

# Part I

## Experimental Investigation

# Chapter 2

## Experimental Setup

## 2.1 Experimental Philosophy

The experiments performed as part of this study were designed to provide combustion environments that exhibit some features of real industrial gas turbine combustors without compromising experimental measurement access. Two burners were designed, a Bunsen type burner and a flat flame ceramic honeycomb burner. The Bunsen type burner with co-flow of air, though laminar, is the closest to real gas turbine combustors using a fluid-mechanically (and heat-loss) stabilized premixed flame. Modeling of the Bunsen burner was restricted to a CFD model and a semi-empirical chemiluminescence model for  $\text{OH}^*$  and  $\text{CH}^*$  as described in Chapter 7.

The second burner used was a honeycomb ceramic burner originally designed by Vivek Khanna for his study of flame dynamics. (Khanna et al., 2000) The honeycomb burner provides a good approximation to a 1-D flame environment and as such can be modeled completely with relative ease compared to the Bunsen type burner.

Methane was used in both burners as the fuel because natural gas, the fuel used in ultra-lean premixed gas turbines, is primarily made up of methane. Another important reason for the choice of methane is the relatively high reliability of the reaction mechanism available for methane, GRIMECH 3.0 (Smith et al., 1999). An unreliable reaction mechanism limits the accuracy of the modeling effort.

## 2.2 Bunsen Type Burner Setup

### 2.2.1 Purpose of of Bunsen type burner setup

The Bunsen type burner experimental setup was designed to provide a steady burning environment for the flame so that accurate, repeatable global mean chemiluminescence measurements are possible. The Bunsen type flame was chosen for the experiment because of its relatively complex stabilization mechanism. The Bunsen type flame itself however is still laminar and therefore lends itself for the study goals given above in Section 1.4.

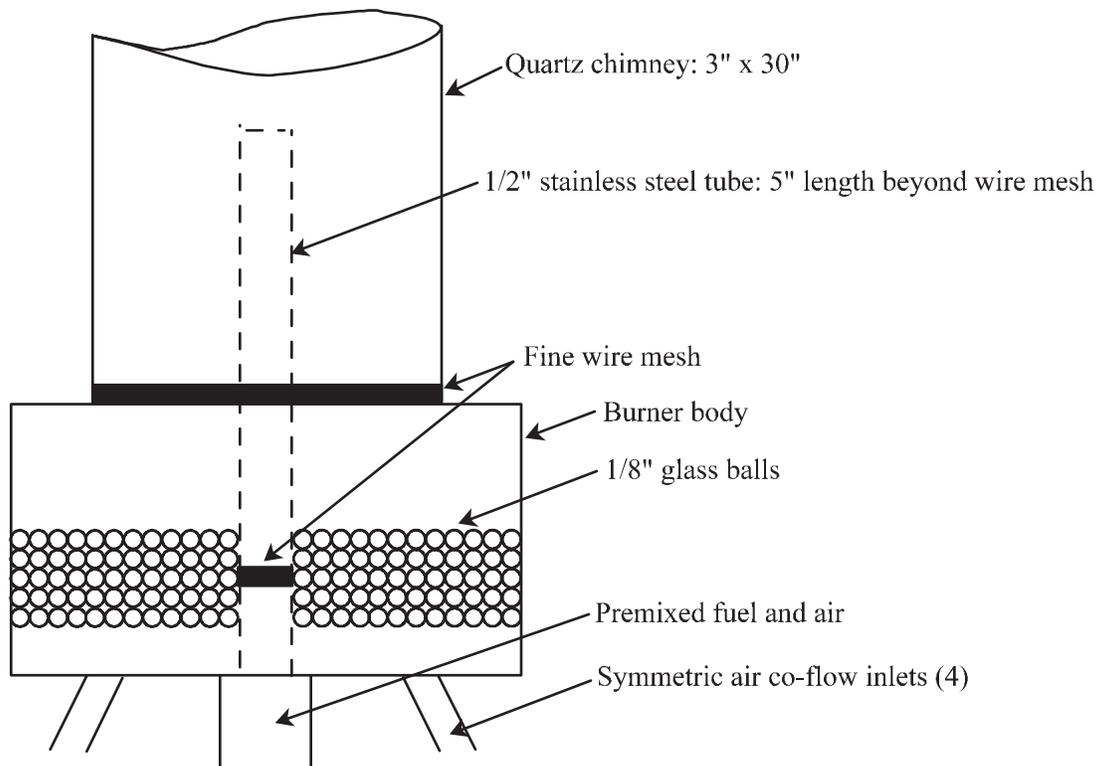
## 2.2.2 Bunsen type burner description

The Bunsen burner is shown schematically in Figure 2.1 and in a photograph in Figure 2.2. The flame is stabilized on a half inch stainless steel tube surrounded by a 30 inch long quartz chimney. Air co-flow is added in the annular area between the stainless steel tube and the quartz chimney to aid in flame stabilization. The purpose of the quartz chimney is to protect the flame from ambient air fluctuations (drafts, etc.). The co-flow inside the quartz chimney is required because the flame does not generate enough momentum on its own to carry out hot combustion products, a deficiency which leads to flame extinction. Even with co-flow, the flow inside the quartz chimney is strongly buoyancy driven, however the flame is stable.

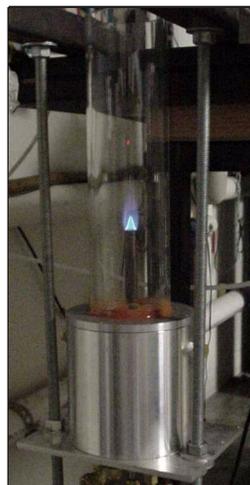
The co-flow is introduced to the burner-body by four copper-tube injectors. A two inch layer of eighth inch glass beads serves to make the co-flow circumferentially uniform. The co-flow is further conditioned using a fine wire mesh. The premixed air and methane gas flow through the half inch stainless steel tube that penetrates the Bunsen burner body. A fine wire mesh is mounted inside the stainless steel tube as well to serve as flow conditioner and flame arrester. Both, burner body and stainless steel tube were leveled prior to any experiment to assure the two flows were as parallel and vertical as possible. Non-vertical alignment leads to a burning asymmetry since the flow is strongly buoyancy driven.

## 2.2.3 Bunsen burner instrumentation

The Bunsen burner setup requires control of three flows: air co-flow, combustion air flow and methane gas flow. The air co-flow is controlled using a low-flow pre-calibrated rotameter. The combustion air and methane gas flows are each controlled using fine needle valves. The combustion air and methane gas flows are measured using Hastings Series HFM 200 mass-flow meters. The mass-flow meters have better than 2% accuracy and a precision better than 0.5%. The air flow-meter has a measurement range of 0-7.5 SLPM (referenced to 273 °K). The methane flow-meter has a measurement range of 0-750 SCCPM (referenced to 273 °K). The 0-5 V output



**Figure 2.1:** Schematic of Bunsen burner



**Figure 2.2:** Photograph of Bunsen Type Burner

is collected by the PC-based data acquisition system described below in Section 2.5. Chemiluminescence is collected using the lens and fiber-optic cable system described in Section 2.4.

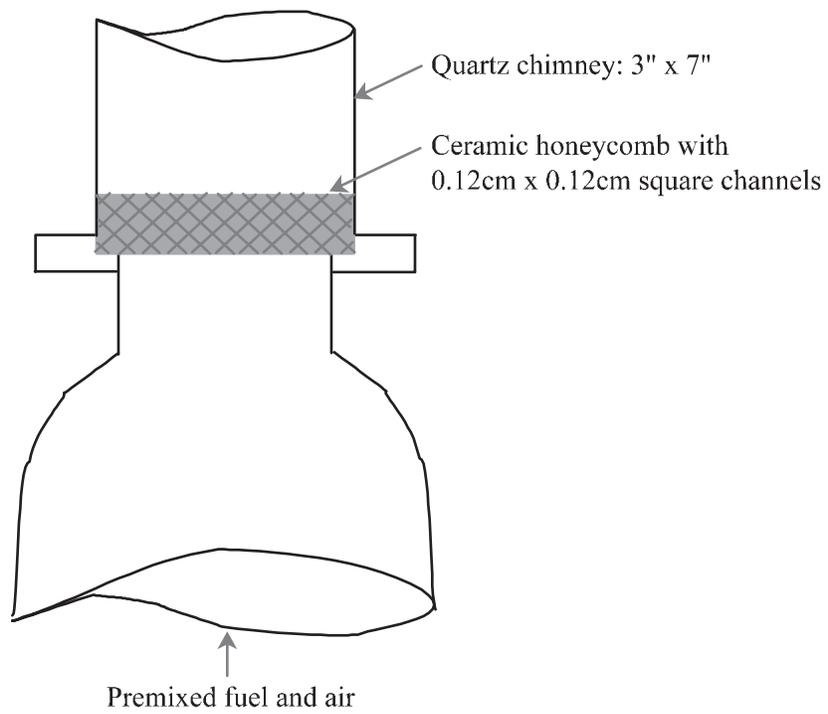
## **2.3 Honeycomb Burner Setup**

### **2.3.1 Purpose of honeycomb burner setup**

The honeycomb burner was designed to obtain a flat flame. The flat flame environment makes it possible to use a 1-D flame approximation in the modeling effort. Another interesting aspect of the honeycomb is the importance radiation plays in flame stabilization and overall flame characteristics. The interaction between combustion and radiation is important in industrial gas turbine engine combustors as well, especially in new generations of gas turbine combustors where the combustor walls are solid with ceramic lining.

### **2.3.2 Honeycomb burner description**

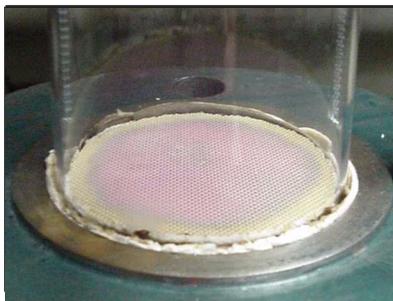
The honeycomb burner is shown schematically in Figure 2.3 and in a photograph in Figure 2.4. A short quartz chimney is mounted to the top of a carbon-steel flange. The quartz chimney has the same purpose in this burner as it did in the Bunsen burner with the difference that the chimney for the honeycomb burner is allowed to be much shorter. The reason for the shorter length requirement lies in the fact that the honeycomb burner generates more heat and unsteady recirculation zones at the exit are therefore considered less likely. Embedded in the flange is the ceramic honeycomb. The honeycomb has a thickness of half of an inch. The channels of the honeycomb are 1.2 mm square with a wall thickness of 0.1 mm. A close-up photograph of the honeycomb is shown in Figure 2.5. A bell-reducer is welded to the carbon steel flange. The narrowing flow area allows the flow into the honeycomb to be more evenly distributed across its face. Upstream of the bell-reducer, the premixed air and gas are injected uniformly across the large cross-section.



**Figure 2.3:** Schematic of Honeycomb burner



**Figure 2.4:** Photograph of Honeycomb burner



**Figure 2.5:** Photograph of Honeycomb material

### **2.3.3 Honeycomb burner instrumentation**

The honeycomb burner air and methane gas flows are controlled using rotameters. The measurement of these flows is performed by another pair of Hastings Series HFM 200 mass-flow meters. The air flow-meter has a measurement range of 0-30 SLPM (referenced to 273 °K). The methane flow-meter has a measurement range of 0-1.5 SLPM (referenced to 273 °K). The 0-5 V output is collected with the data acquisition system described in Section 2.5, the same system also used for the Bunsen burner discussed above. The optics system used to collect chemiluminescence data on the honeycomb burner has nearly the same components as the system described above for the Bunsen burner. Due to the larger surface area of the honeycomb flame, however, a fiber-optic cable with a 1 mm core has to be used. The optical system for both burners is described in detail in Section 2.4.

## **2.4 Optical System Setup and Design**

### **2.4.1 Purpose of optical system**

The optical system is an ensemble of optical components that enable the measurement of flame chemiluminescence. The optical system was designed and implemented initially only to collect an integrated light signal originating from all of the flame. In the design process however, the possibility of accurate local, spatially resolved

chemiluminescence measurements was discovered. The optical system as a whole is discussed in this section along with details on the lens system used. Other components such as the photomultiplier-tube and monochromator are described in greater detail in separate sections, Section 2.7 and Section 2.6, respectively.

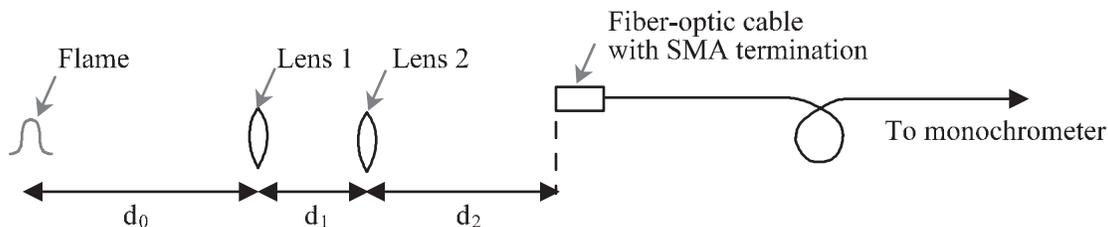
### 2.4.2 Design method used for optical system

The chemiluminescence from the flame needs to be collected, transported filtered and then measured. The measurement of the chemiluminescence intensity is performed by the photomultiplier-tube. (See Section 2.7) The filtering of the light collected from the flame is performed by a diffraction-grating monochromator.(See Section 2.6) Transport of the light signal is accomplished using a fiber-optic cable. The chemiluminescence is collected using a lens system, designed to image the flame onto the fiber-optic cable end.

Of the phases of light measurement described above, the lens system design required the most attention. The challenge originates from the fact that the fiber-optic cable diameter is only 200  $\mu\text{m}$  and the object diameter (for the Bunsen type flame) has a diameter of over 0.5 in. The image of the flame has to be de-magnified greatly to fit onto the fiber-optic cable.

The two-lens system that is used to accomplish the feat is shown schematically in Figure 2.6. Using the thin-lens approximation, basic optical equations were used to obtain expressions for the percentage of light collected from each differential element of the flame surface. The derivation of the equations is given in Appendix C. In the calculation, the flame was assumed flat (with no depth), which can be justified by demonstrating that the flame height is much smaller than the distance from the flame to the first lens (i.e. a large ratio of object distance to object height).(Hecht, 1987) Other assumptions for the flame chemiluminescence were that the chemiluminescence can be considered diffuse and that the flame is transparent to the chemiluminescence (i.e. the flame does not absorb any of the emitted radiation). Both assumptions have been used frequently in flame chemiluminescence work starting with Clark (1958).

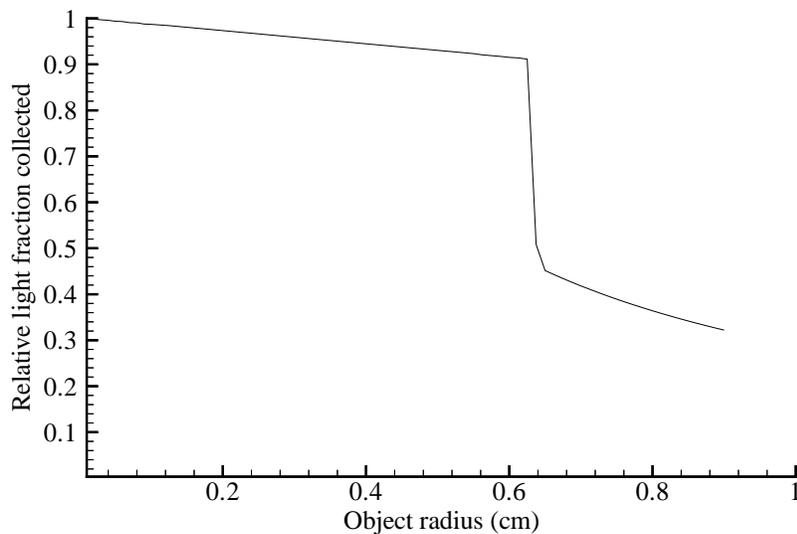
For a given set of  $d_0$ ,  $d_1$ ,  $d_2$  and object height (flame diameter), the variation



**Figure 2.6:** Schematic of optical system

of light collected from each differential element of the flame surface can be plotted against the radial location of the differential element. The variation is shown in Figure 2.7 for the configuration used in global chemiluminescence measurements on the Bunsen burner. The percentage shown is relative to the percentage of light collected for the center of the flame. The steep drop-off observed at 0.65 cm indicates that much less light is collected from outside this radial distance compared to what is collected inside that distance. Since optical systems are reversible, providing a diffuse light source at the exit of the fiber-optic cable will generate a light spot of relatively even luminous intensity with a radius of 0.65 cm at the specified object distance. The reason a spot is observed is the steep drop-off observed in Figure 2.7. The light spot indicates the weighting that will be given to incoming chemiluminescence radiation from the flame inside the spot. Chemiluminescence originating from beyond the spot is essentially ignored and chemiluminescence originating from inside the spot is given an even weighting whether the radiation is originating from near the edge of the spot or the center of the spot.

The design method just described can be easily adapted to designing the optical lens system to measure integrated chemiluminescence from the honeycomb burner as well as the lens design to perform spatially resolved chemiluminescence measurements. The configurations will be discussed in detail in Section 2.4.4.



**Figure 2.7:** Radial variation of percentage of light collected from a differential element of the flame

### 2.4.3 Optical system hardware

The actual implementation of the designs calculated using the method outlined in Appendix C above involved various optical components. Optical posts and items of this nature will not be included in the description although they were certainly necessary in the implementation. The lenses used were 1 in (2.54 cm) diameter fused-silica lenses to allow transmission of near uv wavelengths of light. The focal length of the lenses used in global chemiluminescence measurements for both burners is 1 in (2.54 cm). The lenses used in local chemiluminescence measurements have focal lengths of 25 cm and 50 cm.

The fiber-optic cable used for Bunsen burner chemiluminescence measurements is a 200  $\mu\text{m}$  core diameter fused-silica fiber-optic cable with a numerical aperture of 0.2. The cable has SMA-type terminations on both ends. The fiber-optic cable used in the honeycomb measurements has a 1 mm diameter fused-silica core with a numerical aperture of 0.48, again with SMA-type terminations on both ends.

The fiber-optic cable is mounted to a Newport Series fiber-optic positioning module. The FPR-2 allows translation along the three cartesian axes and rotation

about x- and y-axes, where the x- and y-axes form the plane of the burner surface.

For global chemiluminescence measurements, the lenses are mounted in 1 inch lens-holders that are bolted together, to achieve the small separation distance required by the optical design chosen. For local chemiluminescence measurements, the lenses are mounted in the same lens-holders but each is attached separately to the optical rail.

On the measurement end of the fiber-optic cable, the cable is attached to a collimating-beam lens. The collimating-beam lens attempts to gather all of the light exiting from the fiber-optic cable and align the light beams to be parallel with one another on exit of the lens. Although the lens is not perfect, no particular wavelength of light or light origin is more affected than another, so that the loss is non-wavelength dependent and can be lumped together with the chemiluminescence from the flame that is not collected in the first place. Losses and wavelength efficiencies in the optical system are discussed at length in Section 4.2.

Upon exit from the collimating-beam lens, the light enters the monochrometer. At the exit of the monochrometer, the photomultiplier-tube outputs current proportional to the incoming light intensity. The monochrometer is described in greater detail in Section 2.6; the photomultiplier-tube is described further in Section 2.7.

#### **2.4.4 Final design of optical system**

Table 2.1 shows the choice of the variables for each of the measurement configurations used in the experimental study. For both types of global chemiluminescence measurements, the two lenses and the entrance to the fiber-optic cable are very closely spaced, whereas the spacing in the case of the local chemiluminescence measurements, the two lenses and the entrance to the fiber-optic cable are much further apart. Note also the low object to lens distance for these types of measurements. The assumption that the ratio of object distance to object height is large is not nearly as valid for local chemiluminescence measurements. The use of the local chemiluminescence measurements is, however, at this point purely illustrative and therefore must not be scrutinized at the same level as global chemiluminescence measurements.

**Table 2.1:** Optical system distances (ref. Figure 2.6)

Measurement type	$d_0$ (cm)	$d_1$ (cm)	$d_2$ (cm)
Global - Bunsen	103.0	1.0	0.5
Global - honeycomb	64.0	1.0	0.5
Local - Bunsen	34.0	10.0	15.0

## 2.5 Data Acquisition System

### 2.5.1 Purpose of data acquisition system

The data acquisition system is responsible for collecting and storing most of the relevant information in the experiment. The data acquisition system takes an incoming data stream, interprets it (completely in some instances), organizes the data and then writes the data to a formatted file, for easy post-processing and further evaluation.

### 2.5.2 Description of data acquisition system

The data acquisition system used in the study is PC-based. The hardware used varies for different experiments, but the software driving the data acquisition is the same in all cases.

#### LABVIEW

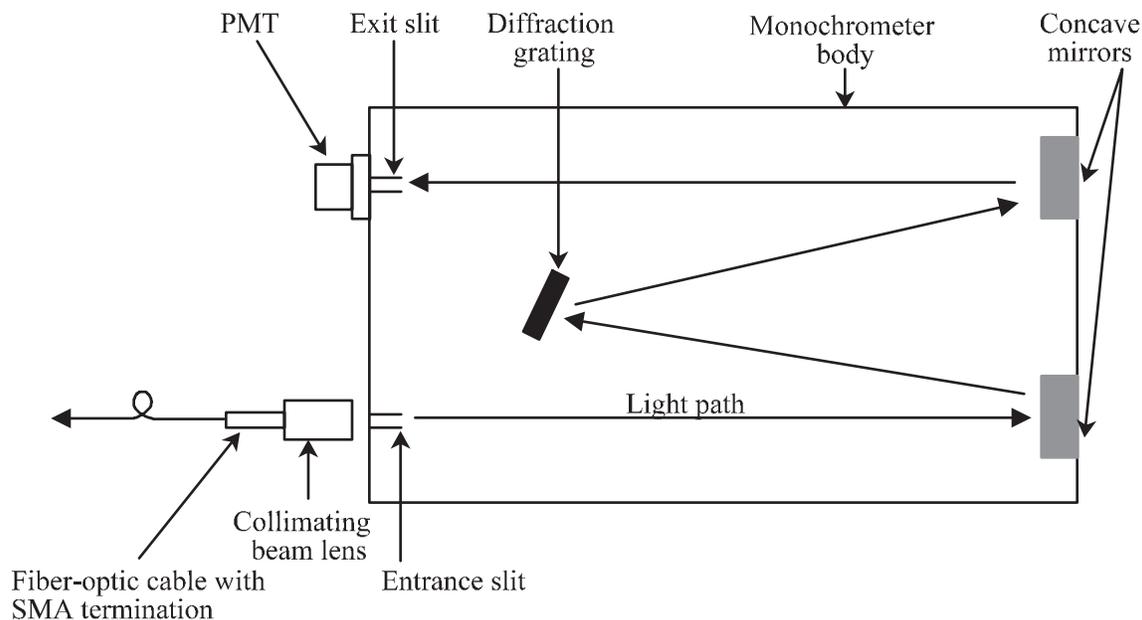
The LABVIEW graphical programming language by National Instruments (National Instruments, 1996) is used in all cases to set up the data acquisition task and then process the data collected on the A/D data acquisition boards. There are several advantages to using LABVIEW compared to more primitive low-level C programming. LABVIEW handles the management of large data chunks internally, and the programmer no longer has to perform these tasks explicitly. LABVIEW also allows the programmer to include a very easy-to-use user interface.

The front-panel, as this interface is called, may contain buttons for program control or display important data. For the mass-flow meters, for example, the front-panel specifies the data acquisition board to be used and the flow-ranges of the particular flow-meters (a.o.). The front-panel also displays the air flow-rate, methane gas flow-rate and the resulting equivalence ratio of the mixture. The result is the possibility of creating what could be called a virtual instrument. (All LABVIEW program files therefore have the extension \*.vi) Several such instruments were created to optimize the efficiency of data collection. Specific programs and their use are described in greater detail in Chapter 3.

### **Data acquisition hardware**

The mass-flow rates are in all cases collected using the SC-1000 (National Instruments) simultaneous sample and hold (SSH) board in conjunction with the AT-64E (NI) A/D conversion board. The A/D conversion on the AT-64E has 16 bit resolution. Global and local chemiluminescence measurements are also collected using this device. Scans of the flame radiation emission spectrum however are collected using a Data Translation 2801-A type board, which is more easily configured for external triggering. The 2801-A board has a 12 bit A/D converter. To interface the Data Translation board to LABVIEW, the special DTV-LINK software was installed. DTV-LINK supplies National Instruments analog routines for use with Data Translation data acquisition boards.

In all cases, the data acquisition boards are configured for unipolar differential input. Chemiluminescence signals on the SC-1000 are collected without additional signal conditioning. Signals collected on the 2801-A are most commonly collected using the 0-2.5V input range (corresponding to a gain of 4). Sampling rates and other data acquisition parameters are described further in Chapter 3.



**Figure 2.8:** Schematic top-view of the monochromator with attached hardware

## 2.6 Monochromator Setup

### 2.6.1 Purpose of monochromator setup

The monochromator is an integral part of the experimental setup as it is the component responsible for filtering out the light with the desired wavelength. The monochromator allows the investigation of an entire spectrum of wavelengths.

### 2.6.2 Description of monochromator

The monochromator is shown in a schematic top view in Figure 2.8. The monochromator is a Jarrel–Ash 0.5 m Ebert diffraction grating scanning monochromator, model 82-020. (Serial#: 50085) The grating installed in the monochromator is etched for 400 nm. The etching wavelength is described further in Section 4.2.1. The monochromator is equipped with entrance and exit slit-width micrometers for precise control of both slit-widths. The slit-width determines how much light enters and exits the monochromator as well as the wavelength resolution of the monochromator.

The narrower the slit-width is set, the better the monochrometer resolution becomes.

Once the light has entered the monochrometer, it is collected and further collimated by a concave mirror. The mirror sends the light to the diffraction grating. The diffraction grating reflects the light of different wavelengths at different angles. Some of the light hits yet another concave mirror which reflects the light onto the exit slit. Turning the diffraction grating causes the concave mirror to reflect light of a different wavelength onto the exit slit.

The diffraction grating is turned by a manual crank or a motor that is connected to a sine-bar. The sine-bar is used to linearize the relationship between the motor or crank rotation and the center wavelength in the exit slit. The tedious wavelength calibration procedure is described fully in the monochrometer manual. (Jarrel-Ash, 1971) The monochrometer can be set to scan through a range of wavelengths at different speeds using the motor. The motor speed is very precisely calibrated to make it possible to associate time with wavelength through the given rotation-speed. Section 3.6 contains more details about how these features are used in experimentation.

## **2.7 Photomultiplier-tube**

### **2.7.1 Purpose of photomultiplier-tube setup**

The photomultiplier-tube (PMT) converts incident light flux to a linearly proportional current. The PMT allows the quantitative measurement of light intensity and as such forms a central part of the experimental setup.

### **2.7.2 Description of photomultiplier-tube setup**

The PMT used in the study is the Hamamatsu R955 with fused-silica windows for uv light intensity measurements. The 955 is among the most light sensitive PMTs available today. The PMT's photocathode collects incoming photons (particles of light) and emits electrons in direct proportion to the incoming light flux. The emitted electrons impact the first dynode stage. The dynode acts as an electron multiplier,

emitting multiple electrons for each incident electron. Several dynode stages are arranged in series, to eventually amplify the electron flux to the extent that a current can be measured.(Engstrom, 1980) The 955 has ten dynode stages. In order for these processes to occur, the PMT must have a large DC-voltage applied to it. The 955 is operated at 1000V.

The PMT performs very well in dynamic applications with a frequency response whose cut-off is in the GHz range. The PMT is however plagued by what is called 'dark-noise'. Dark-noise results from the spontaneous (not caused by incoming light) emission of electrons by the photocathode or any of the dynode stages. Dark-noise is a strong function of the excitation voltage used in the PMT. The higher the applied voltage, the more sensitive the PMT, but also the more dark-noise is observed in the resulting current signal.

The current signal originating from the PMT is input to a current to voltage instrumentation amplifier. The instrumentation amplifier was designed with a 5 k $\Omega$  input resistance to preserve some of the favorable dynamic characteristics of the PMT. The instrumentation amplifier is driven by two 9V batteries and is equipped with a DC-output adjustment.

## **2.8 Local Chemiluminescence Traversing Hardware**

### **2.8.1 Purpose of traversing hardware**

To accomplish reliable spatially resolved measurements, the optical system has to be traversed across the flame using a stepper-motor stage and associated stepper-motor driver and program.

### **2.8.2 Description of traversing hardware**

The optical system is mounted to a linear stage controlled by a stepper-motor. The motor can be turned in 1.8 degree increments (200 steps / revolution). The stepper motor type specification is M-062-FC-4048. The stepper-motor is controlled

using two stepper-motor drivers that provide the stepper motors with the desired 1.6 V and 4.7 A signal. The stepper-motor drivers in turn are controlled by sending digital control signals through the parallel port of a PC.

The complete control of the parallel port is only possible in MS-DOS mode and so the data acquisition computer is not the same computer that controls the stepper-motors. To collect local chemiluminescence data, it is necessary to manually synchronize the stage-controlling and the data-acquiring computers as described in greater detail in Section 3.5.