 4.34 MPa (630 psia) from a compressed nitrogen tank. Its seed liquid reservoir was filled with i-fog fluid and its needle valve was set to 92% closed (as determined by color-coded markings on the valve). These settings were determined after preliminary analyses revealed the sensitivity of particle size and concentration to supply pressure and needle valve position. High supply pressure was required for the atomization of the fluid, but leaving the needle valve more open resulted in detrimentally high concentrations and particle diameters. The resulting spray was directed at the inlet of the TSI 3321 APS for 30 s.

A PIV experiment was then conducted in the Small Boundary Layer (SBL) Wind Tunnel at Virginia Tech. The SBL tunnel is an open-circuit wind tunnel that features a blower capable of delivering 62.30 m³ min⁻¹ of air, a series of honeycombs and screens to eliminate large-scale turbulence, and a 24.13 cm wide × 11.03 cm tall × 199.39 cm long acrylic/float glass optical test section with roughness introduced at the test section inlet for boundary layer tripping and thickening. Details of the tunnel were presented in the thesis by Bennington [23], though for an earlier iteration of the tunnel that included return ducting to form a closed circuit. The SBL tunnel was operated such that the freestream flow velocity was nominally 27 m s⁻¹ in the test section. Relevant flow parameters were obtained with the PIV experiment (details below) and a Pitot-static probe; to fill in the outer region missed by the highly magnified PIV setup, PIV velocity data were fit to a profile of \( \frac{U}{U_\infty} = \left( \frac{y}{\delta} \right)^{1/4} \), where \( U \) is velocity, \( U_\infty \) is the velocity of the freestream, \( y \) is the height above the wall, and \( \delta \) is the boundary layer thickness. This allowed for determination of the thickness and approximate velocities for the full boundary layer. Relevant flow parameters are shown in table 1; friction velocity is a representation of shear stress, and viscous length scale is the scale of near-wall eddies. The displacement thickness and momentum thickness are hypothetical heights of additional surfaces on top of the existing one (in inviscid flow) necessary to match the flow rate and momentum flow rate, respectively, of the real flow. The momentum Reynolds number is the ratio of inertial forces (using the momentum thickness as a length scale) to viscous forces in the boundary layer, and the shape factor is the ratio of displacement thickness to momentum thickness.

The PIV experimental setup is depicted in figure 2. The Venturi seeding mechanism was placed such that its spray was directed into the suction inlet of the tunnel. From there, seeded flow passed through the blower, plenum, and contractions into the optical test section. There, a flat metal plate of height 4.78 mm was secured to the floor to create a standard forward-facing step flow configuration to challenge the measurement system. A two-dimensional/two-component PIV arrangement was used, in the common wall-grazing view imaging configuration optimized for boundary layer measurement [24], which naturally minimizes flare. An EverGreen dual-pulsed 532 nm laser was fitted with a 20 mm cylindrical lens to produce a laser sheet aligned with the streamwise/normal-to-wall plane. A LaVision Imager sCMOS camera (2560 × 2160 pixels), fitted with a 100 mm focal length lens, was used to acquire images from a 32 mm × 32 mm region in the wall boundary layer, capturing the leading edge of the forward-facing step and a 27 mm long section of the tunnel upstream of it. For fluorescent PIV measurements, an Omega Optical 560 nm long pass filter (model 560HLP) was attached to the camera lens to reject 532 nm laser light. It was expected, as per Petrosky et al [17], that KR620 dye would emit Stokes-shifted light mostly above 560 nm. First, a set of 1000 Mie scattering

\[ U_\infty = 27 \text{ m s}^{-1} \]

\[ u_\tau = 0.99 \text{ m s}^{-1} \]

\[ v/\mu_c = 15 \text{ mm} \]

\[ \delta = 39 \text{ mm} \]

\[ \delta^* = 4.29 \text{ mm} \]

\[ \theta = 3.25 \text{ mm} \]

\[ \text{Re}_D = 5930 \]

\[ H = \delta^*/\theta = 1.32 \]

Table 1. SBL wind tunnel flow parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freestream velocity</td>
<td>( U_\infty )</td>
<td>27</td>
<td>\text{ m s}^{-1}</td>
</tr>
<tr>
<td>Friction velocity</td>
<td>( u_\tau )</td>
<td>0.99</td>
<td>\text{ m s}^{-1}</td>
</tr>
<tr>
<td>Viscous length scale</td>
<td>( v/\mu_c )</td>
<td>15</td>
<td>\text{ mm}</td>
</tr>
<tr>
<td>BL thickness</td>
<td>( \delta )</td>
<td>39</td>
<td>\text{ mm}</td>
</tr>
<tr>
<td>Displacement thickness</td>
<td>( \delta^* )</td>
<td>4.29</td>
<td>\text{ mm}</td>
</tr>
<tr>
<td>Momentum thickness</td>
<td>( \theta )</td>
<td>3.25</td>
<td>\text{ mm}</td>
</tr>
<tr>
<td>Momentum Reynolds number</td>
<td>( \text{Re}_D )</td>
<td>5930</td>
<td>—</td>
</tr>
<tr>
<td>Shape factor</td>
<td>( H = \delta^*/\theta )</td>
<td>1.32</td>
<td>—</td>
</tr>
</tbody>
</table>
images was taken with the lens aperture set at f/2.8, the widest possible aperture setting. Another set of 1000 Mie scattering images was taken with the aperture set to f/22, reducing flare and particle intensities alike. Finally, the aperture was set to f/2.8 and the high-pass filter was attached to the lens. Two sets of 1000 fluorescent-filtered images were taken; one for a dye concentration of $1.0 \times 10^{-2}$ mol l$^{-1}$, and one for $2.5 \times 10^{-3}$ mol l$^{-1}$.

Data processing was done in LaVision’s DaVis 8.4 software. The time domain filter method developed by Sciacchitano and Scarano [25] was used on all data sets to improve performance in flare-affected regions. Acquired images were processed with a multi-pass technique; the first pass used 64 $\times$ 64 pixel interrogation windows with 50% overlap, and the second pass used 32 $\times$ 32 pixel interrogation windows with 87% overlap. Spurious vectors were detected with the peak ratio $Q$, or the ratio of the highest to next-highest displacement correlation peak for a given interrogation window [19]. Vectors were considered ‘spurious’ if they had a $Q$ of 1.3 or greater. Additional spurious vector detection was performed with the median test introduced by Westerweel [26]. Vectors were removed if their residual value, $r$, was greater than 2. Removed vectors were replaced with interpolated data.

3. Results

As previously stated, the goals of the experiments were to prove the suitability of the generated particles for PIV, and to demonstrate promising fluorescent PIV performance in regions close to the acrylic lower wall of the wind tunnel which are normally affected by surface flare. In this section, the former is addressed with statistical measurements from the TSI 3321 APS, and the latter is shown through raw PIV images along with comparisons of PIV-based boundary layer profiles and skin friction coefficients for fluorescent and Mie PIV cases.

3.1. Particle sizes

The TSI 3321 APS collected 721,602 particles; a histogram of aerodynamic diameters is presented in figure 3, and statistical
size parameters of the particles are displayed in table 2. An aerodynamic diameter is defined as the diameter of a sphere with density 1 gm cm\(^{-3}\) that settles in still air at the same velocity as the particle in question. This differs from the geometric diameter, which is the physical diameter of the particle itself. Note that the APS was unable to determine diameters below 0.523 \(\mu\)m, which included nearly 8% of particles by number concentration in terms of aerodynamic diameter; this created a possible bias (although expected to be small) in statistical results. Despite this, the aerodynamic median diameter was found to be 0.725 \(\mu\)m, and 92% of particles by number concentration were at, or below, 1 \(\mu\)m in aerodynamic diameter. While ideal particle diameter limitations in any flowfield depend on the expected accelerations, Melling [27] states that 1 \(\mu\)m or less is typically suitable for gas flows. Further information on the performance of these particles can be obtained from relevant Stokes numbers. Using the aerodynamic median diameter of 0.725 \(\mu\)m, the particle lag timescale was found to be 1.7 \(\mu\)s. In the boundary layer flow used for this study’s PIV experiment, this corresponds to a Stokes number of 0.0012 for the integral timescale and 0.3121 for the Kolmogorov timescale. Raffel et al [28] report that tracer particles with Stokes numbers below 0.1 typically yield acceptable accuracy, implying that the analyzed particles are suitable for measuring all but the smallest scale fluctuations in such a boundary layer. The APS data therefore suggest that the Venturi device’s generated liquid particles are generally acceptable for PIV purposes for subsonic aerodynamics experiments at the stated pressure and needle valve settings.

### 3.2. PIV imaging

The PIV experiment was conducted to confirm the effectiveness of the fluorescent particles for PIV and to highlight any differences between fluorescent and Mie scattering PIV. Example instantaneous raw images for the four data sets are shown in figure 4. In these images, both axes are nondimensionalized using the height \(h\) of the aluminum step. The lower tunnel wall, at \(Y/h = 0\), is highlighted with an artificial blue line; its pixel-based location was determined through analysis of images taken prior to each PIV run. Notably, the liquid seeding particles for the 1.0 \(\times\) \(10^{-2}\) mol \(l^{-1}\) case were clearly visible even through the fluorescent filter which blocked the incident laser wavelength, as shown in figure 4(d). Particles for the 2.5 \(\times\) \(10^{-3}\) mol \(l^{-1}\) case were also visible (figure 4(c)), though dimmer. The fluorescent PIV images, as expected, had lower general particle intensities than their Mie scattering PIV counterparts—most 1.0 \(\times\) \(10^{-2}\) mol \(l^{-1}\) fluorescent particles were roughly 50 times less intense than Mie PIV particles at the same aperture setting \((f/2.8)\). They also appeared to show fewer particles than the Mie PIV at \(f/2.2\), but this was an artifact of the images’ unchanged intensity axes from that case. Some localized near-wall ‘bubbles’ of brightness were visible in the fluorescent PIV images; these were likely accumulations of out-of-focus fluorescent particles on the wall itself, as they were seen to grow and shift over time.

As expected, background intensity counts were considerably higher for the Mie \(f/2.8\) case than the other three. Figure 4(a) shows significant flare in the near-wall region, despite the transparent acrylic. This was exacerbated at lower \(X/h\) values, closer to the reflective forward-facing step, which itself was located at \(X/h = 0\). Figure 4(b) shows that reducing the aperture by six full stops to \(f/22\) (thus reducing passing light by a factor of 64) significantly mitigated the flare, but horizontal flare streaks and a discernable thin layer of extreme brightness just above \(Y/h = 0\) were still visible. In figures 4(c) and (d), the fluorescent cases, many of the near-wall flare issues were reduced or eliminated. The region of extreme brightness just above \(Y/h = 0\) appeared thinner, and the horizontal streaks of flare visible in figure 4(b) were no longer present.

Figure 5 quantifies the differences in light intensity approaching the wall for each optical case. Intensity counts are plotted for a 2 mm region above the tunnel wall, at \(X/h = -1\), from data not containing any particles. A nondimensionalized height axis is also provided. The figure shows relatively high intensities for the Mie \(f/2.8\) case throughout this span. The Mie \(f/22\) case and fluorescent \(f/2.8\) case counts appeared similar above a height of 1.5 mm, but diverged significantly below that level. At the wall, the Mie \(f/22\) intensity was nearly twice that of the fluorescent \(f/2.8\) case. While the intensity differences between Mie \(f/22\) and fluorescent \(f/2.8\) were not as stark as in the study by Petrosky et al [17], this was likely due to the grazing angle and the fact that the primary surface in question was a transparent acrylic wall, as opposed to a reflective aluminum plate used in the cited work.

### Table 2. Statistical data for diameters of particles collected by TSI APS.

<table>
<thead>
<tr>
<th>Statistical parameter</th>
<th>Value ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerodynamic median</td>
<td>0.725</td>
</tr>
<tr>
<td>Aerodynamic mean</td>
<td>0.933</td>
</tr>
<tr>
<td>Geometric mean</td>
<td>0.829</td>
</tr>
<tr>
<td>Geometric standard deviation</td>
<td>1.540</td>
</tr>
</tbody>
</table>

---

**Figure 3.** Histogram of aerodynamics diameters of particles collected by TSI 3321 spectrometer.
upstream of the step \((X/h = -5.5)\), where step-induced pressure gradient effects would be the least amongst the analyzed stations. The plot is presented in common wall coordinates, which normalize the velocity and height using friction velocity, which itself relates to the wall shear stress and velocity gradient as \(\tau_w = \frac{1}{2} \rho u^2 \frac{\partial U}{\partial Y} |_{y=0} = \rho u^+ \). The friction velocities were determined using the well-known Clauser chart method \([29]\), which assumes that the velocity profiles follow a universal logarithmic form in the ‘log-law’ region, chosen here to be \(35 < y^+ < 100\). For comparison throughout the near wall region, the Spalding profile \([30, 31]\) was also plotted; this profile blends the viscous sublayer (where \(u^+ = y^+\)) and the log-law region with a fit through the buffer region between them.

Figure 6 shows good agreement between the Spalding profile, Mie \(/f/22\) PIV, and fluorescent \(/f/2.8\) PIV at \(1.0 \times 10^{-2}\) mol l\(^{-1}\). Below the log-law region, these profiles nearly match the Spalding profile as it transitions towards the viscous sublayer. This is not the case for Mie \(/f/2.8\) PIV and fluorescent \(/f/2.8\) PIV at \(2.5 \times 10^{-3}\) mol l\(^{-1}\), which both diverge from the Spalding profile in the buffer region. The clear improvement between Mie \(/f/2.8\) PIV and Mie \(/f/22\) PIV suggests that the effects of increased laser flare significantly hampered \(/f/2.8\) PIV measurements near the wall. There exists a similar clear improvement between the fluorescent PIV at \(2.5 \times 10^{-3}\) and \(1.0 \times 10^{-2}\) mol l\(^{-1}\); the increased dye concentration is

3.3. Boundary layer comparisons

Boundary layer data were extracted for the streamwise mean velocities of each data set. Figure 6 is a plot of the boundary layer profiles at an \(X\)-position that was 5.5 step heights upstream of the step (\(X/h = 0\)); tunnel wall (\(Y/h = 0\)) highlighted with blue line.
necessary for accurate PIV results. In most cases, the fluorescent yield of tracer particles is proportional to dye concentration [32]; so, there must exist a threshold below which PIV performance is negatively affected. However, dye concentrations in the present study were far higher than those used by Lemoine et al., and fell into a regime where significant self-quenching and loss of fluorescence yield would normally be expected. It is possible that the small size of the particles allowed for only small amounts of excitation flux to enter them (relative to the incident laser flux), preventing high levels of self-quenching and thus keeping the particles in the regime where fluorescent yield remains proportional to dye concentration.

As additional verification of both the suitability of the venturi seeding method for PIV and the accuracy of the fluorescent PIV at $1.0 \times 10^{-2} \text{ mol l}^{-1}$, figure 7 compares the normal and shear Reynolds stresses (normalized on wall coordinates) computed from that PIV case (at $X/h = -5.5$) to flat plate turbulent boundary layer data from de Graaff and Eaton [33]. Outlier removal was used to prevent extreme velocity fluctuation measurements from detrimentally affecting the PIV data. Note that the approach boundary layer momentum thickness in the fluorescent PIV case was $Re_{\theta} = 5930$, while the data used from the de Graaff and Eaton study was for $Re_{\theta} = 5200$, the closest match available among published comparison datasets. Fluctuating velocity values on wall scaling were nevertheless expected to be similar between the two cases, and indeed the normal and shear Reynolds stresses appear to match closely across most analyzed $y^+$ values, though some differences are apparent for $\overline{v'^2}$ below $y^+ = 38$. These differences are due to increased measurement variance very near the wall which affects $\overline{u'^2}$ more dramatically than $\overline{v'^2}$ in the determination of the PIV correlation peak.

The forward-facing step created an adverse pressure gradient in the upstream near-wall region; the log-law region of the boundary layer mean-velocity profile could not necessarily be expected to match the Spalding profile closer to the step than $X/h = -5.5$. As shown by Aubertine and Eaton [34] and Wang et al. [35], boundary layer profiles are significantly affected by adverse pressure gradients at their higher $y^+$ values. The general trend is for $u^+$ values in these regions to increase across the gradient. However, at lower $y^+$ values, the boundary layer profiles remain relatively unchanged across the gradient and continue to match the Spalding profile well. Thus, in the present study, the lowest values of the boundary layer profiles ($y^+ < 11$) were matched with the Spalding profile by way of adjusting the friction velocity at each axial station. The resulting profiles in wall scaling are shown in figure 8 for all four PIV cases, in the same style as Wang et al. [35]. As expected, $u^+$ values in the upper regions tended to increase across the adverse pressure gradient (approaching $X/h = 0$) due to the wall friction reduction.

A friction velocity was found at each axial station of each PIV case through the aforementioned adjustments. These were converted to skin friction coefficients, as $c_f = 2u'^2/\rho u_{\text{ref}}^2$, where $u_{\text{ref}}$ is the friction velocity and $u_{\text{ref}}$ is a reference velocity, chosen here to be the freestream velocity of 27 m s$^{-1}$. The resulting friction coefficients are plotted in figure 9. All PIV cases demonstrated a general decreasing trend as the step was approached, consistent with previous computational and oil-film interferometry findings regarding skin friction coefficient in an adverse pressure gradient [36, 37]. The data for Mie f/2.8 PIV and fluorescent PIV at $2.5 \times 10^{-3} \text{ mol l}^{-1}$ descend erratically, however; this conflicts with the smoothness and consistency of the curves found by the cited studies. The data for Mie f/22 PIV apparently have less variance as the flow approaches the step, but the friction coefficient of the fluorescent PIV at $1.0 \times 10^{-2} \text{ mol l}^{-1}$ exhibits the most physically consistent variation across the pressure gradient. The $1.0 \times 10^{-2} \text{ mol l}^{-1}$ fluorescent PIV case exhibits a trend most consistent with the results reported for previous studies. Even for the optimized
Aerosolized fluorescent particles generated using a Venturi-type atomizer were found to be suitable for PIV purposes; this was demonstrated in multiple ways. First, the particles were found to be of acceptable size for PIV in many aerodynamic flows, with a median aerodynamic diameter of 0.725 µm. Second, the fluorescent particles with a dye concentration of \(1.0 \times 10^{-2} \text{ mol l}^{-1}\) produced raw PIV images with good contrast when a filter was used to eliminate the incident 532 nm laser light and long-pass Stokes-shifted fluorescence from the particles. Using the fluorescence-passing filter resulted in significantly reduced laser flare in near-wall regions. Third, the measured boundary layer streamwise mean velocity profile of the fluorescent PIV case with a dye concentration of \(1.0 \times 10^{-2} \text{ mol l}^{-1}\) was in close agreement with the theoretical Spalding profile, while the measured Reynolds stress profiles closely matched known data for a turbulent boundary layer flow.

This method of liquid fluorescent PIV performed comparably to the most optimal Mie scattering PIV case, and additionally showed promise for potentially generating more accurate results in near-wall regions of a flow. The streamwise evolution of skin friction obtained from fits to the Spalding profile for \(y^+ < 11\) showed noticeably reduced variance in the \(1.0 \times 10^{-2} \text{ mol l}^{-1}\) case throughout the adverse pressure gradient compared with the three other cases considered. The smooth and monotonic decrease of the skin friction coefficients from the \(1.0 \times 10^{-2} \text{ mol l}^{-1}\) fluorescent PIV case was in qualitative agreement with trends observed in previous studies through computational means and oil-film interferometry.

Taken together, the results indicate that using a dye concentration of \(1.0 \times 10^{-2} \text{ mol l}^{-1}\) and the Venturi-based atomizer is a viable and cost-effective approach for implementing
fluorescence-based PIV for measurements near surfaces in aerodynamic flows. The method is believed to be scalable for much larger applications as well, provided that sufficient pressure is supplied to the jet. Potential future studies may investigate the quantitative accuracy of its near-wall measurements, and the method’s use for PIV in complex geometries where flare is otherwise difficult to mitigate.

Data availability statement
The data that support the findings of this study are available upon reasonable request from the authors.

ORCID IDs
Adit S Acharya https://orcid.org/0000-0003-4139-8468
K Todd Lowe https://orcid.org/0000-0002-0147-4614

References
[23] Bennington J L 2004 Effects of various shaped roughness elements in two-dimensional high Reynolds number turbulent boundary layers Thesis Virginia Tech
[34] Aubertine C D and Eaton J K 2005 Turbulence development in a non-equilibrium turbulent boundary layer with mild adverse pressure gradient *J. Fluid Mech.* **532** 345–64

