Smoke-Wire Visualization of an Oscillating Flow in a Gas Spring

by

David James Szarko

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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Abstract

The smoke-wire method was used to visualize an oscillating air flow in a gas spring. A harmonic pressure gradient was produced inside of a cylindrical, plexiglas test section by a compressor piston. A stainless steel wire, stretched horizontally through the mid-section of the plexiglas cylinder, was coated with model train smoke fluid and pulsed with electric current to produce a timeline of smoke. An attempt was made to photograph the resulting smoke profiles at various piston positions using a still camera and a strobe for illumination.

It was determined that the smoke-wire technique was not the best method for introducing a photographable tracer into the oscillating air flow, even at very low piston speeds. This was due both to the turbulence of the flow and to the small volume of smoke produced by the wire. Observations of the smoke patterns formed by the flow were made for eight points in the piston cycle. The pattern of turbulent and laminar behavior occurring in the deceleration and acceleration phases of the cycle, respectively, were found to agree with expected results.

Thesis Supervisor: John H. Lienhard V
Title: Associate Professor

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I am very grateful to Professor John H. Lienhard V for overseeing this project and for his direction in ways of improving photographs of the smoke. I would like to thank the technical staff of the M.I.T. Cryogenic Engineering Lab—Bob Gertson for assistance with parts acquisition and advice on fabricational methods, and, especially, Mike Demaree for his invaluable guidance in electronics and assistance with troubleshooting the smoke-wire circuit. Thanks to graduate students Alex Tziranis, with whom I worked on initial design of the test section, smoke wire, and smoke-wire circuit, and Sankar Sunder for additional electronics advice. I also thank Professor Joseph L. Smith, Jr. for permitting me to conduct my work in the M.I.T. Cryogenic Engineering Lab. Final thanks go to my family and friends for their patience and encouragement throughout my stay at M.I.T. and to God for seeing me through.

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Chapter 1

Introduction

1.1 Overview

Knowledge of the behavior of an oscillating flow in a gas spring is important for applications such as power processes involving the compression of a gas. A better understanding of the fluid mechanics of such a flow is essential for optimizing the design and operation of internal combustion engines, Stirling engines, compressors, and other reciprocating machines. For example, the pistons and cylinders of an I.C.E. resemble a gas spring during the compression and expansion strokes when intake and exhaust valves are closed. A gas spring allows the piston in a free-piston Stirling engine to function without mechanical linkages [8, p. 22].

This project entailed the use of a smoke wire for visualizing an oscillating flow in a gas spring. With the timelines and streaklines produced by the smoke wire, qualitative and quantitative information about the velocity profile of the air flow can be collected. Emphasis was placed on the transition from laminar to turbulent flow and on identifying the parts of the cycle where these transitions occurred. A sinusoidally oscillating flow was produced inside of a cylindrical, plexiglas test section mounted vertically on the top of an air compressor. The flow, traced by the smoke, was observed and photographed at various piston positions.

The use of the smoke-wire method has been proposed for flow visualization for several reasons. First, it is one of the simplest methods for visualizing flows and has been successfully employed in turbulent flows (see Ref. [5]). Second, the smoke wire is suited for an enclosed system because smoke streaklines can be generated directly inside the test section with minimal disturbance to the flow under investigation. Moreover, smoke wires produce tiny amounts of smoke, which improves the problem of smoke accumulation within the test section.

1.2 Smoke-Wire Method of Flow Visualization

The smoke-wire method is an effective and commonly used technique for visualizing flow behavior. Although their performance is usually better in laminar flow, smoke wires can be used in turbulent as well as in laminar environments which makes this method a useful tool for studying complex flows. Unfortunately, the smoke-wire method is limited to applications involving low Reynolds numbers based on the wire diameter(<40) [5, p. 50].

The smoke-wire method is the simplest method of producing smoke and has the advantage of being able to generate smoke directly inside of a test section. In order to produce smoke, an electrical current is passed through a fine (on the order of 0.1 mm in diameter), oil-coated, metal wire. As the wire undergoes resistive heating, the oil is vaporized. [1] The oil typically forms into beads along the length of the wire from which thin filaments of smoke (streaklines) originate upon heating the wire. Various substances have been used for coating smoke wires. Machine oils, mineral oil, and commercially available "liquid smoke" for model trains are commonly used examples.

When a short pulse of current is sent through the wire, a line of smoke (timeline) is produced parallel to the wire and is moved along with the flow. Velocity profiles of flows can be visualized in this manner, and if the time period between the current pulse and the triggering of a camera is known, then the flow velocity can be calculated from the distance the smoke line has traveled in the photograph. For further information, Thomas Mueller has written an excellent overview of flow visualization using smoke

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[1] The "smoke," strictly speaking, is actually an aerosol, but will be referred to as smoke for simplicity.

[5].

1.3 Oscillating Flow in Pipe—Theoretical Concepts

Schlichting [9, p. 419] develops the case for an oscillating fluid in a circular pipe. We let x represent distance along the axis of the pipe and denote radial position with respect to this axis by r. By assuming that the pipe is very long, the flow can be said to be independent of x. The Navier-Stokes equation for the time rate of change of the axial component of velocity then becomes

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r}\right) \qquad (1.1)$$

where ρ is the fluid density, ν is the kinematic viscosity, and p is the pressure of the fluid.

Let a piston produce a harmonic pressure gradient of the form

$$\frac{\partial p}{\partial x} = -\rho K cos \omega t \qquad (1.2)$$

where ω is the angular frequency of the oscillation and K is a constant. Boundary conditions at the wall are $u = 0$ and $r = R$, and we assume that the solution has the same form as the pressure function. For the case when the dimensionless group $\sqrt{\frac{\omega}{\nu}}R$ is small (slow oscillations), Schlichting [9, p. 420] shows that the fluid velocity is given by

$$u(r,t) = \frac{K}{4\nu}(R^2 - r^2)cos(\omega t). \qquad (1.3)$$

From this equation, we see that the velocity of the fluid is in phase with the oscillating pressure induced by the piston.

The velocity distribution for an intermediate oscillation frequency ($\sqrt{\omega/\nu}R = 5$) is sketched in Figure 1-1 for various points of the pressure cycle, after Schlichting [9, p. 421]. When the pressure gradient reaches a maximum, the profiles show that the

Figure 1-1: Velocity distribution for an oscillating flow in a circular pipe when the pressure gradient assumes an intermediate frequency ($\sqrt{\omega/\nu}R = 5$), from [9, p. 421].

fluid assumes its maximum velocity at the layers near the wall. This phenomenon has been experimentally confirmed and is known as the "Richardson annular effect" after the investigator E. G. Richardson [9, p. 421]. Visualization of an oscillating flow by Yamada [10] contains examples of this effect.

Many studies on oscillating flows have focused on the laminar-turbulent transition, particularly the determination of a range of Reynolds numbers where this transition occurs. One such example is the work conducted by Merkli and Thomann [4] on the flow of air in a "resonance tube," which contains many similarities to this project. These investigators experimentally determined a critical Reynolds number of $Re^{\delta}_{crit} \approx 400$ with two different methods: hot-wire anemometry and flow visualization using cigarette smoke. Merkli and Thomann and Akhavan, Kamm, and Shapiro [1], describe the forms of turbulence possible for oscillating flow conditions: (1) turbulent bursts which violently appear during phases of deceleration followed by a reversion to laminar flow during acceleration; and (2) turbulent flow throughout the entire oscillatory cycle.

The latter has never been observed in any investigations as of yet.

Chapter 2

Experimental Apparatus

The experimental apparatus, depicted in Figure 2-1, consisted of a cylindrical plexiglas test section which was vertically mounted on the top of an air compressor, from which the cylinder head had been removed. The test section was approximately two feet high with an inner diameter close to two inches. A plexiglas cap sealed the top end of the test section so that the air inside flowed in a completely enclosed space. An oscillating pressure gradient was produced inside the test section by the compressor base, driven by a d.c. motor connected to a variable transformer. The stroke of the compressor was three inches. A second piston was joined to the top face of the compressor piston by a connecting rod. This piston had a smaller diameter than the compressor piston and ran inside of a steel cylinder mounted between the compressor cylinder and the test section. The air compressor, drive system, second piston, and steel cylinder were parts of an earlier experimental apparatus built by Alan A. Kornhauser [3] for his ScD work at the M.I.T. Cryogenic Engineering Lab.

A smoke wire was threaded horizontally through the mid-section of the test section in order to visualize the flow. A thin (0.012 inch diameter) stainless steel wire was used as the smoke wire. In order to produce smoke, the wire was coated with Life-Like (R) Model Train Smoke fluid by drawing it through a syringe acting as an oil reservoir. This syringe was held perpendicular to the test section with the needle inserted through the plexiglas wall.

Pulsing of the smoke wire was controlled by the circuit in Figure 2-2. The circuit,

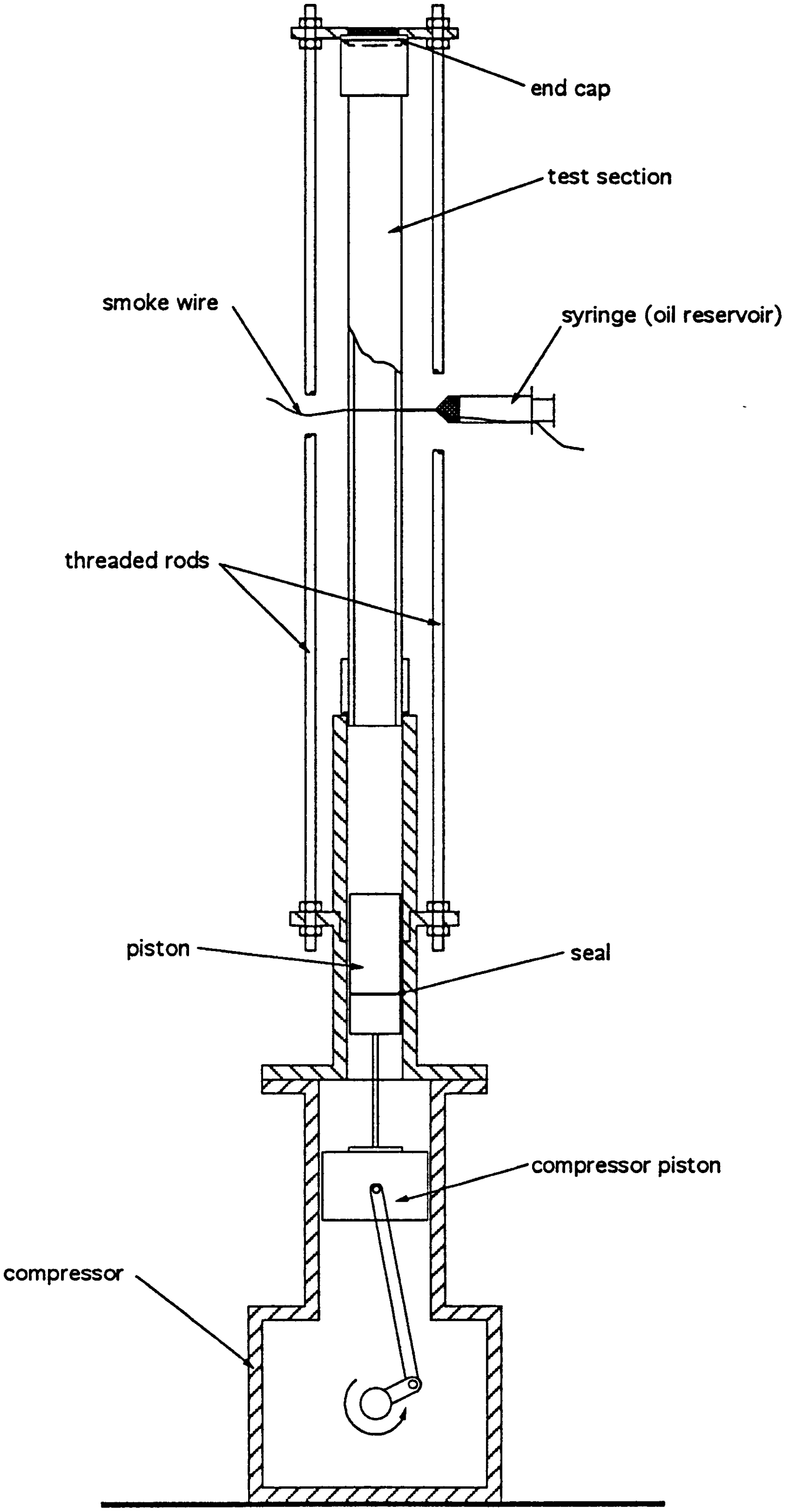

Figure 2-1: Experimental apparatus.

based on a smoke-wire circuit used by H. M. Nagib [6], was composed of three smaller functional parts: the comparator, the relay driver, and the smoke-wire pulse timer. Output from a photoelectric pickoff triggered the circuit, which in turn closed the relay switch to provide power to the smoke wire.

Polaroid photographs of the smoke in the test section were taken with a still motion camera. The smoke was illuminated with a strobelight positioned behind the test section with the reflector aimed at a 30 degree angle from horizontal. The arrangement of the photographic equipment is shown in Figure 2-3. Photographs were taken in a darkened room by opening the camera shutter until the strobe fired.

The strobelight was triggered by a photoelectric pickoff device which detected mylar strips taped to the side of the compressor drive wheel. Each strip represented a different crank angle and, therefore, a different position of the piston. A flash delay unit introduced an adjustable delay between the time the strobe was triggered by the detector and the instant at which it fired.

The appendix carries a more detailed description of the experimental apparatus.

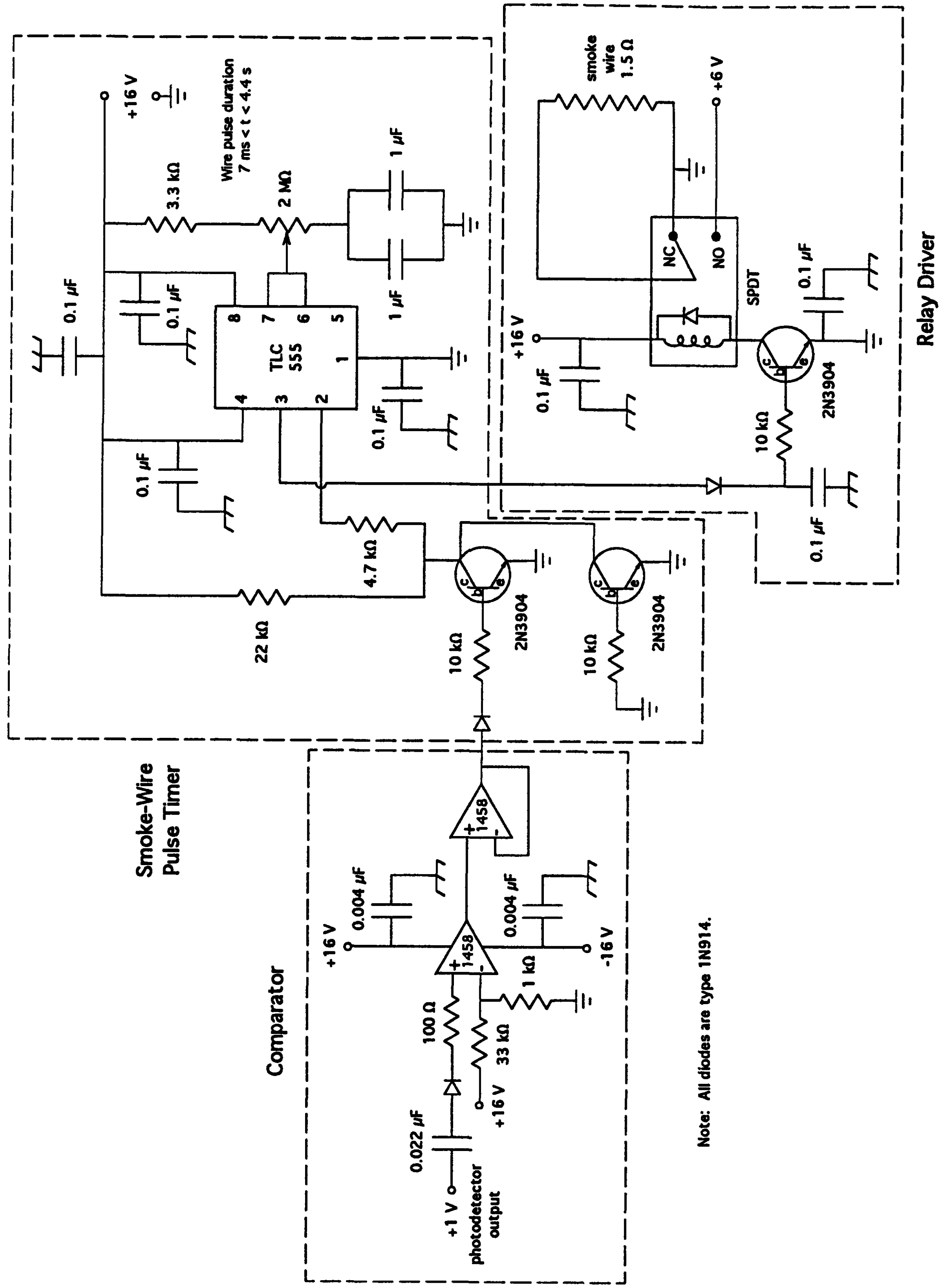

Figure 2-2: Electronic circuit, divided into three functional parts: comparator, smoke-wire pulse timer, and relay driver.

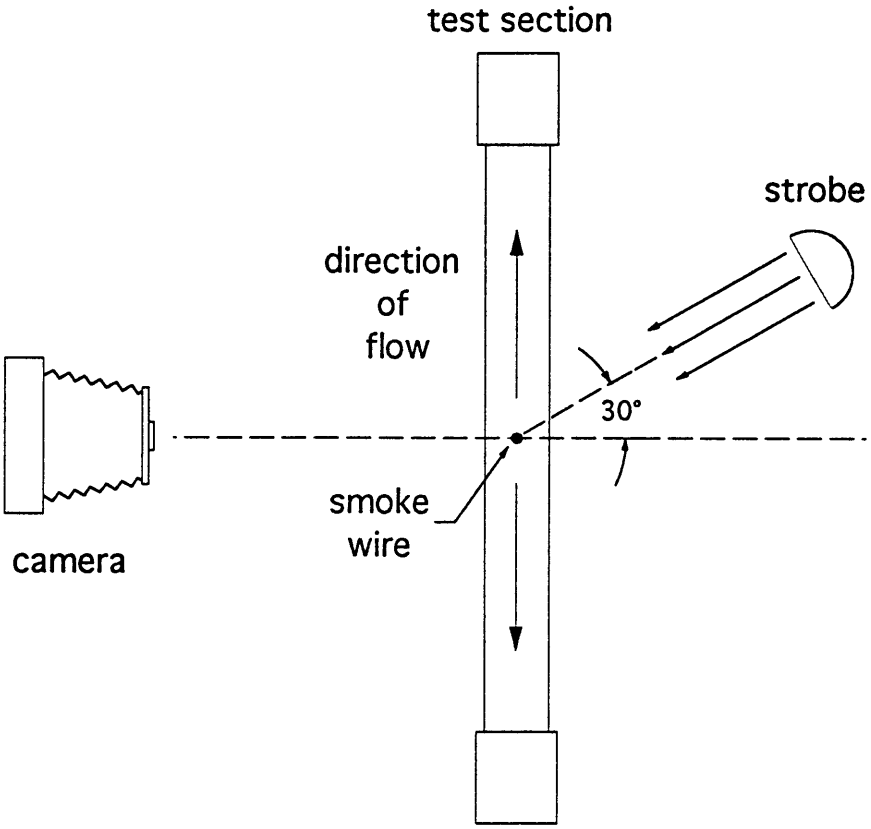

Figure 2-3: Arrangement of the camera and strobe for photographing smoke.

Chapter 3

Experimental Procedure

Before running the experiment, a correlation between the compressor speed and the d.c. motor voltage was determined, and the crank angles at which the flow would be observed were marked on the compressor drive wheel. A speed v. voltage curve was made by measuring the angular frequency of a pulley in the transmission with a stroboscope for a range of voltages. The corresponding angular frequencies of the compressor drive wheel (connected to the observed pulley via a belt) were then computed using the ratio of the wheel geometries. Thus, by monitoring the voltage of the d.c. motor, the speed of the compressor was also known.

Eight crank angles, spanning one revolution, were selected as the points at which the flow would be observed. These angles, ranging from zero to $\frac{7\pi}{4}$ radians, in increments of $\frac{\pi}{4}$ radians, were marked on the compressor drive wheel. The angles were located by removing the test section and measuring the displacement of the piston from a reference point. An angle of $\frac{\pi}{4}$ radians was defined as top dead center and $\frac{3\pi}{2}$ radians as bottom dead center. Markers taped to the side of the compressor wheel triggered a photoelectric pickoff device at the desired crank angle. The angles were selected so that the flow would be visualized at the points of maximum change in the cycle—top-dead-center and bottom-dead-center piston positions, and points of minimum and maximum velocity and acceleration.

In order to take a photograph of the flow, several steps were taken. First, a crank angle was selected at which the flow would be visualized by covering all but the desired angle marker on the compressor wheel with black tape. Second, the d.c. motor speed was set by observing the voltage reading on the voltmeter. The motor was permitted to run for approximately two minutes to allow the system to reach a steady speed. Next, a new section of smoke wire was drawn into the test section to coat the wire with oil. A piece of film was then loaded into the camera.

Since the photographs were taken by holding open the shutter for a minute or two and flashing the strobe to capture the action in the test section, the room in which the apparatus and camera were situated was darkened (photography was mostly done at night). Just before the opening the shutter, the flash delay unit (which also supplies power to the photodetector) was turned on. The shutter cable was then depressed until the strobe fired. The flash delay unit was turned off again between photographs.

A maximum velocity for laminar profiles and an average velocity for turbulent profiles were to be calculated from the photographs by measuring the distance from the smoke wire that the timeline had traveled. The time was the preset delay time between the smoke-wire pulse and strobe flash. When making measurements of images in photographs, a scaling factor must be used to convert the dimensions to actual size. For this purpose, a photograph was taken of a piece of graph paper located next to the smoke wire inside the test section. By comparing photographs of the velocity profiles to the graph, scaling would be automatic (assuming the camera focus had not changed).

Since the smoke wire was mounted horizontally, buoyancy effects of the smoke would have affected velocity measurements and, thus, had to be accounted for. This was planned to be accomplished by taking a series of photographs of the smoke under zero-flow conditions. An averaged "buoyancy effect" could then have been determined.

Chapter 4

Observations and Discussion

Attempts to photograph the smoke in the test section proved unsuccessful. None of the methods or lighting arrangements which were tried were able to sufficiently increase the visibility of the smoke to make it photographable. Moreover, the smoke, in most cases, diffused very quickly as discussed.

4.1 Observations

Since photographs of the flow velocity profiles did not turn out, visual observations of the flow behavior traced by the smoke were made at various crank angles for one compressor speed. The observations, covering a full piston cycle, were made at crank angle increments of $\frac{\pi}{4}$ with the compressor running at approximately 9.2 rpm. A crank angle of zero and π radians represents the piston at mid stroke [1] with an upward velocity and with a downward velocity, respectively. The piston reaches the top of its stroke (top dead center) at a crank angle of $\frac{\pi}{2}$ radians, and the bottom of its stroke (bottom dead center) when the crank reaches an angle of $\frac{3\pi}{2}$ radians.

At zero radians, the smoke inherited a laminar shape, illustrated in Figure 4-1 and smoothly traveled upward from the wire with no turbulent mixing. The flow behaved essentially the same at $\frac{\pi}{4}$ radians. When the piston reached top dead center, the laminar profile still predominated but the smoke began to mix around the smoke

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[1] Mid-stroke is actually attained at 84 degrees from top dead center; see Appendix.

wire after rising a few inches. This is sketched in Figure 4-2. At the next increment, the smoke rose quickly from the wire for a distance of two to three inches but then stopped and began to eddy in place. Figure 4-3 shows the resulting smoke pattern. At mid-stroke with the piston traveling downward, immediate dispersion and turbulent mixing of the smoke was observed. When the crank reached an angle of $\frac{5\pi}{4}$ radians, an interesting profile, sketched in Figure 4-4, was exhibited. Two laminar profiles traveled upward beside each wall of the test section while the smoke at the center of the wire moved downward a small distance and began to mix. At bottom dead center, all the smoke seemed to be pulled towards one wall of the test section in a direction parallel to the wire while simultaneously mixing, as shown in Figure 4-5. At the final increment of $\frac{7\pi}{4}$ radians, a portion of the smoke was observed to rise upwards and another portion to move downwards at a slower rate, but both volumes of smoke exhibited turbulence.

4.2 Discussion of Observations

The observations suggest that the flow in the test section was within the transition region between laminar and turbulent flow. Since no velocity profiles were obtained, it is not possible to calculate an accurate Reynolds number to compare with the findings of Merkli and Thomann [4]. However, the pattern of laminar and turbulent flow behavior appears to agree with expected results. As previously mentioned in Section 1.3, turbulent bursts appear during the deceleration phases of a cycle, but the flow returns to laminar upon acceleration. By defining a crank angle of $\frac{\pi}{2}$ radians as the top-dead-center piston position and assuming a sinusoidal piston motion, we find that crank angles of zero, $\frac{\pi}{4}$, π, and $\frac{5\pi}{4}$ radians correspond to phases of acceleration in the cycle while the remaining increments fall into the deceleration phases.

Laminar flow was observed at zero, $\frac{\pi}{4}$, and $\frac{5\pi}{4}$ radians, but the flow was turbulent at π radians. The profile observed at $\frac{5\pi}{4}$ radians may be an example of the "Richardson annular effect," but this type of profile was only found in this one instance. Turbulence coincided with all of the points of deceleration in the cycle. Vortex formation, as is found by Merkli and Thomann [4], was not exhibited in this project but may not have been visible due to the small amounts of smoke employed.

4.3 Discussion of Difficulties

Failure to obtain quality photographic records of the smoke (either timelines or streaklines) may be attributed to problems with the equipment. These problems mainly concerned the electronics, smoke density, and illumination. First, the electronics circuits were unreliable. The relay was not activated by every trigger pulse from the photodetector, and the timer did not always respond to adjustments of the timing interval during which the relay switch remained closed. In addition, the relay was unpredictable and "fluttered"—that is, the switch opened and closed very rapidly—for a period as long as two to three seconds after initial activation. Consequently, the smoke wire often overheated and occasionally broke because of the long period of time over which it received power. This phenomenon only occurred when a voltage potential was placed across the common input and one of the switch positions. Yet, when the relay was isolated from the trigger circuit and activated with a pushbutton switch (with the switch contacts under the same conditions as above), the relay operated without fluttering. The source of the relay flutter was never located.

The density of the smoke presented another major problem when attempts were made to photograph it. In general, smoke wires are only capable of producing fine filaments of smoke, the density of which depends upon the size of the oil beads and upon the time duration of the current pulse [2] Moreover, when using the model train smoke fluid, streaklines could not be continuously generated. Since the oil's viscosity was small, the wire could be wetted with only a thin layer of oil which vaporized almost instantaneously. The viscosity of the model train smoke fluid may have been able to be increased by addition of a higher viscosity oil (e.g. hydraulic oil), but this was not tried.

Illumination of the smoke in the test section was the third major obstacle. As

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[2] A low current provided over a relatively long period of time will produce a continuous streakline.

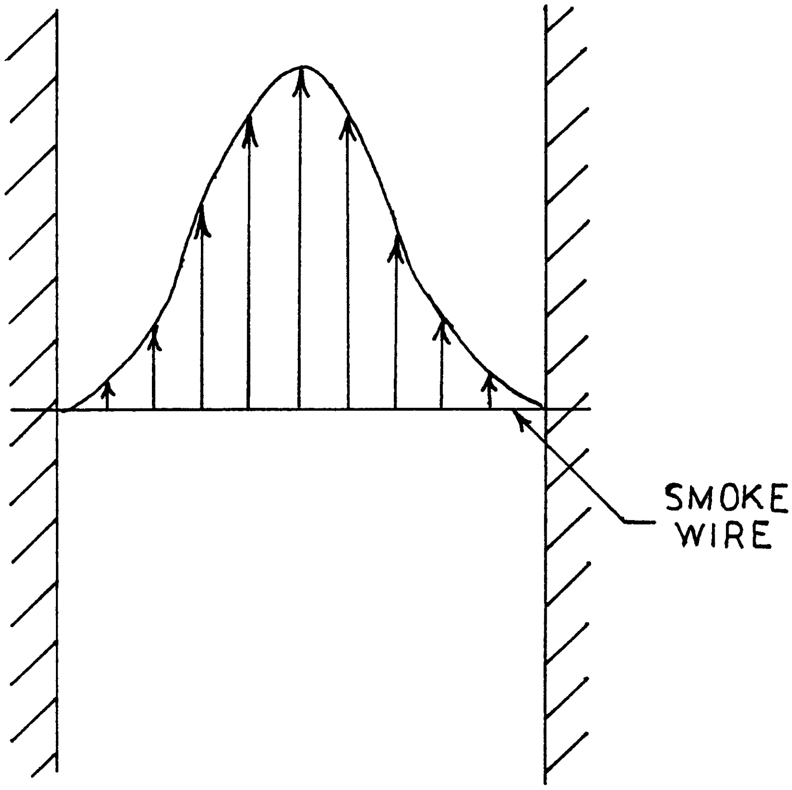

Figure 4-1: Laminar velocity profile observed at zero and $\frac{\pi}{4}$ radians.

previously discussed, various light sources and several different lighting arrangements were tried to achieve the goal of sufficient illumination for photographs with minimal glare from the test section walls. Test section geometry and size were major contributors to this problem. The smoke was most visible when the light source was positioned directly behind the test section, aimed along a downward angle of 60 degrees from horizontal. Unfortunately, one of the threaded rods which held the test section in place stood in the path of the light, but this could have been corrected by changing the arrangement of the rods.

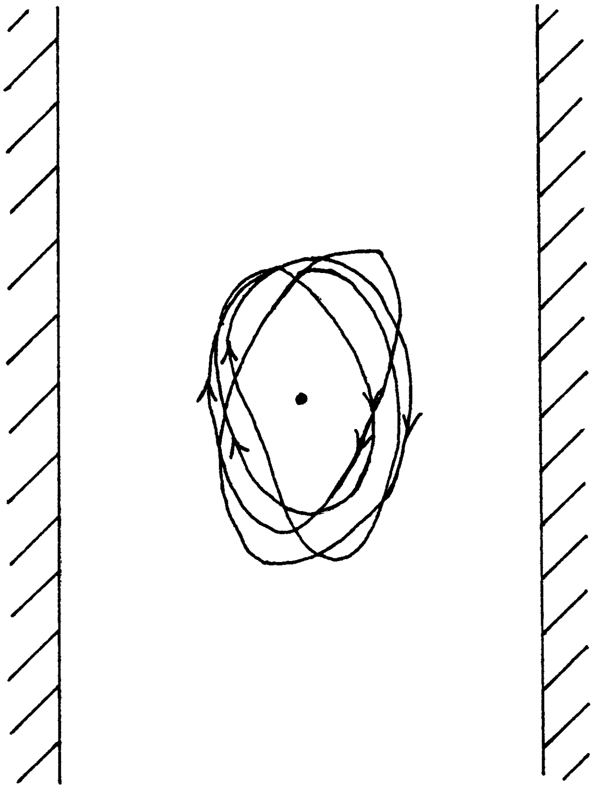

Figure 4-2: Rotation of flow in a turbulent circular pattern around the smoke wire observed at $\frac{\pi}{2}$ radians. Side view shown.

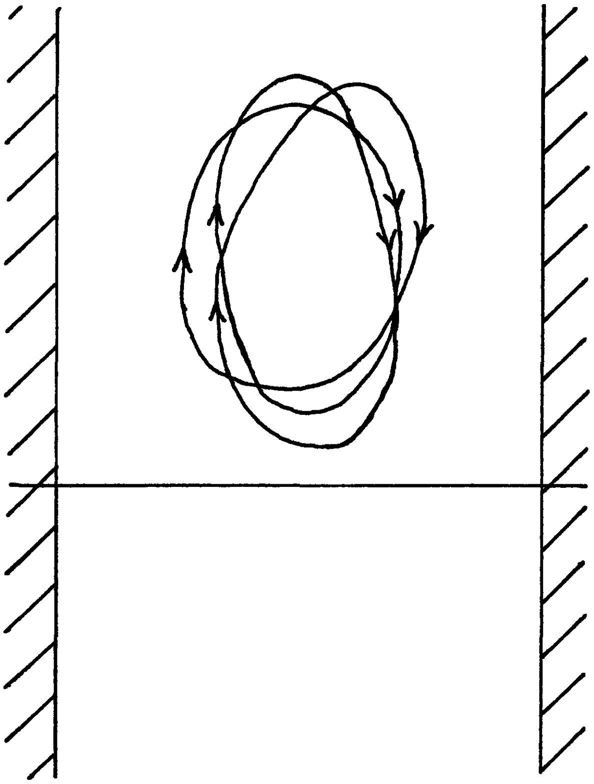

Figure 4-3: Rotational turbulent pattern eddying in place above the smoke wire observed at $\frac{3\pi}{4}$ radians.

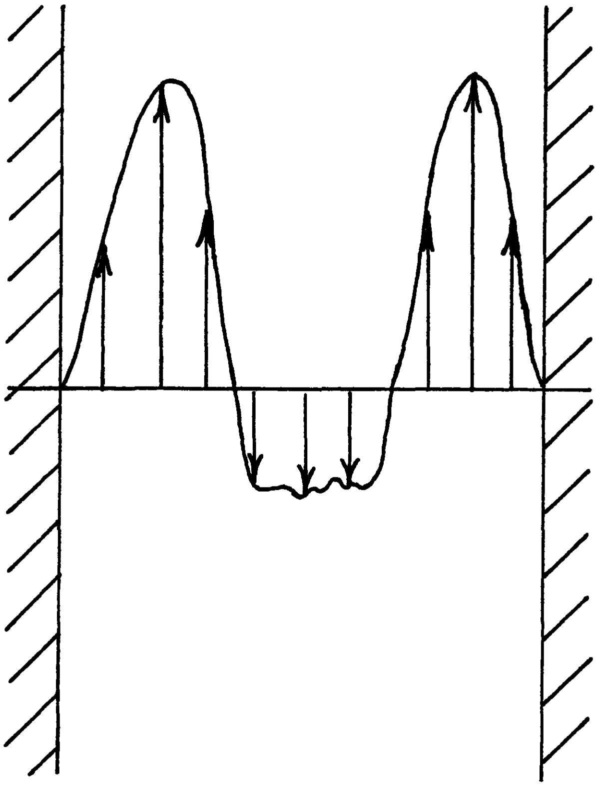

Figure 4-4: Two laminar velocity profiles observed near test section walls at $\frac{5\pi}{4}$ radians.

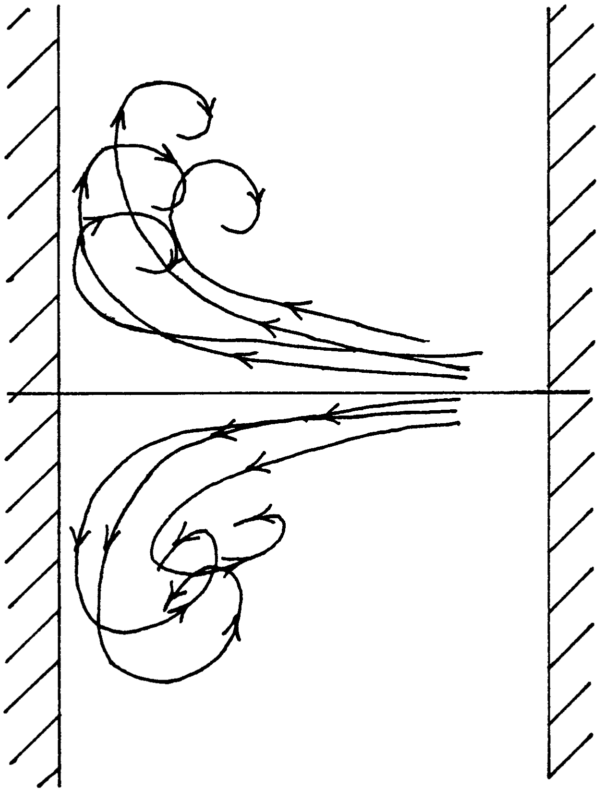

Figure 4-5: Turbulence observed at $\frac{3\pi}{2}$ radians.

Chapter 5

Conclusion and Suggestions for Improvement

5.1 Conclusion

It has been determined that the smoke-wire technique is not the best method for introducing a photographable tracer into the oscillating air flow in a gas spring. Turbulence in the flow caused the streaklines of smoke to quickly dissipate to such an extent that photographic records were unsuccessful. Observations of the smoke lines at eight crank angles for one compressor speed yielded results for transition to turbulence which were in general agreement with results for oscillating flows. Details of the flow were not investigated due to the insufficient volume of smoke produced by the smoke wire, and thus, phenomena such as vortex formation were not observed. End effects were also unknown.

5.2 Suggestions for Improvement

A few suggestions for improving future experimental work in this area can be made based on the experience gained during this project. Since the smoke-wire method did not prove very effective for visualizing the flow in the gas spring, then the first suggestion is to try another method of flow visualization. The shadowgraph, schlieren, and interferometer methods [7, pp. 3–5] are optical methods of visualizing density gradients in fluids. The spark-tracing method is similar to the smoke-wire method in that it produces timelines. Unfortunately, all of these techniques, except for the shadowgraph, are much more complex and require more hardware than does smoke-wire visualization.

If, however, one chooses to stick with a smoke wire, then some suggestions can be given on how to avoid the difficulties encountered in this project. First, if using model train smoke fluid to coat the smoke wire, it is recommended that a viscous oil (such as mineral or hydraulic oil) be added to the model train smoke fluid. This will produce a thicker layer of oil when the wire is wetted, thus allowing the wire to smoke continuously for a longer duration or allowing the wire to be pulsed more than once without recoating (although this depends on the temperature to which the wire is raised). Second, in order to prevent oil from being sucked into the test section from the reservoir [1], two things can be tried. Selecting a smaller diameter needle or similar reservoir opening may alleviate the problem, but it must also be remembered that the diameter effects how the oil coats the wire, such as the size of the oil droplets. Construction of a pressurized reservoir, like the one developed by Corke et al. [2], is a second option. The accumulation of smoke inside a sealed test section may present a problem but largely depends on the overall size of the section. Smoke wires produce such small amounts of smoke that a wire in a large test section could be pulsed many times before smoke accumulation becomes an issue. If valves were built into a test section or somewhere in the enclosed space, then the test section could be periodically purged.

There are a few ways in which one can try to improve the quality of the smoke photographs. Use of a square or rectangular, rather than a cylindrical, test section would both reduce glare from the walls and eliminate distortion of the image within the test section which may result from shooting photographs through a curved surface. The photographic images themselves can be treated in order to enhance certain

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[1] At compressor speeds $> \approx 27$ rpm, this didn't seem to be as much of a problem, possibly because the pressure was changing so rapidly.

flow details by increasing contrast between the white smoke and dark background. Experience in this area is expanding very rapidly with much work being done with high-speed video and digital image processing.

The following suggestions may also be helpful. When the smoke wire is threaded through plexiglas, it will melt the plexiglas around the hole unless some type of insulator is placed between the wire and the plastic. Piston location can be more accurately tracked with a digital encoder. In order to furthur explore the flow in a gas spring, a second camera can be mounted at the end of the test section to photograph the flow in a direction parallel to the cylinder axis.

Appendix A

Experimental Apparatus—A Detailed Description

A.1 Mechanical Components

A.1.1 Test Section

The test section was a plexiglas tube of length 24.45 in (621 mm) with 0.275 in (6.99 mm) walls. The inner diameter was 1.72 in (43.7 mm). The outer diameter had to be expanded on either end of the section in order to fit a steel cylinder on top of the air compressor. Both ends of the tube were machined to accommodate sections of larger diameter (2.76 in (70.1 mm)) plexiglas tube. The ends of both sections fit flush with the ends of the main tube. The large diameter tube at one end was then machined to fit snugly into the steel cylinder and to provide a step on which the test section rested. An end cap was machined from 0.485 in (12.32 mm) thick plexiglas to fit the upper end of the test section. Grooves were cut in both ends of the test section for #036 O-rings to seal the connections. The test section was held vertically between the compressor and a steel plate at the top by three threaded rods.

The piston which oscillated the air in the test section was fabricated from Micarta (R) phenolic [3, p. 150]. The piston had a 0.44 in (11.1 mm) brass head and a steel section to accommodate the seal. A buna-n O-ring between two leather backup rings acted as the seal. The leather rings both prevented shifting of the O-ring and held lubricating oil. The piston was operated within a two-section steel cylinder. A tight seal was produced in the lower section by honing it out; the upper section was bored only. Clearance between the piston and cylinder was approximately 0.004 in (0.10 mm).

A.1.2 Drive

The compressor base used to sinusoidally oscillate the air in the test section was a Quincy Model 230x31 air compressor with a 3.00 in (76.2 mm) stroke [3, p. 151]. The piston head was removed and the lower section of the steel cylinder, welded to a steel plate, was fastened in its place. Dowel pins insured alignment of the cylinder with the compressor cylinder. The top of the compressor piston was connected to the bottom of the second piston by a rod. Some lateral movement was possible in the coupling to the second piston to compensate for misalignment. There was no allowable axial play, however.

Motion of the piston was not perfectly sinusoidal due to the finite length of the connecting rod [3, p. 151]. The connecting rod/crank ratio of the air compressor was 4.80. Consequently, the piston attained mid-stroke at a crank angle of 84 degrees from top center. When operating at constant velocity, the top half of the cycle was found to be 6.7% longer than the bottom half.

The compressor was driven by a 5 horsepower, 230 volt d.c. motor with a compound field winding [3, p. 151]. A manually adjustable variable transformer supplied the armature series field voltage while shunt field voltage remained fixed. The motor, in combination with the transformer, possessed an approximate speed range of 40 to 1800 rpm (0.7 to 30 Hz). A two-stage transmission composed of v-belt pulleys, providing a reduction ratio of 19.8, lowered the speed range to 2 to 90.9 rpm (0.034 to 1.52 Hz).

A.2 Smoke Wire

A.2.1 Wire

A 0.012 in diameter (33 U.S. S.W.G.) stainless steel wire functioned as the smoke wire. The resistance of the wire was measured to be approximately 5.2 Ω /foot (0.2 Ω/cm). Two holes were drilled in the test section walls on opposite sides at the midpoint of the section length. The wire was fed through a syringe which was clamped so that the needle passed through one of the holes but remained flush with the inside surface. The wire was then threaded through the test section and out the second hole. The wire was wound between two wooden spools on threaded rods which also served to keep the wire taught (the wire often sagged during heating due to expansion of the metal).

A.2.2 Oil

The smoke used to visualize the air flow was produced by vaporizing oil. Three different types of oils were tested and compared according to the amount of smoke generated. These were mineral oil, hydraulic oil (Gulf ISO grade 100), and model train smoke fluid manufactured by Life-Like Products, Inc. All three produced white smoke, the easiest smoke to photograph, but the model train smoke fluid was found to generate the most smoke per volume of oil. It also happened to be the least viscous of the three, and, as a result, did not coat the wire as well as the other two. A syringe served as an oil reservoir.

A.3 Electronic Components

The electronic equipment enabled the control of the time duration at which the smoke wire was energized and synchronized the energization of the wire with the photodetector pulse. These main tasks were broken down into three smaller functions: (1) detection of the photodetector pulse; (2) control of the time duration of energization of the wire; and (3) activation of the relay through which power was transmitted to the smoke wire. The trigger circuit in Figure 2-2 is a modified version of a circuit built by H. M. Nagib, presented in Reference [6]. All positive supply and common rails were bypassed with 0.1 μF or 0.004 μF capacitors in order to minimize false triggering from voltage swings.

A.3.1 Comparator Circuit

The first function was accomplished with a simple op-amp comparator. The circuit was necessary because the output pulse from the photodetector (approx. 1 V) was too small to directly trigger the timer chip. The op-amp compares the detector output with a +0.5 V reference. When the detector signal becomes larger than the reference voltage, the op-amp output swings between saturation states, from $-V_{cc}$ to $+V_{cc}$. A voltage follower buffered the op-amp from the next stage of the circuit.

A.3.2 Trigger Circuit

The length of time that the smoke wire was energized was controlled by a TLC555 timer configured to operate in monostable mode (i.e. outputs a variable length pulse upon detection of an input pulse). Since the timer is triggered by a signal which is less than one-third of its supply voltage, a flip-flop was used to invert the positive output of the comparator. Duration of the timer output was set by an RC network according to the approximation:

$$t_T \approx 1.1RC. \tag{A.1}$$

[1] In this case, output pulses ranged from approximately 7 ms to 4.4 s.

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[1] Forest M. Mims III, *Engineer's Notebook. IC Applications.* McGraw-Hill, New York, 1986, p.112.

A.3.3 Relay Driver

A transistor in a common-emitter configuration served as a switch for powering the relay which connected the smoke wire to power because the timer could not source sufficient current for relay activation. When the relay switch opened, the smoke wire was connected to a +6V power source for the length of time preset in the timer stage. A diode was connected across the relay coil to suppress any transients produced when the transistor switch opened, otherwise the relay could have been activated accidentally.

A slight modification of the strobe system was necessary to energize the smoke wire before firing the strobe. The Strobotac unit was designed to have the strobe fire when it received an input pulse from the photoelectric pickoff. An output jack was available on the unit, but this could only be used to trigger an external device when the strobe actually fired. It was therefore decided to trigger the timer circuit directly with the photodetector output before the signal reached the flash delay unit. This was accomplished by connecting the external circuit to the photodetector output through a dual headphone adapter which adapts two phone plugs (3-conductor) to one phone jack.

The smoke wire was initially powered with a large capacitor due to the unavailability within the lab at the time of a power supply with a sufficient current capability. A 5,000 μF capacitor (rated at 50 VDC) was acquired for this purpose. After much experimentation, it was determined that this configuration could not provide enough power to produce the desired density of smoke. Though the use of a capacitor highly limits the power transmitted to the smoke wire, it offers a safer method of power delivery than does the power supply method.

A.4 Photographic Equipment

In order to simplify the photographic equipment and its operation, the strobe light was made the controlling factor. Synchronizing the camera shutter with the smoke-wire pulse and strobe flash would have unnecessarily complicated the project. Moreover, the camera used had no interfaces for shutter control by electrical means. Therefore, the shutter was held open, as for a time exposure, and it was left to the strobe to freeze the action of the flow in the darkened room.

A.4.1 Camera

A general purpose Polaroid MP-4 Land Camera was fitted with a film holder designed for use with 4x5 instant sheet film. The lens employed was 135 mm, offering a range of aperture settings from f/4.5 to f/32. As mentioned above, the shutter was set for time exposure and activated manually via shutter cable. The camera was positioned normal to the direction of the smoke wire threaded through the middle of the test section. The field of view of the photographs covered a distance of more than 3 in (76.2 mm) above and 3 in. below the smoke wire.

A.4.2 Film

Polaroid instant sheet black and white film was selected to allow immediate feedback of results. Film speed varied with the type of light source used. A standard camera flash unit, used to experiment with position of the light source, suitably exposed low speed (ISO 200) film. However, the illumination provided by the strobe light (15 million beam candles) used during the actual experiment made necessary a high-speed film (ISO 3000) in order to obtain adequate exposure. The duration of the strobe flash was much shorter than that of the camera flash unit.

A.4.3 Lighting

Lighting often proves to be one of the most challenging aspects of photographing visualized flows. The cylindrical shape of the test section in this project further complicated attempts to illuminate the smoke. Several approaches to the lighting dilemma were tried during the course of the project. In the early stages of the work, before it was decided to leave the camera shutter open, a fluorescent desk light was used to experiment with different lighting angles and methods. The light was diffused by covering it with wax paper, but this failed to remove the glare from the test section. Back lighting, front lighting, and top lighting resulted in both glare and insufficient illumination (for more information on lighting arrangements, see Ref. [5, pp.51–52]). Pieces of polarized material placed over the light and in front of the camera lens did reduce glare, but it decreased the overall lighting level as well. An attempt was also made to "funnel" the light directly to the test section wall. A tube was attached to the face of the light with the other end placed against the test section, while the rest of the light was covered. Again, both glare and total illumination were reduced.

Greater success was met by switching to a camera flash unit which provided a light output many times larger than that of the fluorescent light. The use of polarized material and the "funneling" method were repeated with the flash unit. The flash was then bounced off of a white card placed at an angle behind the test section in order to soften the light. Glare problems persisted in all of these techniques, but top lighting with the flash successfully illuminated the smoke while eliminating glare from the test section walls. However, photographs were taken without the compressor running, so diffusion of the smoke was not dealt with.

The camera flash unit was replaced by a General Radio 1538-A Strobotac (R) stroboscope. Accessories used with the strobe were the GR 1536-A photoelectric pickoff, the GR 1531-P2 flash delay, and the GR 1538-P2 extension lamp. In order to locate the piston position with the photoelectric pickoff, crank angle positions were marked on the side of the compressor drive wheel with a strip of reflective material (e.g. mylar or silver tape) while the rest of the surface was covered with black tape to insure proper detection of the strips. The strobe was triggered each time a shiny strip passed the photodetector. A time delay between the photodetector pulse and strobe firing could be set with the flash delay within a range of 100 μs to 1 s.

The extension lamp was tried in two different positions. In order to avoid glare from the test section walls, the lamp was first positioned above the end cap to flash along the longitudinal axis of the test section. The lamp was also tried in a second position as an attempt to increase the visibility of the smoke. When visualizing aerosols, it has been found that the intensity of forward-scattered light from the aerosol particles is greatest around an angle of 30 degrees from the axis of incident light. Therefore, the lamp was positioned behind the test section (but not directly behind because one of the threaded rods was in the path of the light), aimed downward along a line 30 degrees from horizontal.

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