Chapter 2

Experimental Setup

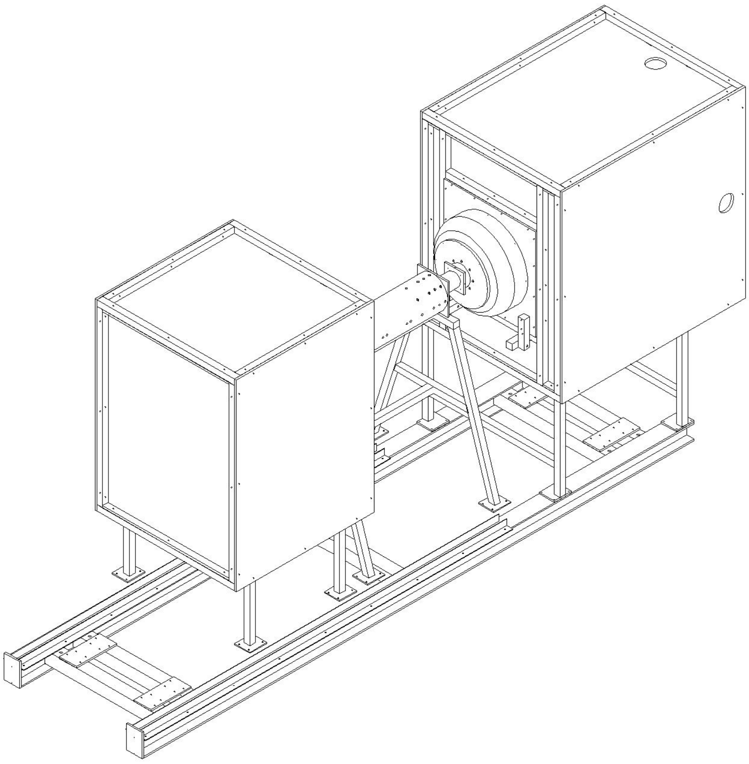

Figure 2.1: CAD Isometric view of experimental facility

2.1 Overview

The experimental setup was designed for a rig flow capacity of 300 SCFM running at atmospheric conditions. The experimental setup will be discussed in nine parts: inlet piping (2.2), inlet settling chamber (2.3), flow seeder (2.4), swirler (2.5), test section (2.6), filter chamber (2.7), acoustic excitation (2.8), undercarriage (2.9) and possible improvements (2.10). The order of the description follows the flow path of the air through the experiment except the last three sections which describe the setup for acoustic excitation, the undercarriage of the experimental facility and possible future improvements to the facility respectively. A CAD isometric view of the experimental facility is given in Figure 2.1 and a labeled photograph of the experimental facility is shown in Figure 2.2.

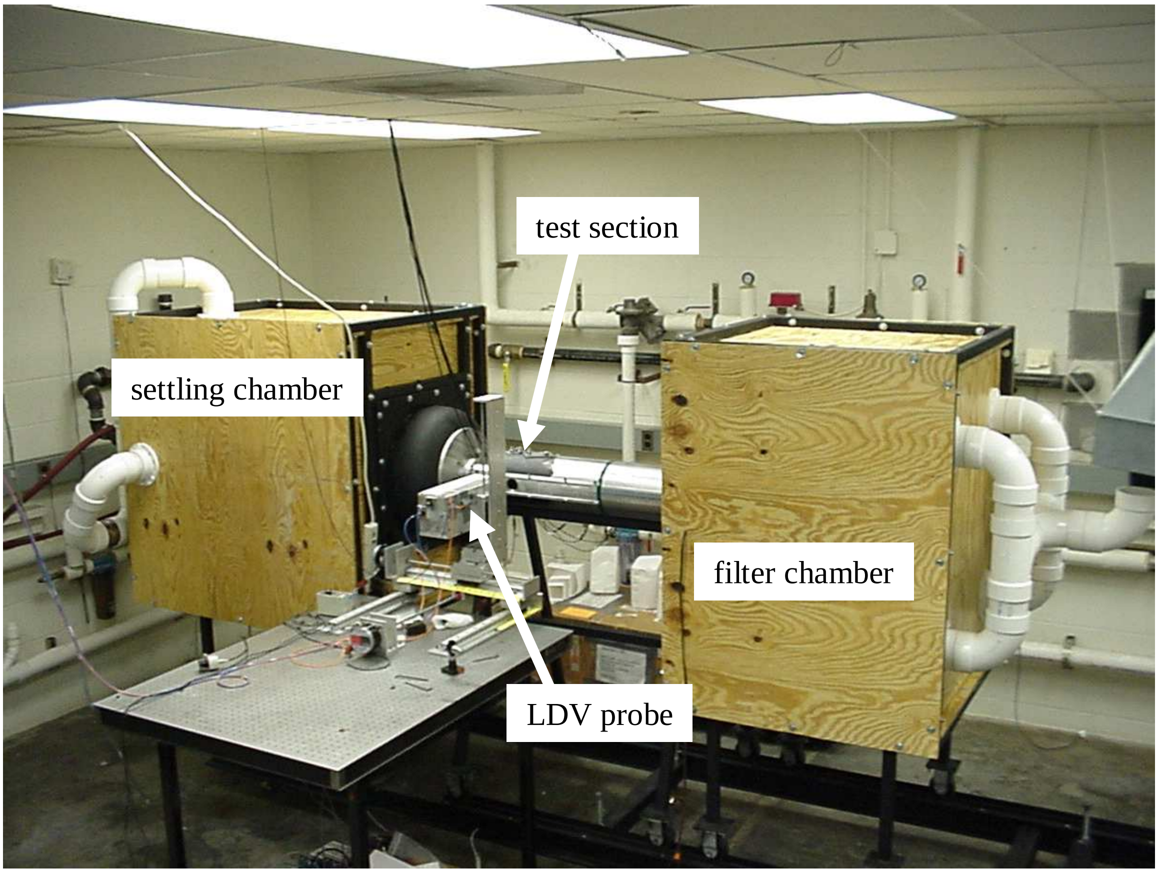

Figure 2.2: Photograph of experimental facility

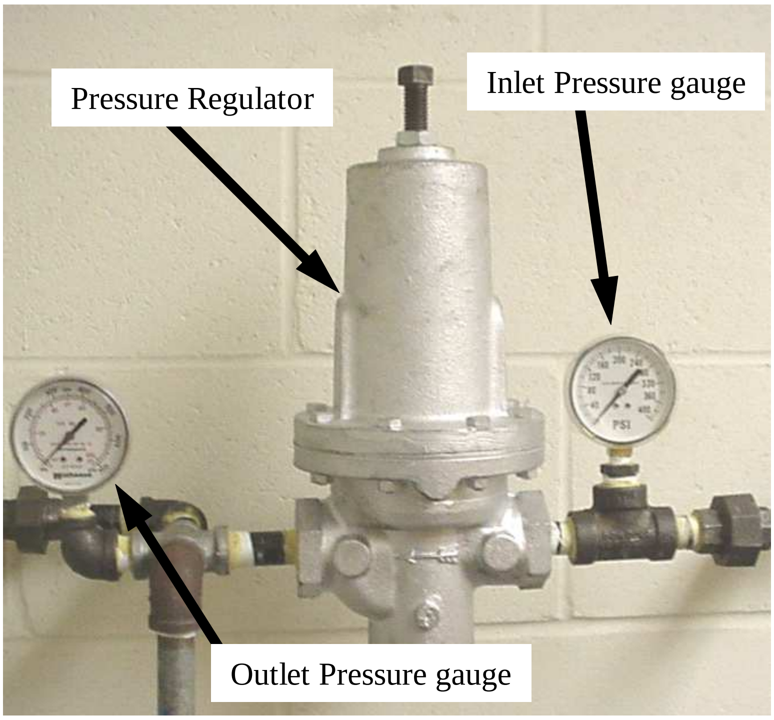

Figure 2.3: Inlet air pressure regulator

2.2 Inlet piping

The air supply for the present experiment consisted of a large capacity high pressure blow–down tank. The tank was filled using a compressor to the desired starting tank pressure (up to 310 psi). The air contained in the tank was then used to supply the experiment. The air flow pressure is reduced using a Kaye & MacDonald ZG 093 pressure regulator. The regulator and gauges are shown in Figure 2.3. The regulator is rated for up to 400 psi inlet pressure. The exit pressure is rated to vary between 70 and 200 psi but experiments were conducted at outlet pressures around 30 psi, although performance of the regulator did suffer under these conditions.

After the pressure was reduced to 26-35 psi depending on the desired experimental condition, the flow passes through two needle valve controlled pipe branches that allow for the regulation of the flow rate. One branch is equipped with a three and a

Figure 2.4: Flow rate regulating valves

half turn 1 inch needle valve that has a flow coefficient of 3.50. The other branch is equipped with a seven turn half inch needle valve that has a flow coefficient of 1.20. The valves are shown in Figure 2.4.

Downstream of the needle valves, the flow is expanded to one and a half inch pipe. An Eldridge Products, Inc. NH 8600 mass flow meter is mounted inline with the one and a half inch pipe. The flow meter contains two coarse flow conditioning grids at its inlet to provide a repeatable flow profile at the measurement location. Two finer screens (30 mesh - mesh number corresponds to number of wires per inch) were added upstream of the flow meter in order to keep debris from impacting the measurement accuracy of the flow meter. The flow meter requires an external power supply for proper operation. The power supply is mounted directly to the circuit board cover as shown in Figure 2.5. The AC 110V supply cable for the power supply contains an ON/OFF switch to control power to the flow meter. The flow meter is factory calibrated to deliver a linear 0-5 V output over a flow range from 0 to 300 SCFM. The accuracy of the flow meter is +/-1% F.S. with repeatability better than 0.05% F.S.

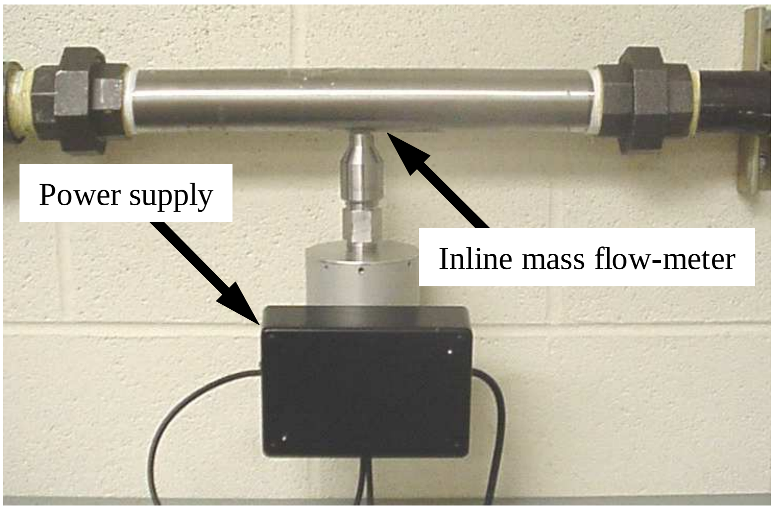

Figure 2.5: Mass flow meter and power supply

Beyond the flow meter, the pipe briefly expands to two inches, before entering the flow noise muffler. The muffler consists of a series of pipe contractions and expansions and an ultra low frequency Helmholtz resonator. The flow noise muffler is shown in Figure 2.6. Finally, the pipe expands to two inch size once more. The pipe section contains more flow quieting elements. The pipe was filled with rocks, stainless steel wool and a short section of honeycomb containing approximately 1/16” passages.

The two inch pipe is expanded to four inches and connected to the settling chamber PVC inlet piping. The PVC inlet piping is shown in Figure 2.7. The flow is separated into four parts using three tees and then brought around to four radial inlets to the settling chamber.

2.3 Inlet settling chamber

The settling chamber has four radial inlets which are supplied by the four inch PVC inlet piping shown in Figure 2.7. The settling chamber is shown in Figure 2.8. The chamber is four feet long, three feet wide and four feet tall. The frame of the chamber was constructed from one and a half inch square steel structural tubing.

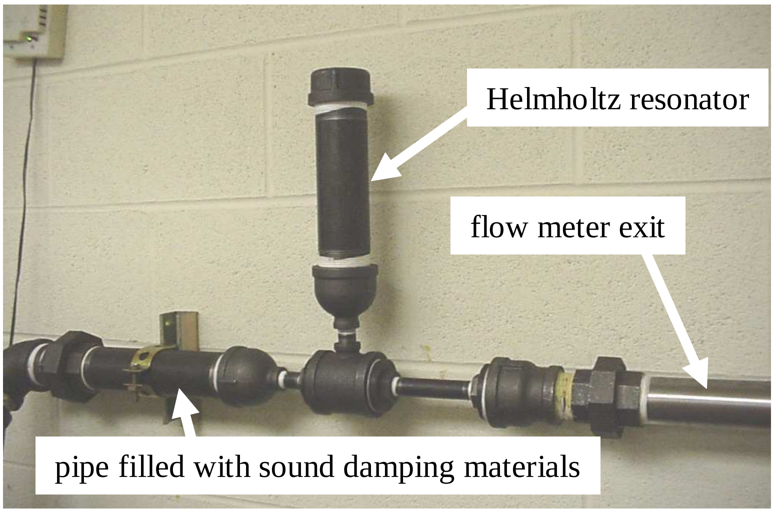

Figure 2.6: Inlet flow noise muffler

The walls are made from plywood, stained and sanded on both inside and outside to withstand exposure to oil (from the seeder). Three stainless steel (ss) 30 mesh screens slide into slots cut into the wood. The screen frames are made from 1/2 x 1/4 inch aluminum bar. The seeder outlet is mounted immediately following the second screen, underneath the settling chamber using a pipe flange. Further details on the seeder design can be found in Section 2.4. The swirler mounts to the front of the settling chamber via structural steel tubing. Further details on the design of the swirler body will be discussed in Section 2.5. All joints and cracks in the settling chamber were sealed using silicone caulk.

2.4 Flow seeder

The flow seeder was designed for use with olive oil and uses a high velocity air jet to atomize the oil. A schematic of the seeder is shown in Figure 2.9. The seeder can contain up to five olive oil atomizers. For the experiments discussed here, a maximum of two atomizers were used. Valves have been set up that can vary the number of atomizers used between one and four. The fifth atomizer has been

Figure 2.7: PVC pipe settling chamber inlet

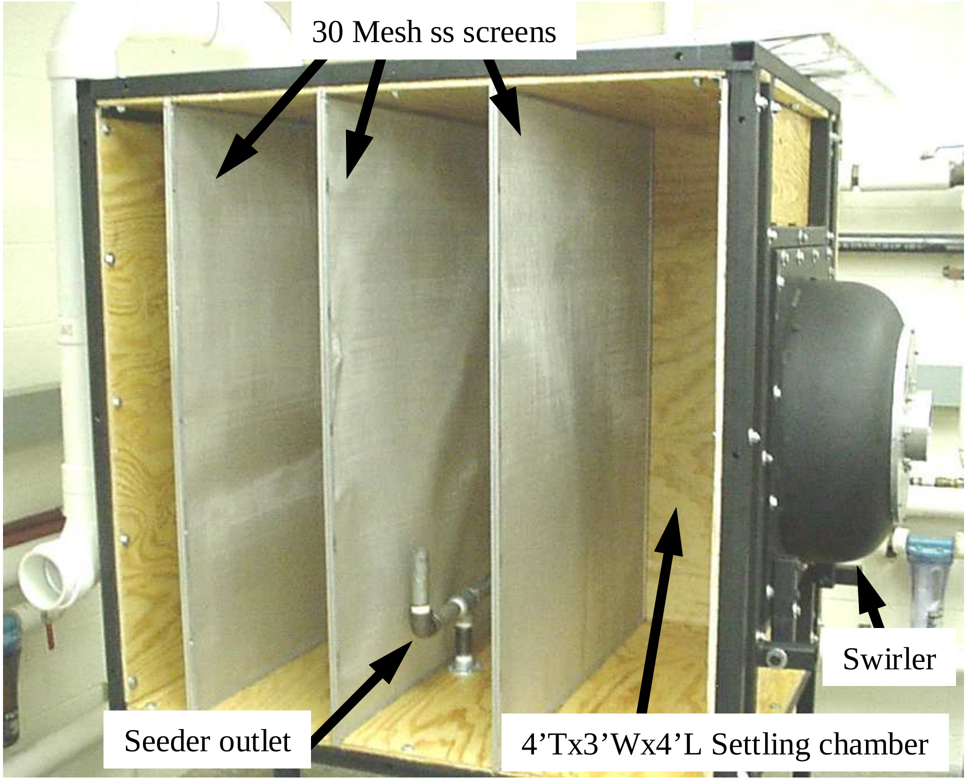

Figure 2.8: Settling chamber

removed because it was not needed. A picture of an atomizer is shown in the inset of Figure 2.10. Each atomizer consists of a capped aluminum tube. Four radial holes (0.02” diameter) are drilled into the aluminum tube spaced at 90 degrees. A disk is mounted just below these four holes. The disk itself also contains four small holes of the same size. The holes are oriented at 90 degrees to the radial holes, parallel to the aluminum tube. The air jet exits radially over the disk’s holes and due to the jet’s locally lower pressure draws oil through the disk’s holes and atomizes the oil into fine droplets. This mechanism of atomization functions even if the atomizers themselves are submerged in olive oil. Larger droplets are prevented from exiting the cavity by the droplet separator plate which only leaves a very small annular area for the olive oil mist to escape. The thickness of annulus is approximately 0.032 inches. Additionally, the one inch pipe exit of the seeder is threaded close to the top surface of the separator plate providing an additional large droplet filter. The design closely follows that recommended by TSI Inc., manufacturer of complete LDV systems for LDV operation. A photograph of the seeder is shown in Figure 2.10.

2.5 Swirler

The swirler is bolted to the end of the settling chamber. A photograph of the front of the swirler is shown in Figure 2.11. The swirler is shown uncovered in Figure 2.12. In addition to the bolts, the swirler is also connected to the settling chamber via a rotating joint (shown in Figure 2.13), that allows the swirler, when unbolted to be tilted away from the settling chamber without removing the swirler all together. The swirler is shown rotated away from the settling chamber in Figure 2.14.

Some relatively coarse filter material (relative to the HEPA filter in the filter chamber) is added to the annular swirler inlet to help distribute the flow evenly in the annulus. The covered inlet can be seen in Figure 2.14 and is also shown in Figure 2.15.

The swirler body is made from two large carbon steel pipe caps. An exploded view of the swirler body is shown in Figure 2.17. The outer shell of the swirler is

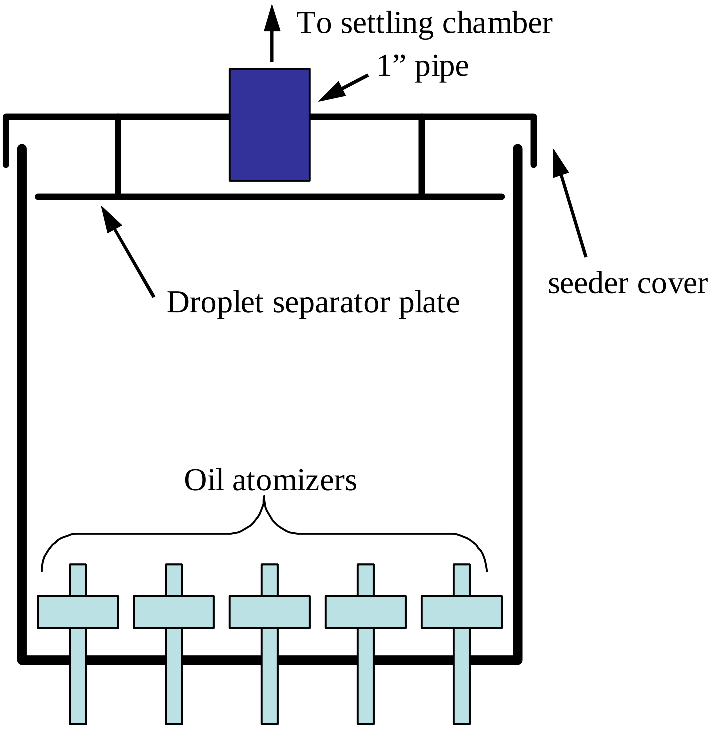

Figure 2.9: Seeder schematic

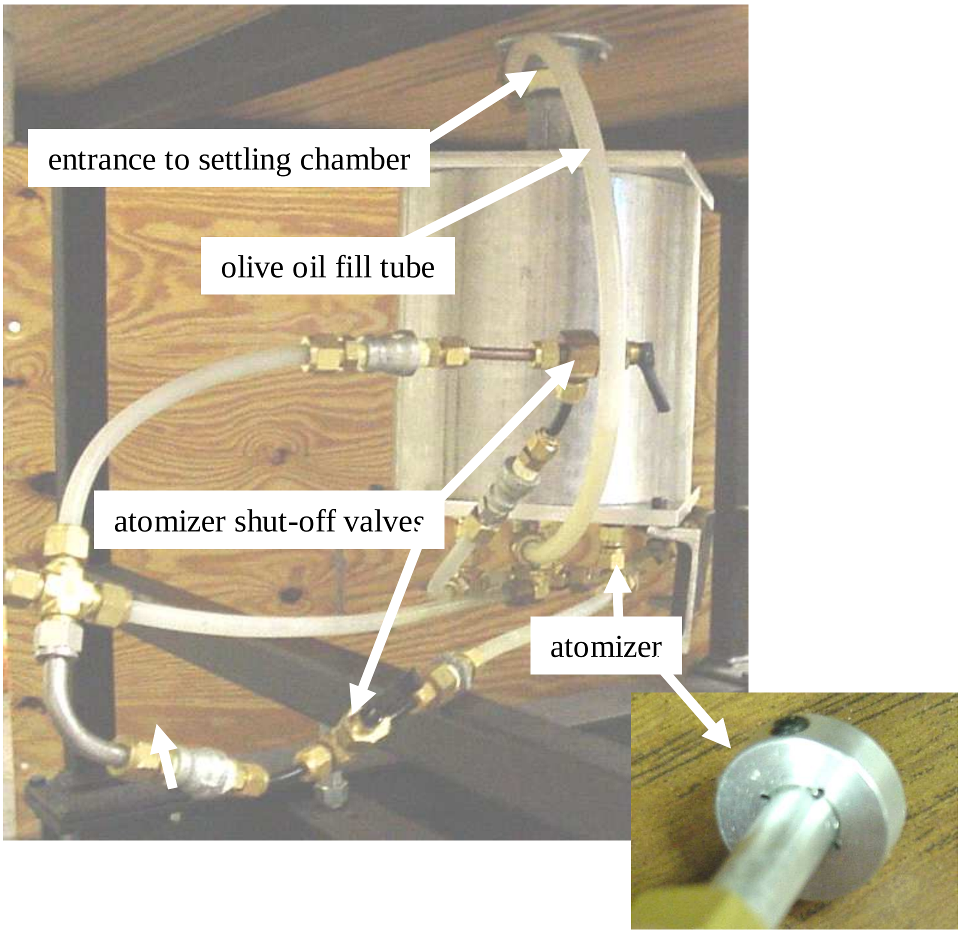

Figure 2.10: Seeder photograph

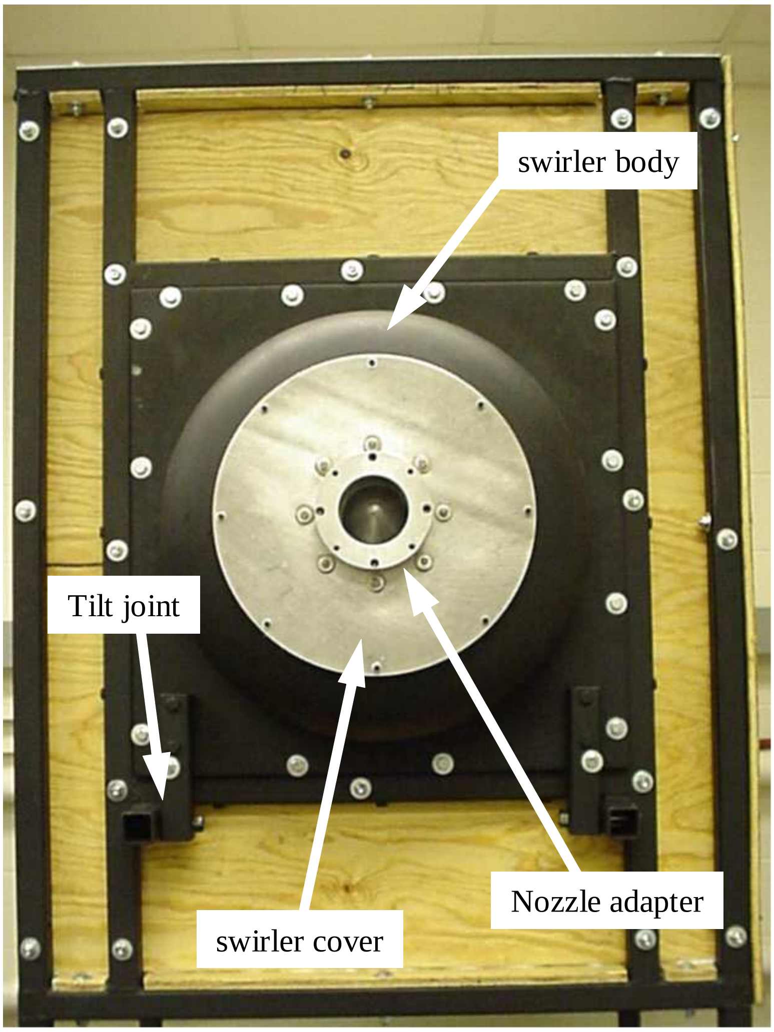

Figure 2.11: Front of swirler

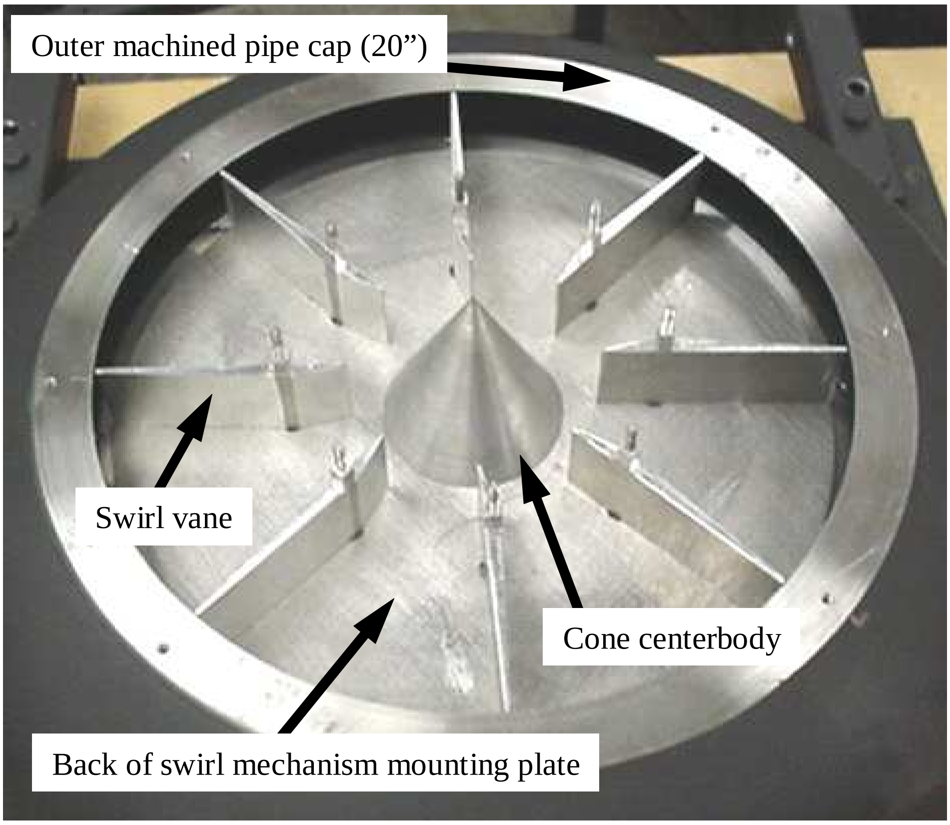

Figure 2.12: Swirler uncovered

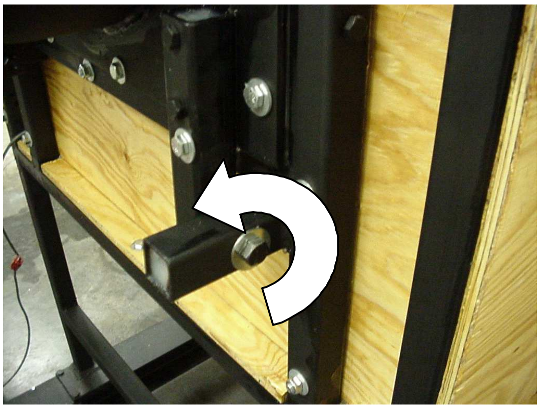

Figure 2.13: Rotating joint for tilt-away maintenance of swirler

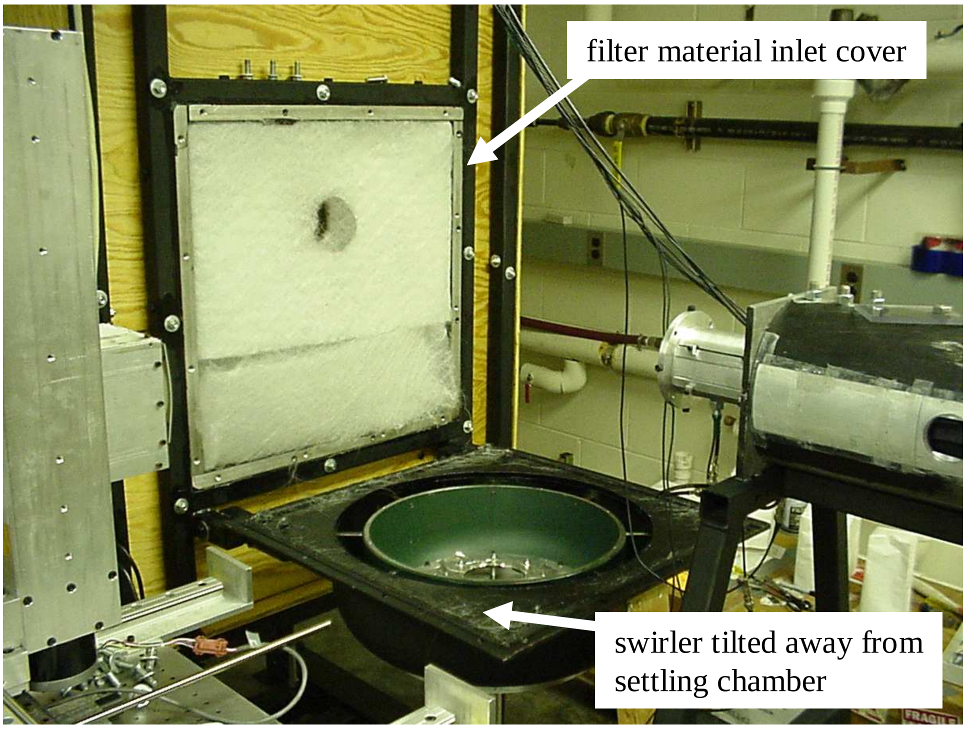

Figure 2.14: Swirler tilted away from settling chamber

Figure 2.15: Filter material added to swirler inlet

Figure 2.16: Swirler entrance annulus

made from a 20” pipe cap and the inner shell is made from a 16” pipe cap. The pipe caps were used because they offer a smooth curvature, evenly turning the flow toward the pipe center. The two pipe caps form an annular inlet (shown in Figure 2.16). Accurate machining of the pipe caps proved difficult but there were no cost effective alternatives. Ideas for possible improvements to the experimental setup and design are given below in Section 2.10.

The two pipe caps are connected using four bolts and approximately two inch long half inch cylinders. Both the inner and outer pipe cap were machined to hold the swirl vane mechanism. The swirler pipe adapter is an aluminum plate that connects the swirler mechanism mounting plate to the inner swirler shell. The swirler mechanism mounting plate is not directly connected to the inner swirler shell. The swirler cover is bolted directly to the outer swirler shell. The swirl vanes are mounted between the swirler mechanism mount and the swirler cover. There is very little space between the vane and these two plates. Due to the lack of accuracy in the machining process of the pipe caps, a significant amount of interference exists between the vanes and the plates for negative angles of swirl. The direction of positive swirl is defined as the clockwise direction.

The swirler is designed so that all eight vanes can be moved together using one stepper motor as the driver. In order to accomplish this, each vane is connected to a fine tooth stainless steel gear (64 pitch-2” pitch diameter-128 teeth). Each of these

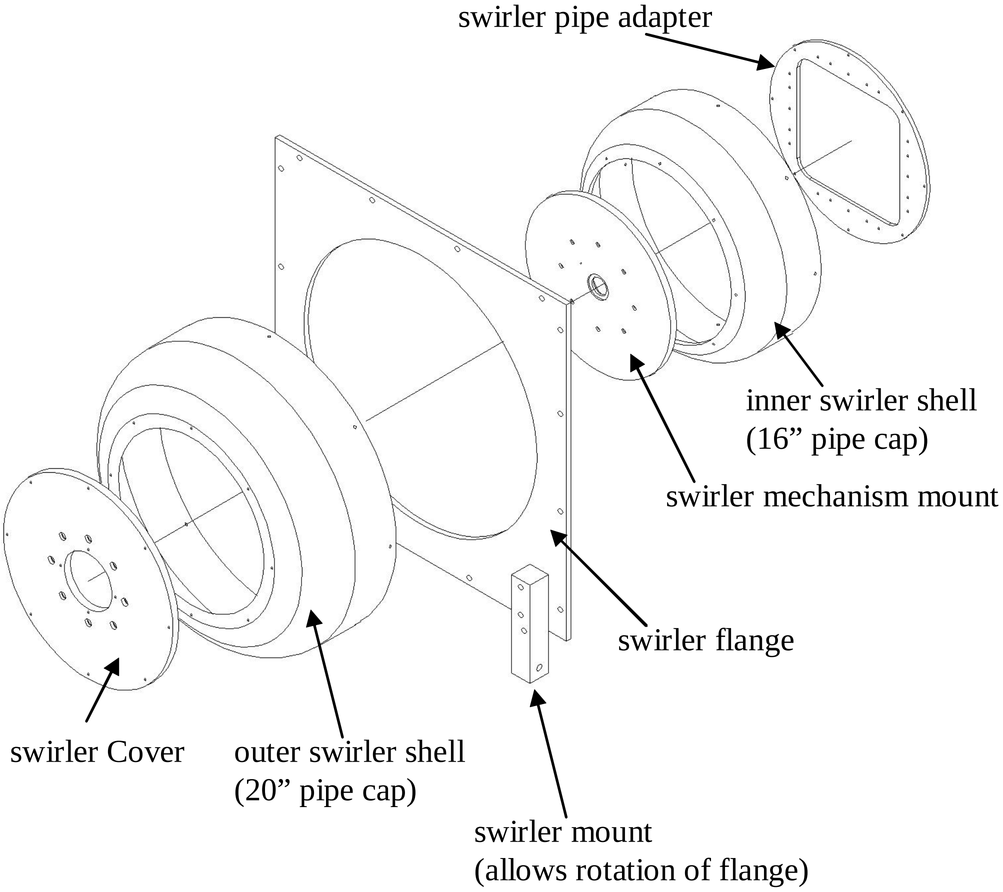

Figure 2.17: Exploded view of swirler body

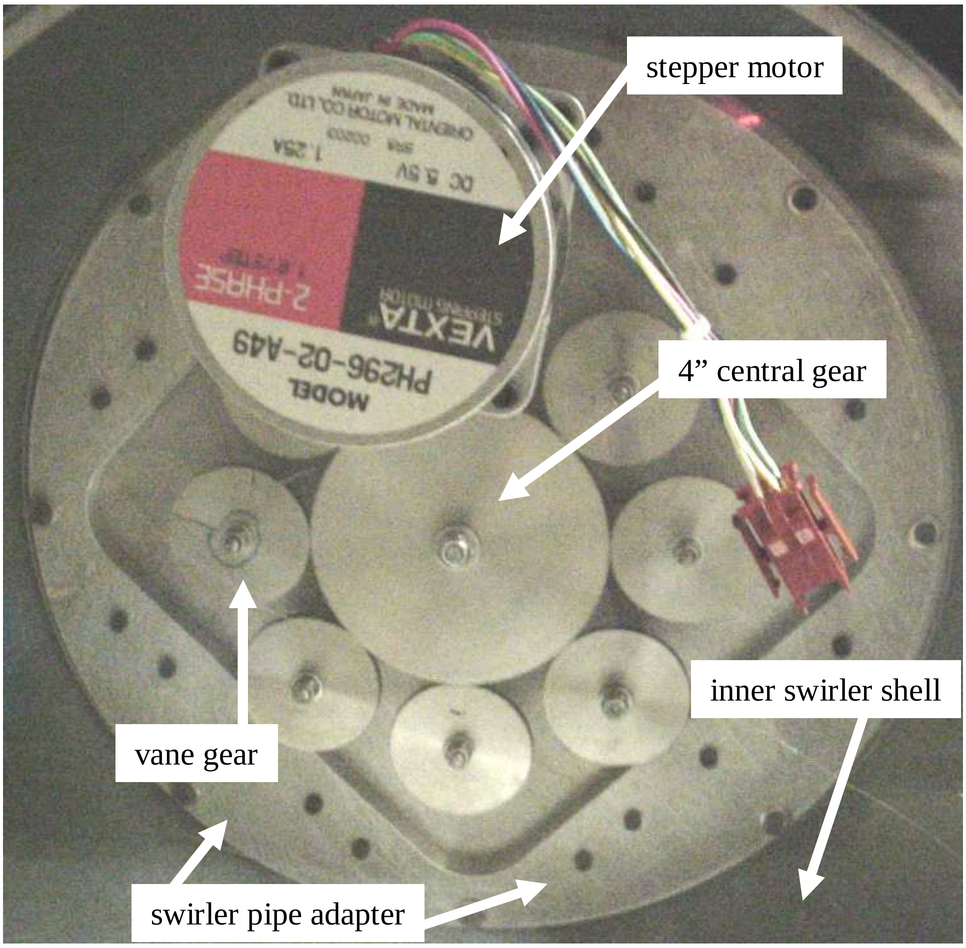

Figure 2.18: Swirler gears

eight gears is connected to the other using a large central gear of the same pitch with 4” pitch diameter. Additionally, one of the vane gears is driven by a small 1” pitch diameter gear that is connected to a stepper motor. The stepper motor thus moves each of the gears equally and at the same time by half the angle commanded through the stepper motor rotation. The backlash for the mechanism is calculated to be 0.2 degrees for a center displacement of 0.01”. Two photographs of the gear mechanism are shown in Figures 2.18 and 2.19.

In reality, due to how the gears are connected to the swirl vanes, the actual backlash is about 4.5 degrees. The mechanism connecting the gear to the vane is

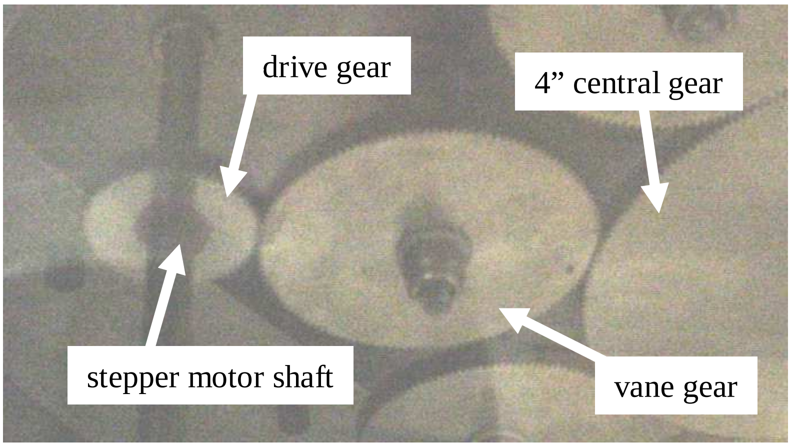

Figure 2.19: Swirler drive gear

shown in Figure 2.20. The vane (shown separately in Figure 2.21) has square ends that are tapped with 8-32 threads. A square keyway inside a sintered bronze bearing is located on the back side of the swirler mechanism mounting plate. The square end of the vane inserts into the square keyway. An adapter with square ends is inserted into the other end of the square keyway. The other end of the adapter is round with a machined flat. The gear fits this round end and a set screw prevents rotation of the gear independent of the vane. The mechanism is kept from coming apart by fastening a locknut and washer to the top of the gear, at the end of a length of threaded rod long enough to thread into the vane’s 8-32 threads.

The side of the vane not connected to the vane turning mechanism is connected to the swirler cover. The connection is made similarly. The square end of the vane is held in place by a short square keyway inserted into a sintered bronze bearing on the outside of the swirler cover. A piece of threaded rod is screwed into the swirl vane. The threaded rod, together with a washer and locknut, holds the square keyway inside the bearing.

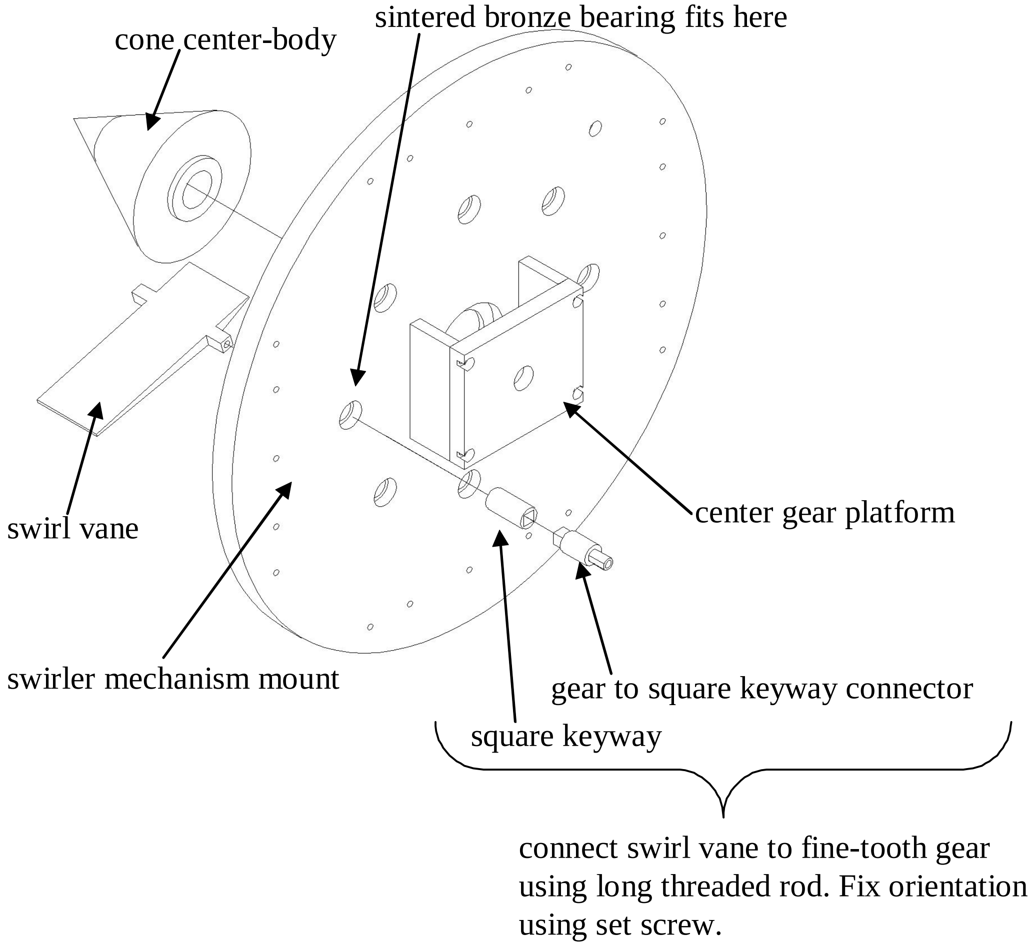

Figure 2.20: Exploded view of swirl vane connection

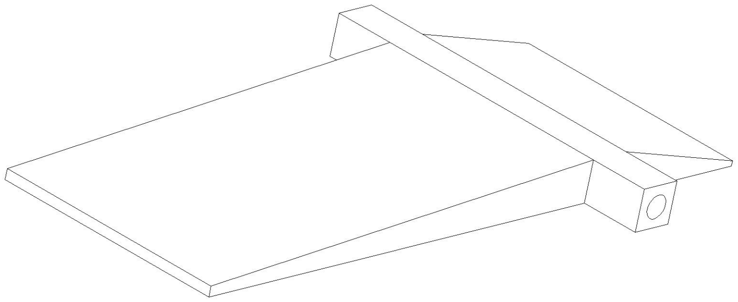

Figure 2.21: Swirl vane

2.6 Test section

The test section is shown in a photograph in Figure 2.22. An exploded view of the assembly is shown in Figure 2.23. The flow exits the swirler through the nozzle adapter. The nozzle adapter further contracts and accelerates the flow even after the flow has passed the cone center body from an inner diameter of 4" to inner diameter of 3". The continued flow acceleration prevents flow separation and helps dissipate some vane generated turbulence. The nozzle adapter leads the flow into the inlet nozzle which is the first part of the test section. The nozzle and nozzle adapter are connected using a machined flange.

The nozzle section is six inches long and is machined from three inch schedule 80 pipe (I.D. = 2.9", O.D. = 3.5"). The first 0.5" inches of the pipe were machined to smoothly match the exit diameter of the flow adapter to the pipe inner diameter. The nozzle contains a 5 inch long, one and three quarter inch tall window section which is used for optical experimental access. The nozzle also contains four acoustic pressure ports. The ports are machined in pairs, each acoustic port pair is spaced ninety degrees circumferentially. The two pairs are located two inches and four inches upstream of the entrance to the combustor.(The test section beyond the nozzle is called the combustor because the flow modeled is that in a combustor. The facility is however not designed for combustion experiments.)

In order to minimize flow disturbance a full-size window should not be installed. Small one inch pipe sections were machined to conform to the pipe curvature. One of the pipe sections was counter–bored to fit a 20 mm window. The small window was sufficient for LDV access 0.2 inches beyond the nozzle centerline. A small pipe window cover is shown in Figure 2.24. The section machined for optical access is shown in Figure 2.25. In addition to the free vortex flows able to be generated with the center–body in the form of a cone, the tip of the cone can be removed and then replaced by a one inch cylindrical rod that extends all the way through the nozzle section to the sudden expansion. The fully round nozzle passage is transformed into an annular passage simulating the type of geometry often encountered in real combustors. In lean premixed type combustors for example, the annular passage would contain an axial swirler with fuel injection immediately after the swirler. The cylindrical center–body would also serve to provide pilot fuel for primary zone combustion under off-peak load conditions.

Two flanges connect the nozzle to the combustor section. The small flange connects to the nozzle section radially and to the large flange axially (along the flow direction). The large flange is connected to the combustor section axially using holes threaded axially directly into the pipe that makes up the combustor section. The combustor section is made from 8 inch aluminum tubing with a 3/8 inch wall thickness. The area expansion from nozzle to combustor is thus $7.25^2/2.9^2 = 6.25$. The combustor section also contains a large number of acoustic ports distributed both axially and around the circumference.

A large window is also machined into the combustor section. Again however, pipe sections had to be machined to maintain the pipe curvature and avoid flow disturbance. One of the pipe sections was counter–bored for a 2 inch diameter window for LDV access. The window is large enough to give the LDV probe access to one inch beyond the tube centerline. The window is shown in Figure 2.25.

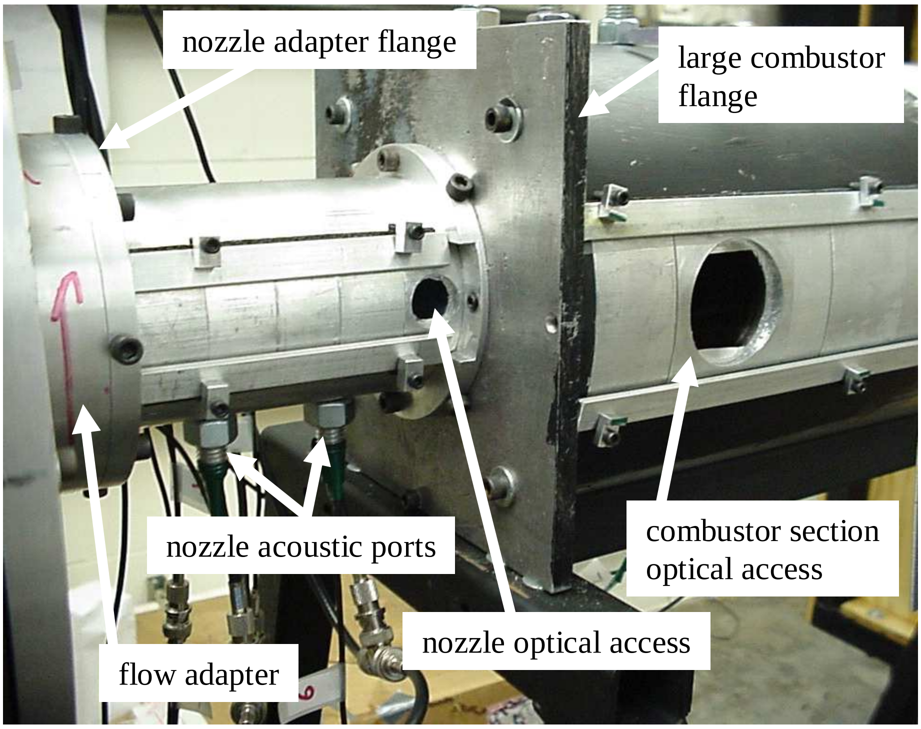

Figure 2.22: Photograph of test section

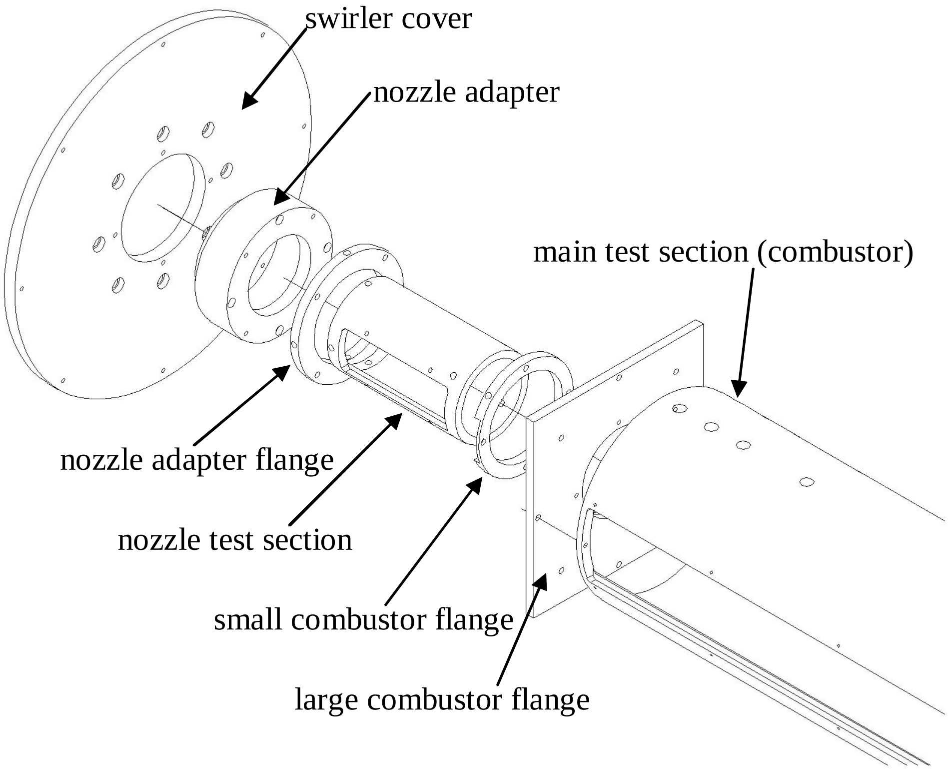

Figure 2.23: Exploded view of test section assembly

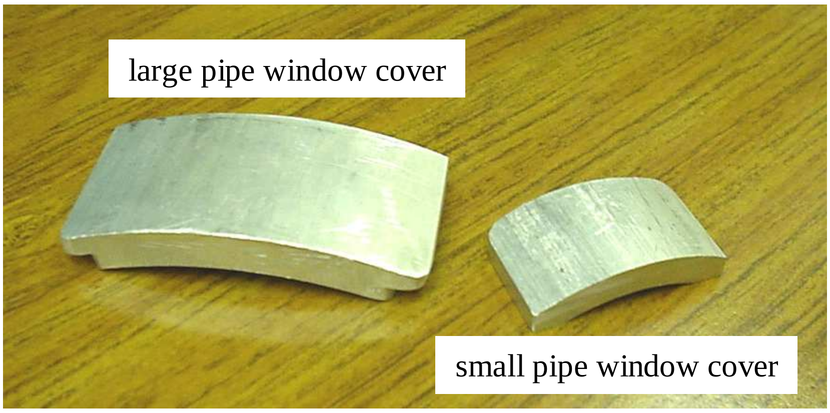

Figure 2.24: Pipe window covers

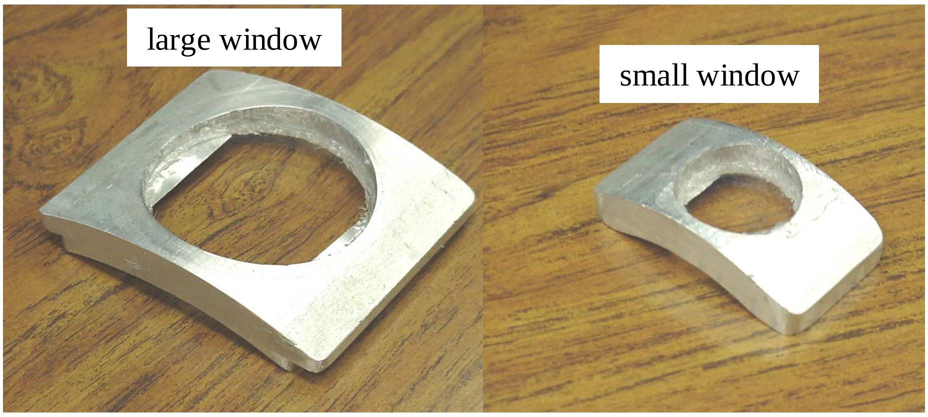

Figure 2.25: Optical access windows

2.7 Filter chamber

The large diameter combustor test section exhausts to the filter chamber. A photograph of the filter chamber is shown in Figure 2.26. The purpose of the filter chamber is to remove as much of the olive oil seed as possible before the air is handled by the ventilation system. Seed removal prevents the frequent clogging of the building ventilation filters. The filter chamber measures three feet tall, three feet wide and three feet long. The outer structure of the filter chamber is again constructed from 1.5 x 1.5 inch structural steel tubing. The walls are made of wood and similar to the settling chamber were stained and sanded for resistance to oil exposure. A speaker is mounted inside the filter chamber about seven inches beyond the flow entrance to the filter chamber. Details of the acoustic excitation strategy are given in Section 2.8. The combustor test section is connected to the filter chamber by a large machined flange. The filter chamber also contains a 30 mesh screen to help distribute the flow evenly over the cross section of the large HEPA quality filter. Finally, the air exhausts through four exit ports which are linked together using PVC pipe. The exit of the PVC pipe exhausts into a ventilation hood which allows the air to exhaust to the atmosphere.

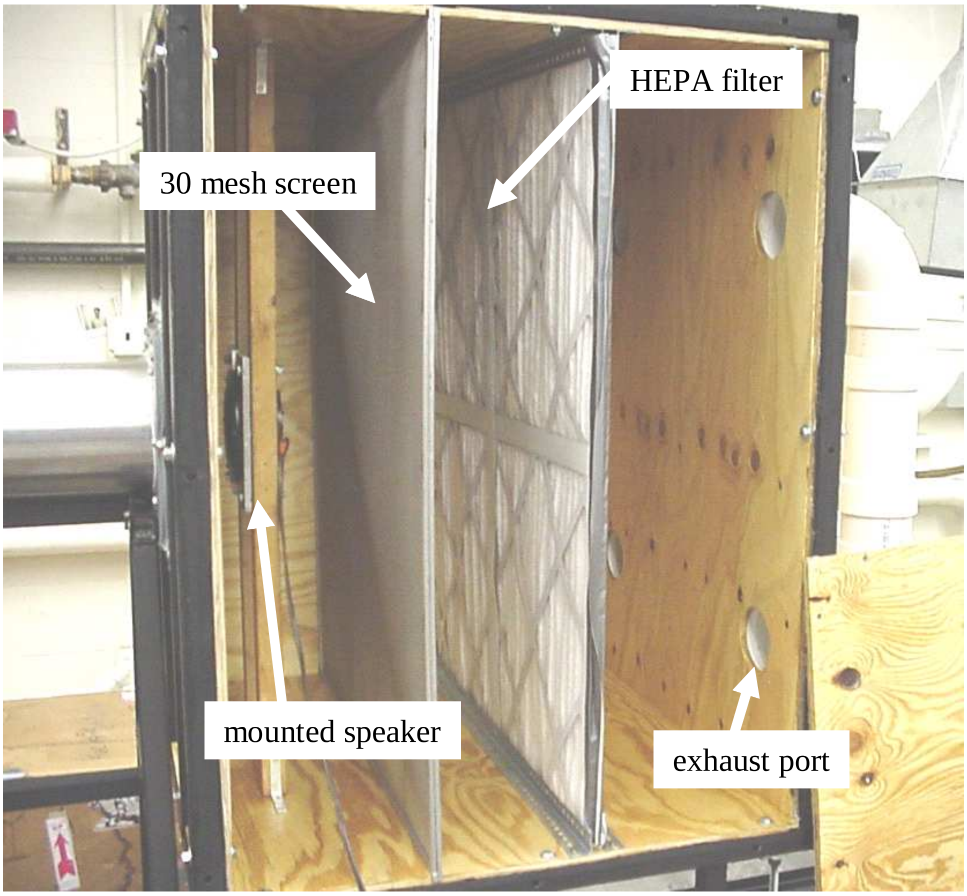

Figure 2.26: Filter chamber

2.8 Acoustic excitation

Acoustic excitation is used to attempt to lock flow instabilities to the excitation allowing for phase resolved measurements. Since upstream excitation was not feasible in the present experimental setup, the source was placed downstream at the exit of the test section. A ten inch low frequency 100 W_{rms} speaker was mounted inside the filter chamber aligned with the center of the test section. The speaker has a low cut-off frequency of 24.5 Hz. A photograph of the mounted speaker is shown in Figure 2.27. The speaker allowed significant velocity oscillations to be induced all along the test section, especially at low frequencies. At frequencies above about 150 Hz, the imparted velocity oscillations become a function of space due to fact that at these frequencies the acoustic wavelength becomes comparable to the length of the test section. In addition, it was found that although the speaker was placed downstream of the sudden expansion, significant velocity oscillations could be induced in the nozzle and immediately downstream of the nozzle. More detailed results can be found in Chapter 5.

2.9 Structural undercarriage

The entire experimental facility is mounted on two 4x4 I-beams. Only the settling chamber is rigidly mounted to the I-beam structure. Both the test section and the filter chamber are on wheels and allow the components of the facility to be separated. The undercarriage is shown in Figure 2.28. The I-beam structure can be raised and mounted on wheels itself, should transit of the facility become necessary.

2.10 Possibilities for improvement in design

After assembly and completion of experiments, it became apparent that certain changes to the original design and fabrication of the test facility could be beneficial. The major design modifications recommended are listed below:

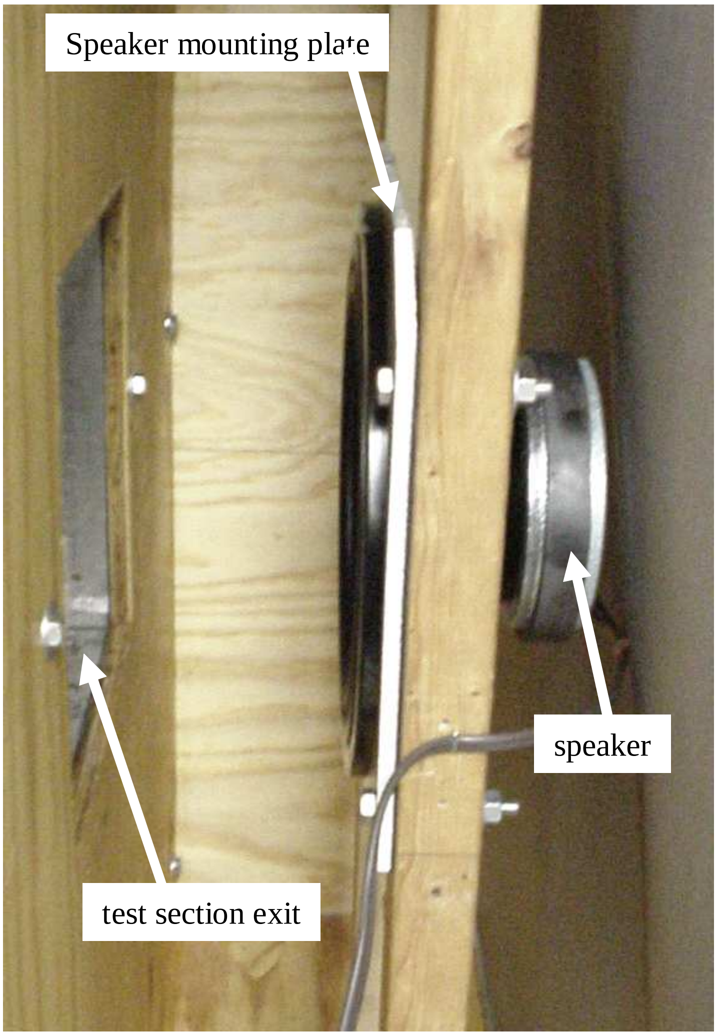

Figure 2.27: Mounted speaker

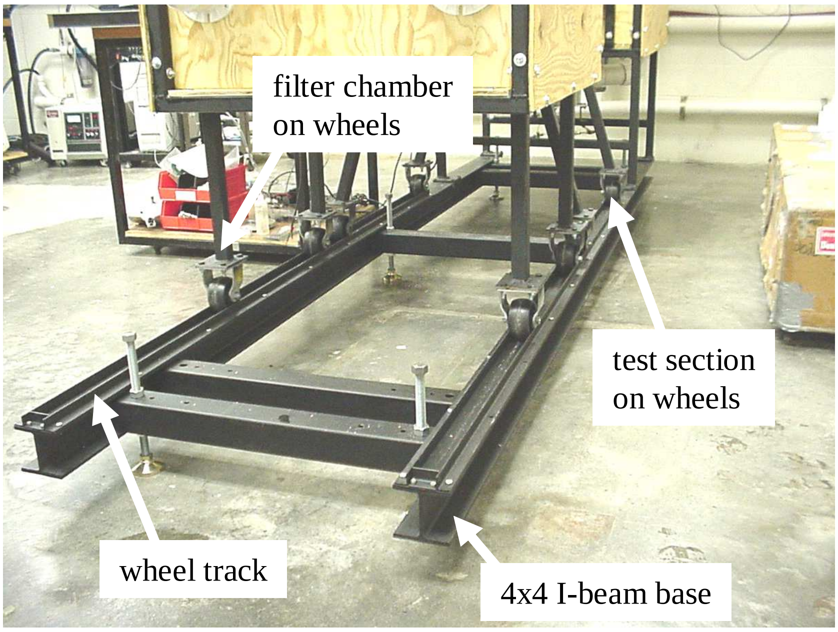

Figure 2.28: Undercarriage of experimental facility

- It is helpful to have visual access to the settling chamber swirler and filter chamber. Plexiglass windows should be installed in the chambers and the swirler cover should be machined out of Lexan (hard plexiglass).

- The large effort expended to obtain smooth turning of the flow into the swirl vanes can be avoided by simply having the flow enter the swirler radially inside the settling chamber. The swirl vane mechanism could be more accurately mounted and swirl vane interference would not be a problem.

- The vane turning mechanism can be improved by removing the square key way and replacing the adapter with one that has a rounded square female end. Additionally, a set screw should be used to prevent relative motion between the swirl vane and the adapter.

- A more precise connecting shaft should be used to hold the adapter, swirl vane and gear together. The slop between the threaded rod and the adapter hole is another source for backlash of the vane mechanism.

- The seeder should be redesigned for smaller capacity to allow better fine tuning of the required seed level in a given experiment.
- A second pressure regulator should be installed in the high pressure air line to minimize the number of adjustments needed for the valves and/or regulator settings.