Chapter 3
Experimental Setup and Equipment

"If God has made the world a perfect mechanism, He has at least conceded so much to our imperfect intellects that in order to predict little parts of it, we need not solve innumerable differential equations, but can use dice with fair success."
-- Max Born

This chapter discusses the equipment and experimental procedures used to collect the data presented within this dissertation. The descriptions of the equipment are presented first, followed by the experimental procedures. Although the arrangement and procedure varied slightly from test to test, the procedures presented here are considered the norm. Any deviations from these procedures are discussed on a case-by-case basis within the relevant chapter.

3.1: Lab Equipment

The equipment description is presented according to the system to which it belongs; the flow system (3.1.1), power system (3.1.2), data acquisition system (3.1.3), and accessory equipment (3.1.4). The experimental procedures are discussed in Section 3.2.

3.1.1 The Flow System

The flow system is separated into two subsystems, the torch feedstock system and the injector system. When referring to a gas throughout this dissertation, the terms injectant and feedstock will be used. Injectant refers to any gas fed through the injector. In some cases, the word fuel will be used as a synonym when ethylene is used as an injectant. The term feedstock refers to any gas fed through the plasma torch, regardless of its chemical composition.

3.1.1.1: The Torch Feedstock System

The torch feedstock system consists of the gas storage cylinders (argon, methane, ethylene, propylene, propane, nitrogen and air), dual-stage regulators, tubing, fittings, and valves. Control of the torch chamber pressure was made by adjustment of the bottle regulators and a 10-turn needle valve before testing began. Flow to the torch was initiated by means of a pneumatic valve controlled by a voltage pulse from a PC.

3.1.1.2: The Injector Fuel System

The injector fuel system consists of four ethylene gas storage cylinders, a bottle manifold, a single-stage regulator, and an array of valves. Control of the fuel flowrate to the injector was made by adjustment of a ball valve and needle valve in parallel, allowing for course or fine adjustment respectively. Flow to the injector was initiated by means of a voltage pulse to a pneumatic valve.

3.1.2: The Power System

Power was supplied to the torch via five Miller DC arc welders connected in series. Four of the welders are Miller SR-150-32s, while the fifth is a Maxstar 152, a more modern version of the other models. The SR-150-32s each produce an open-circuit voltage (OCV) of 67 V, and the Maxstar 152, an OCV of 95 V, for a total OCV of 363 V. In almost all tests, only the four SR-150-32s were used. Occasionally, such as with nitrogen tests involving larger arc gaps, the fifth welder was used to compensate for the higher voltage requirements. Most tests were conducted at currents of 40 A or below, with the norm ranging from 15-25 A.

A high-frequency starter, a Miller HF-251D-1, was used to initiate the arc. This starter was connected in series between the torch and welders via welding cables. A frequency selection knob allowed the voltage oscillation rate to be adjusted, but this was always left on the lowest setting. The arc was initiated by means of a voltage pulse fed to the starter, producing a 0.25 second burst of high-frequency current. Once the arc was initiated, the starter was turned off, allowing the torch to run on pure direct current.

3.1.3: The Data Acquisition System

The control of various pieces of equipment and the collection of data were accomplished by use of a PC and a 16-channel, 16-bit A/D converter. LabVIEW was used to coordinate the timing and control of the various pieces of equipment.

3.1.3.1: The Spectrometer

The CCD spectrometer system consists of three Ocean Optics S2000s, each with a spectral resolution of 0.08 nm and a total spectral range from 196 nm to 730 nm. Three separate spectrometers were used to achieve a good spectral resolution while being able to maintain a spectral range encompassing the entire visible region. The average integration time for observing the plasma jet was 125 ms, but varied from 25 to 200 ms, depending on the type of test and the luminosity of the gas. Photons emitted by the plasma jet entered a 1.0 or 0.5-mm diameter scope, which was a long tube used to reduce the viewing area of the spectrometer. This scope was fitted with a baffle to reduce the amount of reflected light entering the assembly. The 0.5-mm scope was used only for measurements made of the plasma jet. Measurements of the downstream products were made through the 1.0-mm scope, which allowed more light to enter. The scope was attached to a 2-mm collimating lens, through which the photons were focused onto a fiber optic cable. The spectrometer fiber optic cable was split three ways by means of a trifurcated splitter, each leg of which went to one of the three S2000s. A motorized positioning device allowed movement of the point of observation while the plasma torch was in operation. Calibration of the spectrometer was performed every several months using a hydrogen-argon lamp source.

3.1.3.2: Temperature Probes

Total temperature measurements were made by the use of three, exposed-junction, 0.25-mm diameter, type-E thermocouples, arranged within a probe rake. The probe rake consists of three 1.59-mm OD, 1.04-mm ID, tubes spaced 6.4 mm apart. Each probe tube has a capture area of 0.85 mm^2, with four small holes drilled into the tube to improve the recovery factor. The ratio of probe capture to recovery area is 5 to 1, resulting in a recovery factor of 0.95.

3.1.3.3: High-Speed Cameras

Two digital high-speed cameras, a Hadland Photonics 4-CCD Imacon 468 and a Reticon EG&R, were used to observe unsteady plasma jet phenomena. The Hadland Photonics camera has the ability to capture four sequential pictures with variable exposure and interframe times and was triggered via computer by a voltage pulse. For observation of the plasma jet, the exposure time was set between 200 μs and 100 ns, depending on the brightness of the jet and whether a spectral filter was used. Interframe time was usually set to 1.39 ms, allowing four pictures to be taken within one voltage cycle (180 Hz) of the plasma jet. The Reticon camera has the capability to capture up to 2048 frames at a frame rate of 1000 frames per second. This allowed easy tracking of various lower speed phenomena such as electrode emission and plasma jet pulsation.

3.1.3.4: Other Data Acquisition Equipment

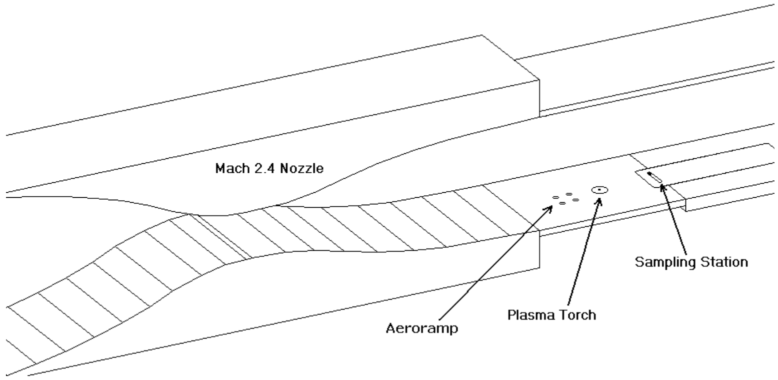
Video and 35-mm cameras were used for other types of optical investigations of the plasma jet and surrounding regions. The video camera was most often used to observe the flame plume produced by the plasma torch when operating on hydrocarbon feedstocks, but was also used to observe the oil distribution during oil-flow visualization tests. The 35-mm camera was used for qualitative spectral studies of excited species in and around the plasma jet by taking pictures through spectral band-pass filters.

A stereoscope was used to study the electrode surfaces after testing. The stereoscope allowed low-magnification, high-resolution pictures to be taken of the electrode surfaces by means of a Polaroid camera mount.

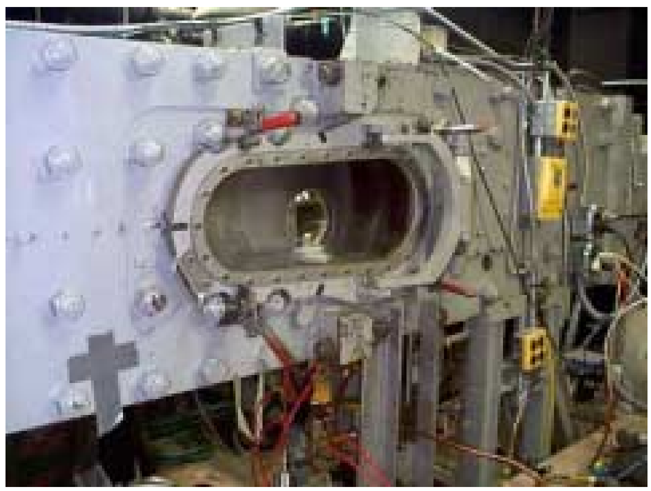
3.1.4: Other Laboratory Equipment

3.1.4.1: The Supersonic Tunnel

The plasma torch was placed in the floor of a Mach 2.4 wind tunnel, as shown in Figure 3.1. The wind tunnel is a blow-down design with a full nozzle to accelerate the airflow to Mach 2.4. The nozzle outlet area is 23 cm by 23 cm, with a 30-cm long test section. The test duration was typically 8-10 seconds at a freestream total pressure of 378 kPa and a total temperature of 281 K. These conditions correspond to a freestream velocity of 550 m/s and a Reynolds number of 4.2×10^7.



(a) A Schematic of the Supersonic Tunnel



(b) A Photo of the Tunnel Test Section

Figure 3.1: Tunnel Schematic Showing Injector, Torch and Equipment Locations

3.1.4.2: Positioning Stages

Two positioning stages were used to allow accurate movement of the spectrometer line of sight. The positioning devices are Velmex® MB2506KJ unislide assemblies, arranged so that the point of observation can be controlled in the x and y directions with an accuracy of ±10 μm. The stages and their orientation are shown in Figure 3.2. An optical bench is used to provide a solid base to which the stages are bolted. Control of the stages is handled through a dual-channel controller, also by Velmex®, which is then controlled by a LabVIEW program.

Figure 3.2: Velmex® Positioning Stages

3.1.4.3: Argon Laser

Spark shadowgraph techniques could not be used to produce shadowgraphs when the torch was in operation since the light emitted by the plasma jet washed out the light from the spark source. Therefore, a Spectra Physics 164 argon laser, operating at a nominal power of 0.7 W and a central wavelength of 514.5 nm, was used to replace the nanopulser as the light source. The beam was focused through the test cell and onto the Hadland camera lens by means of a variety of lenses, mirrors, and a band-pass filter. The setup is described in more detail in Section 3.2.4.

3.1.4.4: Spectral Band-pass Filters

A number of filters were used to create the filtered photographs presented within this dissertation. The filter information is presented in Table 3.1. When used with any of the cameras, the filter was mounted in front of the camera lens with the mirrored side facing the plasma jet. Electrical tape was used to block any light that might enter through the gap left between the filter and camera lens.

Table 3.1: Spectral Filter Specifications

Filter Type	Manufacturer	Center Wavelength (nm)	Half Bandwidth (nm)	Maximum Transmission Rate (%)
H_2	Ealing-Electro Optics	601.1	9.8	52
C_2	Ealing-Electro Optics	515.1	8.8	52
H	Ealing-Electro Optics	656.7	11.1	54
OH	Ealing-Electro Optics	310.0	10.0	Not provided
CH	Ealing-Electro Optics	431.4	8.1	46
CN	Oriel Instruments	391.9	10.3	48
NO	Ealing-Electro Optics	410.9	10.2	49

3.2: Experimental Procedures

The experimental procedures used to collect the data presented within this dissertation are outlined here. As an aid, the chapter numbers within which these experimental procedures were used are included next to the procedure title.

3.2.1: Plasma Torch Setup (4-9)

Unless a test required a specific torch modification, such as arc gap adjustment, the plasma torch was set up identically for each test. First, the electrodes were replaced if they showed sufficient wear to be inadequate for the planned test series. Electrode wear was evaluated qualitatively and replacement depended on the type of test being performed. As an example, tests involving qualitative pictures of the plasma jet required less frequent electrode replacement than those involving quantitative measurements such as total temperature sampling. The cathode was always machined from 2% thoriated tungsten; but depending on the test, the anode was copper, molybdenum, pure tungsten, or a tungsten-copper blend. The anode material used is reported for each test as it is discussed within the dissertation.

Gap adjustment was made by the use of the torch micrometer and an ohmmeter. The multimeter was connected across the anode and cathode to check for continuity. The cathode was forced to make contact with the anode by adjusting the micrometer drive until the multimeter showed no electrical resistance between the anode and cathode. The cathode was then backed out until continuity was broken. From this point, the cathode was backed out an additional 0.178 mm as prescribed by Stouffer (1989). Once the gap adjustment was made, the micrometer was locked down using a lock nut and the plasma torch was bolted into the test cell. At this point, the welding cables were attached via welding clamps and the torch chamber pressure was set through adjustment of the gas bottle regulators and valves within the flow system.

3.2.2: Spectroscopic Analyses

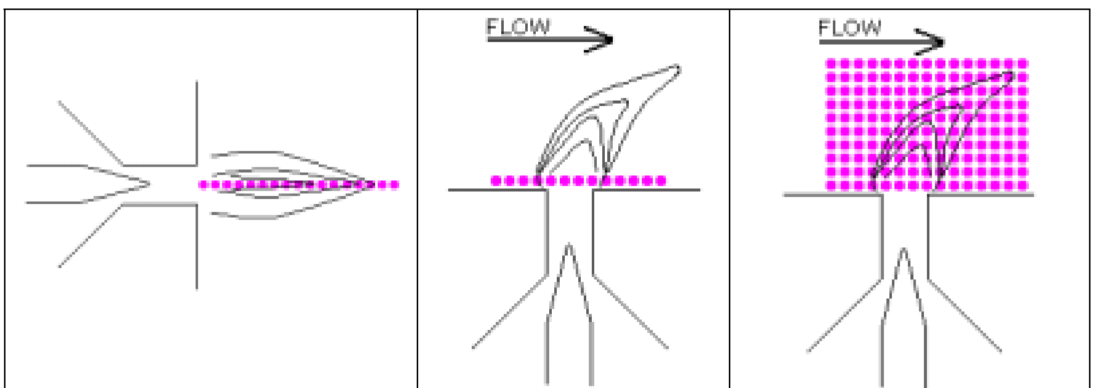
3.2.2.1: Basic Spectroscopic Studies (5)

Basic spectroscopic studies are defined as those including no spatial variation and were used as a means of producing a spectrograph for the purpose of identifying species within the region of interest (i.e. plasma jet, flame plume, etc.). The goal was to determine the spectroscopic characteristics of various hydrocarbon and inert plasmas. Identification of the species within the plasma jet was conducted solely in a quiescent environment. The spectrometer was fitted with a 0.5-mm scope at a distance of approximately six inches from the plasma jet (as measured from the collimating lens). The integration time was adjusted to account for the different intensities of the plasma produced by different feedstocks and power.

Spectroscopic analyses of the flame plumes produced in the supersonic environment were conducted in much the same way. However, because of the low intensity of the flame compared to that of the jet, no scope was used to maximize the amount of light entering the spectrometer. The spectrometer was usually oriented at an angle (as shown in Figure 3.4b), allowing observation of the plume approximately 2-in. downstream of the jet. Spectral measurements were made through a fused silica window, maximizing visible light transmission.

3.2.2.2: Spatial Spectroscopic Studies of the Plasma Jet (6, 7)

Spatial spectroscopic studies involved the use of the Velmex® positioning stages to move the spectrometer line-of-sight during torch operation. These studies were conducted in both one and two-dimensional arrays to produce what are called exit profiles or centerline profiles (one-dimensional studies along the torch exit and jet centerline respectively) and two-dimensional H_β-line profiles of the entire jet. These types of profiles are illustrated in Figure 3.3, where magenta dots represent measurement points. Centerline profiles were conducted solely in the quiescent environment, without the presence of a crossflow to induce plasma jet deflection. The exit profiles were conducted solely in the supersonic tunnel to measure the spectral intensity across the torch exit and were constructed with the spectrometer line of sight perpendicular to the flow (i.e. across the test section floor). The two-dimensional H_β-line profiles are plots of spectral measurements taken around the entire plasma jet and were made in both the quiescent and supersonic environments. The H_β-line label refers to the spectral line of atomic hydrogen used to make the profiles. Atomic hydrogen was chosen because it is known to be a combustion-enhancing radical. In all plasma jet studies, a 0.5-mm scope was used to increase the resolution and to reduce the amount of light entering the spectrometer, thus allowing a higher integration time to be used and reducing the effect of quick, transient phenomena.

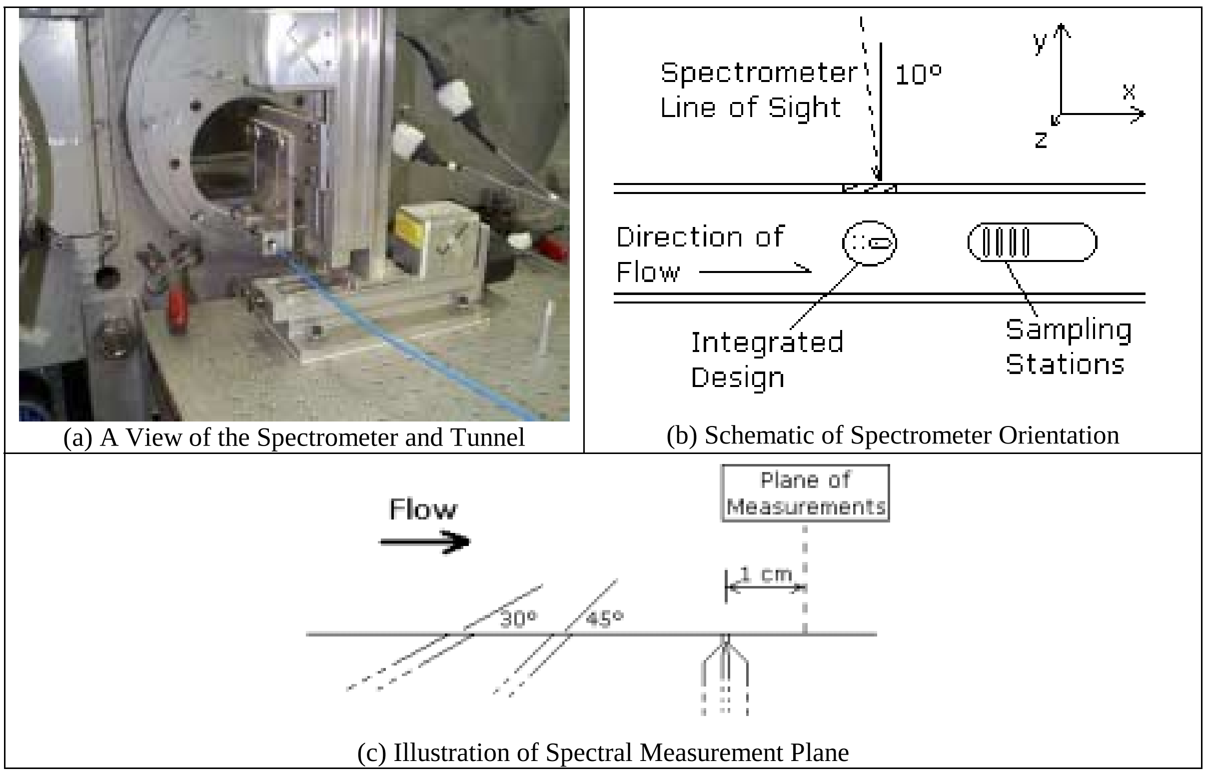


(a) Centerline Profiles (b) Exit Profiles (c) Two-Dimensional Profiles

Figure 3.3: The Measurement Locations of Centerline, Exit, and Two-Dimensional H_β-Profiles

3.2.2.3: Spatial Spectroscopic Studies of the Plume (9)

Spatial spectroscopic studies of the plume refer to studies conducted solely within the supersonic environment and are in reference to the plume of excited species downstream of the plasma jet produced when fuel was injected through an upstream aeroramp. Due to the geometry of the test section, the spectrometer line of sight was 10° from the perpendicular, as shown in Figure 3.4, to allow the measurement of species farther downstream than a perpendicular orientation would allow. Several seconds after the tunnel was started and the torch was ignited, the spectrometer would begin its upward traverse (z-direction), stopping every 1.5 mm to take spectral measurements of the plume. For all plume studies, the 1-mm scope was used to allow sufficient light to enter the spectrometer and allowed integration times of 125 to 200 ms, depending on the brightness of the sample. These integration times were sufficient to increase the signal-to-noise ratio of the spectral data well above 100. To perform spatial studies in the x-direction, the spectrometer scope would be moved a certain distance, usually 1 mm, along the x-traverse, between each run. This traverse distance was then converted into an actual spatial change of observation by accounting for the off-axis line of sight.



(a) A View of the Spectrometer and Tunnel

(b) Schematic of Spectrometer Orientation

(c) Illustration of Spectral Measurement Plane

Figure 3.4: Spectrometer Setup for Plume Studies

3.2.3: Total Temperature Sampling (6-9)

Total temperature measurements were made using the probe rake discussed in Section 3.1.3.2. This rake was moved vertically (z) through the flow during the runs by means of a motorized traverse. The probe rake would traverse a set distance (usually about 1.59 mm) and would stop to collect 25 to 40 temperature measurements. These measurements were then averaged to create a single data point for that spatial location.

The process would then be repeated until the probe extended above the region of interest. This would be accomplished during the 8 to 10 second run time. Between each run, the probe rake would be repositioned to the left or right of its original location (referred to as a station) to measure the temperature adjacent to the previous run. These data sets were then normalized to the freestream temperature, $T_{t,\infty}$, and used to create total temperature profiles, which are two-dimensional representations of the total temperature field at the plane of measurements.

3.2.4: Stereoscopic Investigations (4-6)

Stereoscopic investigations were made of the torch anodes on a regular basis to study the effect of arc attachment point and anode material on the wear patterns of the anode. A stereoscope is a type of low-powered microscope, which offers a large depth of field. The anode to be studied was placed on a flat positioning device, which allowed short, precise movements of the anode, an important consideration using high magnification. Once the magnification, light adjustments, and anode position were acceptable, a picture was taken of the anode surface by means of a Polaroid camera attached to the stereoscope.

3.2.5: Shadowgraphs (7, 8)

Shadowgraphs of the torch were taken using an argon laser (514.5 nm), the Hadland-Photonics CCD camera, and a variety of lenses and first-surface mirrors, as shown in Figure 3.5. The beam generated by the laser (1) passed through a beam spreader (2) and onto a flat mirror (3) positioned at the focal length of the first parabolic mirror (4). The beam then passed through the test section and onto another parabolic mirror (5), which focused the light onto a third, smaller parabolic mirror (6). This mirror redirected the light through a spectral band-pass filter (514.5 nm) (7) and a converging-diverging lens (8). The location of the converging-diverging lens was adjusted to focus the test cell image onto the CCD array of the Hadland Photonics camera (9). During a test, the camera would be triggered via a voltage pulse and capture four sequential images, each with a specified exposure time and frame rate depending on the test conditions.

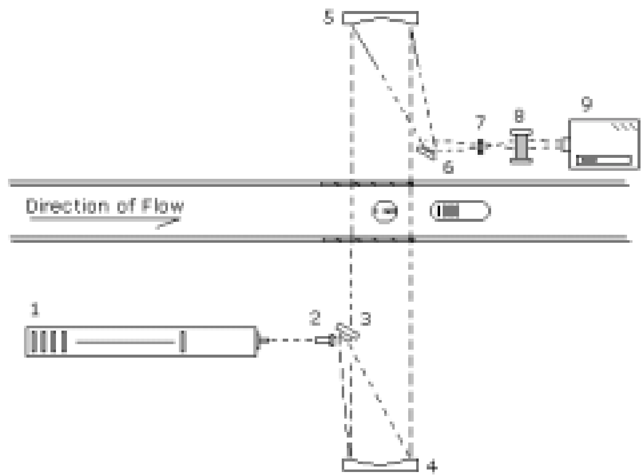


Figure 3.5: Laser-Shadowgraph Setup Schematic

3.2.6: Surface Oil Flow (6, 7)

The flow patterns on the surface of the supersonic tunnel test section were studied using surface oil flow techniques. These techniques provide a somewhat nonintrusive look at the direction of flow, position and shape of the bow shock, plume expansion and identification of separation regions. Silicon oil with a viscosity of 500 cSt was mixed with a green fluorescent dye and thinly brushed over the region of interest. A strip of oil mixed with red dye, to provide contrast, was placed 0.5-in. upstream of the torch exit spanning about 1-in. in the cross-stream direction (y). This type of setup is shown in Figure 3.6. After the oil was applied to the test surface, the tunnel was started and the oil was swept downstream by the crossflow. After the test, the oil was illuminated by means of a UV lamp and pictures were taken of the fluoresced region with a 35 mm camera.

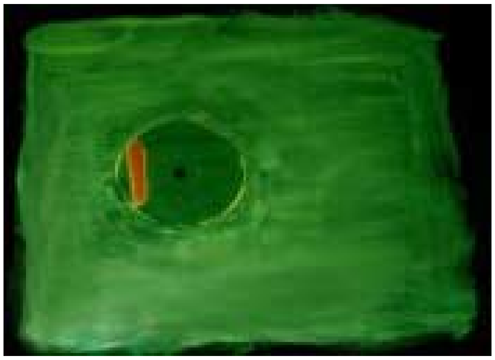


Figure 3.6: Surface Oil Flow Setup

3.2.7: High-Speed Digital Photography (6, 9)

High-speed photography was used to study the transient nature of the plasma jet in both the quiescent and supersonic environments. In all cases, the camera, whether the Hadland-Photonics or the Reticon, was oriented so that the center of the camera lens was level with the torch exit, minimizing reflected light off the tunnel floor or torch surface. A reference photo was taken to provide scale before each test sequence began. A variety of camera lenses, f-stops, integration times, and filters were used, depending on the application. These settings are discussed in more detail where the photos are presented.

3.2.8: Filtered Photography (7, 9)

Filtered photographic techniques were used to qualitatively support spectroscopic measurements and were taken primarily during the tests conducted in the supersonic tunnel. Normally, a 35 mm camera was used; but this was occasionally replaced by one of the high-speed cameras in order to observe transient phenomena. While the torch was in operation, pictures would be taken through a spectral filter to provide a qualitative image of various radical distributions within the plasma jet and surrounding regions. Three to five pictures were taken during each 10-second run, all at different exposure settings to increase the chance of producing a high-quality picture. Normally, these pictures were taken with the camera lens level with the test section floor (to prevent reflection) and with the camera line of sight perpendicular to the direction of flow; although other orientations were used as well, depending on the goal of the study. Pictures taken of the plasma jet in the quiescent environment were conducted in much the same way, except that the Hadland Photonics digital camera was used in place of the 35-mm camera.

3.2.9: Video Observation (7)

Video observation of the supersonic test section was conducted primarily to observe flame phenomena. A standard VHS video camera with a zoom lens was positioned slightly above and upstream of the test section to provide a good angle of observation.