Chapter 7

Discussion, Conclusions and Recommendations

7.1 Overview of experimental results

7.1.1 Free vortex geometry

Free vortex geometry flows exhibit a wide range of behavior depending not only on swirl number but also and equally significantly on Reynolds number. The dependence on Reynolds number is surprising because the Reynolds numbers are clearly far into the turbulent regime (>30,000). However, as the Reynolds number is increased an ever smaller amount of swirl will cause vortex breakdown to occur inside the nozzle, immediately downstream of the cone center–body. The resulting axial velocity flow field inside the nozzle has the form of a wide wake, slowly recovering downstream. If the amount of swirl is chosen such that the vortex core remains intact through the nozzle for two different Reynolds numbers, the resulting normalized flow fields are very similar.

With the vortex core intact inside the nozzle, an axial momentum surplus is observed at the nozzle center. The surplus increases with increasing swirl. As the flow proceeds through the sudden expansion the surplus is dissipated and for high enough swirl replaced by an axial momentum deficit at the center without reversed flow. Flow development is rapid for all cases with swirl. Flow development speed is directly proportional to the swirl level. Flow development parallels the consumption of azimuthal momentum. The magnitude of the turbulent shear stress $\overline{u'w'}$ is a good marker for intense mean momentum redistribution.

Turbulence levels reach 40% of the area mean inlet velocity. Concentrations of turbulent energy were observed near the regions of maximum swirl. For the cases with swirl, local maxima were hence observed at the center of the flow and at the outer shear layer. The local maxima become broader downstream and eventually the outer shear layer maximum overtakes the turbulent energy maximum at the center of the flow field and a single maximum associated with the outer shear layer remains with a local minimum at the center of the flow.

The dynamics observed for the flow fields studied in the free vortex geometry are very broad band and no narrow band spectral features were found. The only significant spectral concentration is observed for the case of zero swirl. A broadband peak at around St = 0.30 is found to develop with the flow. Flow development for the case of zero swirl is very slow due to the absence of the mixing capabilities of swirl. The broadband peak achieves maximum visibility at the center of the flow but increases in magnitude toward the outer shear layer. At the point of maximum mean shear however, the spectral concentration can not be identified.

7.1.2 Annulus geometry

With the center–body in place for the nozzle section, the nozzle flow remains similar for the entire range of swirl numbers studied and no sensitivity to Reynolds number is observed. Reynolds number similarity is maintained through second order statistics. Spectra show some quantitative differences.

All flows studied exhibit a wake like profile immediately downstream of the bluff body (i.e. at combustor entrance). The speed of recovery of the wake differs greatly with swirl level. For zero swirl the wake recovery occurs at an axial distance proportional to the diameter of the center–body. Relative to the nozzle diameter this development appears relatively fast and at the last station measured, the flow profile resembles that measured in the free vortex geometry in the absence of swirl. Only the turbulence profiles contain evidence of the redeveloped wake.

The wake flow recovery is further accelerated for low levels of swirl (S=0.2). Further increases in swirl result in a strengthening of the wake early in the flow development (S=0.3). Overall, however, flow development speed increases still and at the last station measured, even the external recirculation zone has almost closed. Further increases in swirl result in a slower redevelopment of the flow as a strong central recirculation zone develops ($S > 0.35$). At the last axial station measured the flow takes the form of a slowly recovering wall jet.

The turbulence levels are directly proportional to the level of swirl for swirl numbers lower than 0.35. At this point a strong central recirculation zone develops but the turbulence levels do not increase further and for some axial locations are actually lower than for the S=0.30 case, for example. Radial turbulence intensity distributions again show evidence of two turbulence production sources. The first is the outer shear layer associated with the sudden expansion of the flow. The second is due to the inner shear layer which for the annulus geometry combines the influences of swirl and the center–body. In the free vortex geometry, the turbulence production in the outer shear layer dominated. For the annulus geometry the inner shear layer turbulence production dominates except in the cases of very low or zero swirl (S<0.2), consistent with the free vortex geometry results).

The annulus geometry flows are also very interesting from a dynamic standpoint. For large swirl levels a large scale flow oscillation is observed immediately downstream of the sudden expansion. Some evidence of the oscillations can be observed in the nozzle and downstream. Nozzle oscillations increase with increasing swirl. Downstream evidence of oscillations increases with decreasing swirl. The oscillations increase in frequency with increasing swirl and disappear suddenly as the central recirculation zone weakens and the inlet swirl number decreases. The frequency of oscillations is linear with flow rate and thus occurs at a constant Strouhal number regardless of Reynolds number. The magnitude of the oscillations increases with swirl but the radial distribution of the oscillations retains the same form regardless of axial position or swirl strength. The maxima of the axial velocity oscillation magnitude distribution (called axial eigenfunction hereafter) line up approximately with the points of maximum shear in the local axial velocity profile. The same is true for the swirl eigenfunction. The result is that the axial eigenfunction has a node at the centerline and near the point of maximum velocity. A weaker third node can be identified for some cases. The swirl eigenfunction exhibits a maximum at the centerline and a node near the point of maximum swirl velocity. The swirl eigenfunction then goes to zero as the shear in the swirl velocity profile decreases outside the outer shear layer.

At swirl levels below S=0.35, the oscillation is absent but the flow remains dynamically active. Significant low frequency intermittence can be observed at intermediate distances downstream of the sudden expansion for the S=0.30 case. Closer to the sudden expansion the intermittence is weaker. Downstream, very high turbulence levels are observed but no trace of intermittence is found. Flow development here is very rapid and the outer flow recirculation zone is the smallest of all experimental conditions studied. The strength of the intermittence not only depends on the axial coordinate but also on the radial coordinate. Strongest evidence of the intermittence can be found at the edge of the inner shear layer. The form of the intermittence is consistent with a periodic radial inward and outward motion of the annular jet exiting from the nozzle.

7.2 Overview of analytical results

7.2.1 Convective stability

Convective stability results show very strong broadband energy amplification in the outer shear layer. Consistent with the results of Morris (1976) and Cohen and Wygnanski (1987b), little difference between azimuthal wavenumbers in shear layer amplification characteristics is observed for the velocity profiles measured. The scales of the shear layer thickness are significantly smaller than the jet circumference. The addition of swirl stabilizes the outer shear layer for axisymmetric and positive azimuthal modes and destabilizes the outer shear layer for negative azimuthal modes. The stabilizing and destabilizing effects are proportional to swirl.

The free vortex geometry nozzle velocity profile with axial momentum surplus analyzed is shown to be stable in the range of Strouhal numbers studied, although some modes are only very lightly damped. The least stable modes are associated with inner shear layer created by the swirl generated axial momentum surplus.

Two shear layer modes are observed for velocity profiles with significant wakes, regardless of whether the velocity profile studied stems from data in the free vortex or annulus geometry. These modes are associated with the inner and outer shear layers respectively. The outer shear layer mode eigenfunction is influenced by the presence of the wake but the inner shear layer mode eigenfunction shows no influence of the outer shear layer. Inner shear layer dynamics are significantly changed through the addition of swirl. Axisymmetric inner shear layer wake modes remain stable under the addition of swirl and negative azimuthal modes are stabilized by the addition of swirl. Continued increase in swirl will eventually also lead to the stabilization of the positive azimuthal modes.

Velocity profiles with central recirculation exhibited a very confused convective stability picture. The reason for these incomprehensible results is the existence of an absolute instability for these velocity profiles. The results from the analysis are summarized in the next section. The reason that other velocity profiles studied exhibit a more organized structure is due to the fact that these flows are absolutely stable. For absolutely unstable flows a more organized picture is obtained by increasing the imaginary part of the real frequency (spatial stability) above the saddle point value.

7.2.2 Absolute stability

For velocity profiles with central recirculation, an absolute instability was identified. The strength and frequency of the instability increase with swirl as observed in the experiments. The calculated absolute instability frequency however does not match the experimentally observed frequency. The frequency observed in the experiments is about double that calculated analytically.

The addition of external back-flow to the velocity profile does not affect the absolute stability characteristics as both frequency and growth rate remain essentially unchanged even with 20% external back-flow.

The eigenfunctions calculated at the saddle point have some similarities with the experimentally determined eigenfunction. Similar to the experiments, nodes are located near the points of zero shear in the mean velocity profile. However, significant differences also exist. The distribution of the maxima observed in the experiments is different from that calculated by the analysis. In particular large differences are observed between the measured and calculated swirl eigenfunction. Here however it is possible that experimental limitations contribute to the discrepancy. As the vortex center is approached, the distinction between radial and swirl velocity becomes more and more difficult and even small misalignments from the vortex center will cause a combination of swirl and radial velocities to be measured.

Based on the analytical study for the wake profile alluded to above, absolute stability can be described as a resonance between two shear layer modes. The convective stability calculations showed that positive azimuthal wake modes are destabilized by the addition of swirl. Simultaneously, the outer shear layer mode growth rate decreases with the addition of swirl, but remains unstable. The interaction of these two modes leads to the condition of absolute instability. Negative azimuthal modes, although convectively perhaps destabilized by the addition of swirl for the outer shear layer modes, remain absolutely stable because the wake modes are entirely stabilized.

7.2.3 Turbulent stability

Turbulent stability calculations, accounting for a non–uniform turbulence distribution, were performed for the case of the free vortex geometry nozzle flow. The results show that non-uniform viscosity preferentially destabilizes low frequencies and stabilizes higher frequencies, essentially skewing the flow's response to lower frequencies.

However, the Reynolds numbers resulting from the turbulent viscosity model are so low that the dominant effect of turbulence is a stabilization of the inner shear layer. The turbulent viscosity model does not distinguish among the scales of turbulence involved. A very large amount of the energy is contained in very long time scales. It is not possible to account for the length and time scale distribution of the turbulence in the present simplistic turbulence model. The description of the loss of stability given in Chapter 4 remains a plausible explanation. (see Section 7.3)

7.3 Flow dynamics in turbulent flows

The study of the dynamics of free shear layers is often performed in highly controlled environments with turbulence levels reduced as much as possible (Cohen and Wygnanski, 1987b). Under these conditions, the turbulence produced by the action of the free shear layer dynamics quickly dominates the flow field. In the experiments presented in this dissertation, the inlet flow already has significant turbulence and flow history becomes extremely important in the shaping of the spectral characteristics of turbulence. Additionally, the presence of swirl provides a perpetual source for turbulent energy away from the solid boundaries of the flow.

Turbulence production for non-swirling flows is confined to the boundaries of the flow where as the flow develops, a balance between turbulence production and dissipation is achieved and the flow eventually becomes invariant without changes in geometry (turbulent pipe flow). With the addition of swirl the flow will never achieve balance until all azimuthal momentum is consumed and converted to turbulent energy by the action of turbulence production at the center of the flow.

The dynamics observed in the experiments are thus not only due to free shear layer dynamics but also due to the history of the flow field and in cases with swirl, the presence of swirl. The visibility of free shear layer dynamics is thus lowered in less idealized environments. Linear stability analysis shows that in the initial stages of free shear layer development, the amplification of disturbances occurs over a wide range of frequencies and a range of azimuthal modes have similar amplification rates. The presence of significant fluctuation energy and the broad band amplification of the energy by a combination of free shear layer modes leads to a further complication in the prediction of spectral characteristics.

As the flow develops downstream, linear stability shows that the range of amplified frequencies decreases while the amplification rates, although lower than in the initial development stages, remain significant. The experiments showed that here some spectral coloration by the shear layer dynamics can be observed. However, the coloration of spectral energy was only observed for cases without swirl. The reason for this is that in the presence of swirl, flow development is accelerated and dynamic characteristics change relatively briskly. The rapid flow development leads to a relatively rapid decrease in the shear layer amplification rates downstream in addition to a continuous significant shift in the amplified frequency range. No significant accumulation of energy in any particular frequency range can thus be expected under these circumstances.

The only possibility for high visibility of shear layer dynamics in these types of non-idealized flows, in the absence of excitation is the existence of absolute instability. In this case, a resonance of two shear layer modes exists that causes the flow to behave as a self-excited oscillator. For the case where large narrow band velocity oscillations are found in the experiments, linear stability analysis shows the flow to be absolutely unstable. Furthermore, the absolute instability calculated was found to have an azimuthal wavenumber equal to one, as found in the experiments. Convective stability calculations showed that although the negative azimuthal mode of the outer shear layer is destabilized by the addition of swirl, the inner shear layer mode is rapidly stabilized. Even with swirl, no unstable axisymmetric inner shear layer modes could be found. The growth rate of the first positive azimuthal mode of the outer shear layer decreases with the addition of swirl but is not stabilized. At the same time, the addition of swirl can cause a destabilization of the first positive azimuthal mode of the inner shear layer. The conditions for amplified interaction between the two shear layer modes are thus only given for the first positive azimuthal mode. As indicated in the absolute stability calculations and shown in the convective stability calculations, the addition of swirl eventually has a stabilizing influence, even for the positive azimuthal mode.

Parallel linear stability analysis, although unable to correctly predict the frequency of the instability or its exact form, has elucidated the cause of absolute instability in the interaction of two simultaneously unstable shear layer modes. Clearly, existence of two simultaneously amplified shear layer modes does not guarantee absolute instability, because otherwise absolute instability would have been found for a wider range of experimental conditions. The experimental results showed that the instability became much weaker as the reverse flow at the center became weaker. Simultaneously, the flow divergence and the thickness of the inner shear layer decreased relative to the outer shear layer. Thus it is unclear whether reverse flow itself is required for absolute instability or if a matching of the inner and outer shear layer scales is a more important factor. The linear stability characteristics of the inner and outer shear layer will become more and more similar as their thicknesses become similar and such overlap intuitively would ease interaction.

The nonparallel character of the flow fields studied represents a further complication to the success of the application of plain parallel stability analysis in the understanding of the observed flow dynamics. However, the experimental results of the absolute instability point to the fact that some information can still be gained from a plain parallel analysis. The similarity of the eigenfunctions for the absolutely unstable flows is similar to that observed for slowly developing jet flow. In jet flow the eigenfunctions calculated as part of a non-parallel linear stability analysis match those calculated in parallel stability analysis. Furthermore, the amplification rates calculated by the non-parallel analysis match those calculated by the parallel analysis closely. The influence of non-parallelism is significant but limited to the variation of phase speed not only with axial coordinate but also with the flow variable considered. The similarity found in the experimentally measured eigenfunctions supports the argument that although flow development is more rapid in swirling flows, the simultaneously observed larger amplification rates allow the cautious application of parallel linear stability analysis to obtain qualitative information on dynamic flow behavior.

In the study of the dynamics of turbulent flows, a persistent question remains the mechanism of turbulence production. Early on, linear stability analysis was thought to hold the key to the cause of turbulence transition. Recently pseudo-spectral analysis has been able to shed more light onto the subject of transition for the 2-D case of flow between two flat plates. The analysis shows how perturbations can be amplified on a transient basis because the Orr-Sommerfeld operator is non-orthogonal, allowing communication among the different modes. Pipe Poiseuille flow is found to be stable in the inviscid limit and thus also exhibits transition to turbulence without unstable eigenvalues. However the disturbance equation operator for the 2-D case still determined the transient amplification of disturbances and it is expected that the same is true in cylindrical coordinates. The experimental study in particular highlighted the production of turbulence by the presence of the inner free shear layer that always exists when the flow contains swirl. In particular the free vortex nozzle velocity profile was found to be stable in linear stability analysis begging the question of the mechanism of turbulence production in the inner shear layer. It was not possible to perform a pseudo-spectral analysis to this point but the experimental results point to the value of a more fundamental study of the properties of the operator governing the disturbance equations in cylindrical coordinates.

The linear stability analysis modified for the addition of turbulence was not able to provide help in the explanation of the loss of stability of the flow inside the nozzle for the free vortex case. Experimentally, Chapter 4 introduced the loss of stability as a failure to be able to transport enough of the turbulence generated at the center of the flow to the outer parts of flow field. In an attempt to distribute the generated turbulence the flow executes larger and larger motions (visible in the larger energy content of low frequencies), eventually causing the flow to reorganize entirely with vortex breakdown moving up into the nozzle and to the base of the cone center–body. This description of the loss of stability relies on the distinction of turbulent scales and thus it should not be surprising that the turbulence model used here fails to accurately predict the loss of stability. Nevertheless, the increased damping of higher frequencies and destabilization of lower frequencies points to the fact that the turbulence will be shifted to lower frequencies as is indeed observed in the experiments.

Finally, the role of acoustics in the observed flow dynamics must be briefly treated. Although acoustic measurements were to this point only performed superficially, the interaction of incompressible flow dynamics and compressible acoustics is of pivotal importance in the understanding of possible hydrodynamic feedback mechanisms in combustion instabilities as observed by Paschereit et al. (1999) for example. In the case of an absolutely unstable flow, the appearance of a combustion instability may be simply caused by a narrow-band noise source (the self-excited flow field with superimposed and hence oscillating combustion) driving a lightly damped acoustic network. However, hydrodynamics paced by acoustic feedback have also been observed. Without combustion, such feedback is only possible in relatively high Mach number flows where the flow itself becomes a significant source of noise.

In the presence of combustion however, such a requirement is absent because oscillating heat release is a volume source of acoustic velocity, regardless of the underlying flow Mach number. Suppose for a moment that the flame dynamics are purely characterized by the dynamics of mixing (fast chemical time scales) which in a simplified view are tied closely to the flow dynamics. The noise produced by the flame is thus related to the turbulence produced in the flow field. The noise produced forces the acoustic field of the combustor inducing some distributed acoustic velocity oscillation. In order for an instability to develop these acoustic velocity oscillations (or the associated pressure waves) must be fed back to the flow dynamics that originally forced the acoustic field. Since for most combustors, the Mach numbers observed are relatively low, a direct interaction between the incompressible flow dynamics and compressible acoustic waves is unlikely. A postulated mechanism for feedback is the dissipation of acoustic energy and conversion into vorticity at solid boundaries, as observed by Bechert et al. (1977) in a study of jet noise pipe transmission. Experiments performed here could not support or refute the postulated mechanism. It is mentioned here to underline the importance of the hypothesis and hopefully to inspire further study.

7.4 Toward flow control

One of the main final goals of the research described here is the successful implementation of flow control in real devices. Flow control, as the term is used here, encompasses active, semi-active and passive control of the flow structure and dynamics. Active control uses a continuous time dependent input to modify the flow field in some desired manner. Semi-active control uses an operating condition dependent input to help optimize the flow field for each operating condition. Passive control uses an overall permanent change to the flow configuration to improve a particular aspect of the observed flow field.

Based on the experimental results presented here, passive and semi-active control appear most promising for universal application in real devices. Active control is less likely to be successful. To affect the incompressible flow dynamics, the control input must have a magnitude at least comparable with the background fluctuations. The experimental results show that even in the nozzle, prior to the sudden expansion, the turbulent fluctuations have significant magnitude. Beyond providing an input of sufficient magnitude there are further complications arising from the large control input required. One of the reasons free shear layer flows are attractive for active control is exponential amplification of small control inputs. With a significant amplitude control input, non-linear effects will limit the exponential amplification further reducing the control authority over the flow field.

Based on the experimental and analytical results presented, semi-active and passive flow control hold greater promise for success. A wide range of flow characteristics is observed for very small changes in the amount of swirl. Between S = 0.2 and S = 0.35 swirl goes from providing rapid wake recovery in the center of the flow to enhancing the center wake and causing significant coherent oscillations. At the center of the range, an optimal point is reached in terms of the speed of flow development. For this condition, wake recovery is slowed somewhat but the associated radial outward deflection of the incoming jet allows more rapid redevelopment in the outer part of the flow field. Wake recovery, although slower matches the speed of development of the outer flow field thus representing an optimal condition in terms of the mixing and dissipation of mean momentum. For combustion stabilization, rapid mixing is essential. However, the flow field measured at S = 0.29 did not exhibit recirculation, which would enable hot combustion radicals to initialize combustion in the incoming reactant stream. Some further increase in swirl may thus be necessary for increased combustion stability. Recirculation may however be caused simply by the addition of heat release to the flow field as observed by Gouldin et al. (1985).

The main point here is that mixing is not a monotonic function of swirl based on the experimental results presented. Rather, there is an optimal point where flow divergence from the axial direction and swirl induced turbulence production balance each other to produce the rapid flow development observed in the experiments. The tradeoff is thus between the radial pressure distribution, responsible for the flow divergence and wake profile at the center of the flow and the turbulence production. Under the assumption of a constant vortex core size (neglecting mean radial velocities), turbulence production is a linear function of the maximum in swirl velocity, whereas the radial pressure gradient is a quadratic function of the maximum in swirl velocity. As swirl is increased from zero, turbulence production dominates the effect of swirl. Eventually however, a point is reached where the effects of the radial pressure distribution become equally important. This is the optimal point for the most rapid flow development. Further increases in swirl lead to a domination of radial pressure distribution effects over the effects of turbulence production.

The radial pressure distribution caused by the presence of swirl also has an important influence on the post combustion flow field. Any residual swirl will organize the flow field with the lowest density in the center of the flow, thus automatically providing for an increase in the pattern factor. The design of the primary combustor flow must thus be careful not to incorporate any excess swirl, not only because increased swirl may represent a suboptimal mixing condition but also because residual swirl can significantly effect the pattern factor at the turbine inlet.

Passive control in the form of design changes or semi-active control in the form of operating condition dependent flow budgeting can move the flow closer to optimal conditions. Because swirling flows are so sensitive, relatively small changes in design or in a control flow can move the flow field significantly closer to optimal conditions.

Also of importance to flow control is one of the most significant influences of swirl on the dynamics of a flow field and must be underlined here because of the importance to the mixing capabilities of the flow field. Any addition of swirl causes an increase in the integral time scales. This increase in integral time scales shows that the scales of the largest turbulent structures increase with the addition of swirl providing better global mixing in the flow field.

Finally, it is important to address the expected flow behavior at higher Reynolds numbers. The experiments presented in this dissertation showed very little influence of a doubling of the Reynolds number. However, to reach real device Reynolds numbers, the Reynolds number would have to be increased by almost an order of magnitude beyond the highest Reynolds number studied here. The most important effect of such an increase in Reynolds number can be expected to be a much greater separation of the energy containing scales from the dissipative turbulence scales. For the Reynolds numbers studied here, there is significant overlap in these scales. With the separation of these scales, the energy transfer processes are moved to higher frequencies (inertial subrange), and the turbulence production picture may become clearer. Because the dissipative range of scales moves up in frequency, there is less overlap between the dissipative frequencies and the broadband shear layer amplified frequencies. Lower overlap may allow greater amplification and generation of turbulence before the nonlinear dissipative effects become important. Furthermore, mixing will benefit from an even wider range of frequencies covered in the energy cascade. The wider range of frequencies, extended to higher frequencies from lower Reynolds numbers, will provide improved small scale mixing along with the same excellent large scale mixing. The discussion of the influence of higher Reynolds numbers thus shows that the opportunities for flow control increase with Reynolds number.

7.5 Conclusions

7.5.1 Experimental findings

The experiments conducted in the two different experimental geometries led to an overall understanding of the development of swirling flows. At the heart of the understanding is the tradeoff between effects due to the radial pressure distribution induced by swirl and the turbulence generation induced by swirl. The local radial pressure gradient is a quadratic function of the local swirl velocity whereas the turbulence generation is proportional to the gradient in swirl velocity. Rapid consumption of azimuthal momentum by turbulence generation can lead to a significant adverse pressure gradient on the flow axis, promoting a wake type flow field. The magnitude of the adverse pressure gradient increases with increasing inlet swirl.

As swirl is increased from zero the effects of turbulence generation by swirl dominate, leading to for example rapid redevelopment of bluff body wakes. Further increases in swirl begin to make the radial pressure distribution significant. The associated wake enhancement causes the flow to be deflected radially outward slightly. At the point of balance, interesting global dynamics are observed as the flow field is torn between a radial pressure gradient dominated flow field and a turbulence generation dominated flow field. Further increases in swirl are accompanied by the appearance of a significant central recirculation zone for the annular geometry and a loss of vortex stability in the nozzle for the free vortex geometry.

Experiments in the annular geometry showed the presence of significant coherent oscillations in the higher swirl regime. The oscillations were observed to coincide approximately with the first measurement of significant recirculation at the first measurement location beyond the sudden expansion.

The power spectra extracted from the experimental measurements allowed significant insight into the dynamics of the flows, revealing for example the significant amplitude coherent oscillations found in the annulus geometry for high levels of swirl. The power spectra alone however are not always enough to obtain full understanding of the observed flow dynamics. Two additional very valuable tools are the inspection of histograms and time histories of velocity.

7.5.2 Value of linear stability analysis

The linear stability calculations reported in Chapter 6 showed both the limitations of the analysis as well as the significant insights that can be gained. Quantitatively, linear stability analysis fails to predict the frequency of absolute instability and the form of the eigenfunction of the absolute instability. Due to the large levels of background turbulence, linear stability analysis cannot be used to effectively predict spectral concentrations of turbulent energy. Turbulent linear stability analysis as introduced here is not able to capture the loss of stability of the vortex core in the free vortex geometry as swirl is increased. These limitations do not prevent the same analysis from also providing very useful insights into the dynamics of the observed flow field.

Linear stability analysis helps in the understanding of turbulence generation by illustrating the large amplification rates found in free shear layers for a wide range of frequencies and azimuthal modes. Linear stability analysis was able to explain why for zero swirl the spectral concentration of turbulent axial velocity fluctuations observed could not be identified in the swirl velocity oscillations. The swirl eigenfunction for the n=0 mode responsible for the spectral concentration of energy is identically zero across the radius.

Linear stability analysis helps in the identification of the origin of turbulence production through the examination of the calculated eigenfunctions. For the case of free vortex nozzle flow this analysis correctly identified the source of the produced turbulence as the inner shear layer of the flow field. Although intuitively already suspected, the analysis helps lay the foundation for these intuitive thoughts and their extension.

Similarly, linear stability analysis was able to explain the experimentally observed absolute instability as a resonance between two shear layer modes. Here, the analysis corrects intuition. Intuition would expect that the absolute instability be observed for negative azimuthal modes where the outer shear layer is most unstable. However, the inner wake shear layer is stabilized by the addition of swirl for negative azimuthal wavenumbers and the required interaction of two shear layer modes for absolute instability is not obtained. Although the outer shear layer growth rates are lower for the first positive azimuthal mode when swirl is added, the mode is not stabilized immediately. Meanwhile, linear stability analysis shows that swirl initially destabilizes the first positive azimuthal mode of the wake, thus making an amplified resonance possible. In summary, although intuition may have suspected the interaction of the inner and outer shear layer in the absolute instability, the azimuthal mode number of the instability is perhaps less expected.

Additionally, linear stability analysis shows that simultaneously unstable shear layer modes are not enough for absolute instability. A certain overlap in the scale and frequency of the instability is also required. This finding again supports intuition.

The experimental study provided an excellent platform for the evaluation of the value of linear stability analysis in the understanding of turbulent swirling flows and their design. The experience with the analysis shows that some important information can be extracted from it although the analysis cannot stand by itself. In value it is comparable to the value of the eddy viscosity model in the modeling of turbulent flows. Although some important physics are captured by the model, and significant insights can be gained from it, predictions by the model are not reliable enough to stand alone.

7.6 Recommendations

7.6.1 Experimental Setup and Methods

Some modifications to the experiment were suggested in Section 2.10 of Chapter 2. Beyond these near term suggestions the main thrust of experimental design should be oriented in expanding the available range of flow rates so that higher Reynolds number flows can be studied. With this in mind improvements in the LDV system should also be planned as described in Section A.8 of Appendix A.

An important addition to the experimental capabilities in the facility would be the ability to perform flow visualization studies. Flow visualization would lead to interesting insights into the wide variety of dynamic and steady phenomena discussed in this dissertation. With regard to flow visualization, seeding becomes critical. Seeding the outer shear layer near the exit is relatively straightforward. The center-body could be used to seed the inner shear layer but design of the seed path becomes non-trivial.

LDV measurements near the centerline ($\pm 3mm$) are difficult to interpret because the mean circumferential velocity component and the mean radial velocity component vanish at the centerline. Velocity oscillations in these directions however still exist and it is not possible to distinguish among them. As the error in the centerline location of the flow decreases, so does the error in the interpretation of the velocities. Every effort should thus be made to accurately locate the centerline of the flow field accurately.

7.6.2 Further Experiments

There is always a desire for more experimental information. The experiments conducted here covered two geometries in relatively good detail. Now that an overall picture of the types of flows encountered is established, the understanding of these flows can be further refined by targeted experiments. These experiments are listed here:

1. Determination of flow characteristics for marginally absolutely unstable flow in annulus geometry
2. Variation of maximum swirl number before breakdown with Reynolds number in free vortex geometry
3. Identification of flow dynamics when breakdown has moved up into nozzle

A matter of some importance deserving further attention is the coupling between acoustics and incompressible flow dynamics. Simultaneous velocity and pressure measurements can shed light on whether any measured acoustic energy loss is found converted into vorticity in the velocity measurements. These experiments are single frequency pressure excitation experiments and will also allow some conclusions to be drawn about the interaction of the acoustic wave with the sudden expansion.

Finally, to determine in greater detail the absolute stability characteristics and to move in the direction of flow control, a method for azimuthal actuation in the experiment should be developed. Azimuthal actuation will allow the absolute instability to be phase locked and investigated in detail. Such actuation can then also be used to attempt active control for convectively unstable flows, although the reservations about the success of such a study were described above.

An interesting avenue for future experiments, especially with an eye towards flow control, is given by the introduction of geometrical asymmetries in the flow field. The effect of the asymmetry on the dynamics may provide a path to passive flow control methods in these types of flows.

7.6.3 Analytical work

The linear stability analysis work presented here is somewhat incomplete in terms of the possible parameter variations that could have been performed. The value of these parameter variations is however unclear, and they may only serve to dilute the knowledge gained from the analysis as presented.

Perhaps a more interesting continuation of the analytical work can be found in an extensive study of the properties of the operator governing the disturbances. Specifically, pseudo-spectral analysis holds significant promise in explaining how apparently convective stable swirling flows (e.g. nozzle flow) are such efficient producers of turbulent energy at the flow center. Such an analysis may clarify the mechanism by which the swirl induced shear produces the turbulence.

Important information may also be obtained from a Ginzburg Landau type equation analysis accounting for the spatial distribution of absolute stability characteristics. Such an analysis may still not lead to a more exact prediction of the instability frequency but may elucidate the requirements for the existence of coherent absolute instability oscillations further. Along the same lines, the extension of the analysis to include the effects of variable density can point to the importance of the instability mechanism identified here in real combustor flows, downstream of the flame.