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A NEW DIFFUSION FLAME BURNER AND PRESSURE VESSEL FOR HIGH PRESSURE SOOT FORMATION STUDY[§]

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1. Introduction

Soot and/or soot precursors are produced in most hydrocarbon combustion systems[1]. In engines and turbines, the presence of soot represents inefficient combustion, an environment pollutant, and a health concern. Conversely, in heat generation devices, such as furnaces and boilers, soot is beneficial for improved radiative heat transfer from the combusting gases to circulation fluids. Soot is also purposefully created in the form of carbon black for use in tires and other rubber goods[2]. Clearly soot can be both beneficial and problematic. A complete understanding of the conditions which lead to soot formation and destruction is critical for better control of its presence and form, which will enable improvements to combustion systems.

With increased environmental and health awareness and new legislation on particulate emission, *e.g.* [3, 4] it would be logical to identify the key combustion sources of particulate emission (e.g., diesel engines) and focus research efforts towards improving their performance. Unfortunately, investigations into the structure, scalar properties, and, in particular soot distributions in practical engines and turbines have proven difficult because of problems associated with measurements in these systems[5, 6]. These problems include inhibited optical accessibility and complex flame geometries, as well as the range of time and length scales inherent in such devices. When measurements have been made, it has proven very difficult to relate macroscopically observed changes in flame structure or pollutant emission to the smaller scale chemical and fluid dynamic processes which determine the behaviour of the flame[7, 8].

One solution to the problem of obtaining soot measurements in full-scale turbulent diffusion flames is to focus research on soot formation in controlled small-scale simplified experimental diffusion flame burners[8-11]. Results from such studies have been shown to be somewhat representative of soot behaviour in full-scale turbulent flames through measurements of mean soot distribution[7, 12]. As well, the relative importance of dilution, chemical additives, and flame temperature on soot formation have been investigated[10, 13-16]. Finally, studies on soot formation in controlled laboratory burners have been useful in the development of the laminar flamelet sub-models which can be used in reacting flow codes for numerical prediction of flame behaviour in full-scale combustion systems[17, 18].

Since most practical combustors operate at high pressures (20 – 80 *atm*) there is interest in understanding how pressure influences the combustion phenomena and in particular the soot formation pathways. There have been a number of fundamental studies using premixed flat flames, e.g. [19-23], counter-flow diffusion flames, e.g. [24-27], and co-flow diffusion flames, e.g. [28, 29]; however, these studies have not comprehensively addressed the issue of soot formation at high pressures.

A new collaborative study on high pressure soot formation has been initiated by the National Research Council of Canada, Combustion Research Group (NRC), the University of Waterloo (UW), and the

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University of Toronto (UT). The overall objective of the proposed research is to investigate the relationships between pressure and soot formation in a laminar annular ethylene diffusion flame for ambient pressures ranging from 1 - 80 atm. The information on soot properties will be used to improve descriptive mechanistic models of soot formation in high pressure flames. To facilitate this project, it has been necessary to design and build a versatile experimental rig. Additionally, it will be necessary to extend soot optical diagnostics appropriate for measurements of soot properties for application in high ambient pressure and high soot loading conditions.

This paper provides a preview of the new high pressure combustion facility and of progress with a new implementation of the spectral soot emission diagnostic[30] (SSE) which will be used as part of the project. Some preliminary soot volume fraction and temperature measurements obtained from the burner operated at atmospheric conditions are presented.

2. High Pressure Combustion Apparatus

2.1 Diffusion flame burner

At atmospheric conditions, diffusion flame burners have been shown to provide a good medium for soot formation studies, e.g., [8-11, 13-15, 16]. At raised pressures, the diffusion flame has again shown good flame stability as well as maintained optical and physical accessibility[28, 29, 31, 32].

The burner design developed for this study follows the design developed by Miller and Maahs[28] with which they achieved a stable flame over a pressure range of 1 to 50 atm (the upper limit was set by the pressure limit of the combustion chamber). A schematic and picture of a prototype of the burner is included in Figure 1. Clearly, the burner is very small with a fuel nozzle exit diameter of 3 mm and an air shroud diameter of 25 mm. Sintered metal foam elements are included in the fuel and air nozzles to straighten the flow and reduce instabilities. A tapered fuel nozzle improves the interfacing of the two fluids and reduces eddy recirculation[28]. Preliminary measurements reported later in this paper were collected using this prototype burner operated at atmospheric conditions.

2.2 Pressure vessel

There is a wealth of information in the literature on high pressure combustion chamber designs[20, 28, 33-41]; however, few chambers were designed for operation at 80 *atm* and of these, none match the configuration that is desired for the present work. Nonetheless, all have been considered along with additional communications with some of the researchers[42-44] in the design of the combustion chamber for the current study.

A schematic of the chamber is included in Figure 2. The chamber is composed of a cylindrical main body with internal access provided through flanges on the top and bottom. The main body is constructed out of stock materials (10 *in* Schedule 160 SS pipe with 900 *lbs* slip-on end flanges) to reduce cost and manufacturing time. The three optical ports (0, 90, and 180^{o}) are also 'off the shelf' units. Due to the high pressure requirements for the chamber and the need for accessibility, the chamber will be very heavy, approximately 700 *kg*. The burner is mounted to the base flange of the chamber, rather than being integrated into the base flange itself. This will allow for greater flexibility in future for the testing of different burner designs and experimental configurations. The combustion chamber is currently under construction and will be ready by this summer.

3. Imaging Spectral Soot Emission

3.1 Spectral Soot Emission Background

In previous CS/CI meeting, details of a spectral soot emission diagnostic (SSE) have been presented[45]. A limitation of SSE, is that numerous line-of-sight measurements are required to characterize a single height of an annular flame. This process is time consuming and labour intensive. A new version of the diagnostic, referred to as imaging spectral soot emission (ISSE) was developed which will greatly improve the speed with which flame soot concentration and temperature can be characterized. The features new to ISSE are discussed below. For details on the theory which is common to SSE and ISSE, the reader is referred to Snelling et al.[30]. In conclusion to this introduction to ISSE, some preliminary measurements obtained from the new high pressure diffusion flame burner are presented.

In brief, SSE is a diagnostic in which spectrally resolved measurements of the absolute emission intensity of soot present in flames are used to determine local soot temperature and volume fraction. The technique is a line-of-sight diagnostic and so line averaged properties are obtained; however, SSE can be applied to axi-symmetric flames by using a series of measurements through a flame at a given height. Using an inversion algorithm, the local differential emission intensity can be determined from the set of measurements. Using Planck theory and information about the soot refractive index, the local soot temperature and soot volume are resolved. For the ISSE diagnostic, we are replacing the spectrometer with an imaging spectrometer (American Holographic, HyperSpec VS15 – *f*/2, slit width: 12.5 μm, field-of-view: 15 *mm*, dispersion: 111*nm/mm,* spatial resolution 50 μm). The spectrometer entrance slit is oriented horizontally (see Figure 3) such that a set of parallel chords through a flame at a particular height can be measured in a single acquisition. Experiments which previously took several hours have been reduced to several minutes. As well, it will now be possible to obtain sufficient data to perform noise analysis of the emission spectra measurements.

3.2 Absolute calibration of the ISSE apparatus

The determination of soot concentration using the ISSE requires that the measurements be calibrated in absolute intensity units (*e.g.*, $W/m^2\ nm$). This has been achieved using a previously calibrated filament lamp. During calibration, the lamp is placed at the object plane of the imaging system (*i.e.*, at the location of the centre of the burner) and measurements are made of the lamp using the imaging spectrometer. The known emission intensity from the lamp is divided by the measured counts on the detector, thus providing a pixel dependent calibration which can be applied to subsequent measurements[30]. Since the filament lamp is less than 2 *mm* in width, of which only the centre 0.5 *mm* can be assumed to emit uniformly, while the field-of-view of the optical system is 15 *mm*, the calibration is achieved through a series of lamp measurements where the lamp position is shifted between measurements. The spectrometer calibration is created from a composite of the acquired images. An example calibration is shown in Figure 4(a). The calibration does vary across the width of the entrance slit and with wavelength. A sample image collected from a diffusion flame is shown in Figure 4(b), before calibration, and in Figure 4(c), after calibration. As is expected, once calibrated, the intensity increases with wavelength over the range of wavelengths sampled ($496\ nm < \lambda < 993\ nm$). The calibration also removes blemishes evident in the uncalibrated image.

3.3 Data acquisition, post processing, and analysis

To determine the soot volume fraction and temperatures for a given flame height, two images must be captured using the imaging spectrometer. The first is a measure of the background or ‘dark count’ of the detector and is measured before the flame is lit. The second is a measure of the flame emission at the height of interest. The background image is subtracted from the emission image and the resultant image is binned

in the horizontal (spatial) axis in groups of five pixels and in the vertical (spectral) axis in groups of eight to reduce the measurement noise. The resultant image has a spatial resolution of 120 μm per pixel and a spectral resolution of 25 *nm* per pixel. The images are converted to absolute measures of spectral emission using the above mentioned calibration routine.

A sample data set, acquired from the new high pressure burner at a height of 14 mm above the burner tip, is shown in Figure 5. In Figure 5(a), the binned data is shown for several wavelengths. It is observed that the flame is quite symmetric, as demonstrated by the good agreement between the left and right sides of the flame, and that the radius is approximately 2 *mm*. The data is inverted using an Abel inversion[30], thus returning the local emission intensity. Again, good symmetry is observed, though there is some noise on the burner centreline. Using the theory outlined in[30], the temperature is determined from a curve fit to a function of the local emission intensity. For the calculations, the refractive index function, *E(m)*, is assumed to be 0.258 for all wavelengths[30]. A statistical analysis of the precision of the line fit to the emission data is used to estimate an error in the temperature measurements (see Figure 5(c)). It is observed that the error is less than 20 *K* for radial position less than 2 *mm*. Beyond this radius, the error climbs rapidly. This is to be expected, as there is negligible emission intensity beyond the radius of 2 *mm*. The temperature measurements shown in Figure 5(d) for the left and right side of the flame are in good agreement for the region of 0.5 to 1.7 *mm*. Outside of this region, the difference is as large as 30 *K*. For radii above 1.7 *mm*, the temperature drops off rapidly. It is uncertain whether this is representative of the flame temperature, or an artefact of the technique functioning poorly at the edge of the flame. Further investigation is necessary. Soot volume fraction measurements are summarized in Figure 5(e). The regions of difference between the left and right hand side follow the differences in temperature observed in Figure 5(d) which is logical since the soot volume fraction measurement is dependent on the accuracy of the temperature measurement. It is for this reason that the edge of the sooting region is not clearly defined – the low soot temperature measurements raise the soot volume fraction measurements.

3.4 Characterization of the high pressure burner at atmospheric conditions

The ISSE technique has been applied to the prototype high pressure burner. The fuel burned is ethylene at a flow rate of 0.0726 standard litres per minute (*slpm*). The air flow rate is 9 *slpm*. The flame has been characterized at height increments of 2 *mm*, beginning at 6 *mm* below the tip of the burner. Below this height, the soot emission intensity is very low and the resulting measurements very noisy. For each measurement height, two data sets were acquired to give a preliminary indication of the repeatability of the measurements.

A summary of the measurements is included in Figure 6. The temperature measurements have been cropped to include only those regions where the measurement error was below 20 *K*. As discussed previously, the drop-off in temperature observed for some flame heights at the outer edge of the soot region are considered suspect and will be investigated further. The temperatures range between 1750 and 1975 *K* and show greater variation lower in the flame. The average temperature rises with height above the burner tip.

The measured soot concentrations show an annular sooting zone low in the flame which begins to fill in by a height of 10 *mm*. The centre is fully developed by 14 *mm*. Soot concentration drops from 14 *mm* to 18 *mm* and is negligible by 20 *mm* above the burner tip. The consistency between the two data sets, in terms of both temperature and soot concentration, is very good.

4. Concluding Remarks

The need for improved understanding of the influence of pressure on soot formation is the motivation for the study described here. A chamber and burner have been developed which will allow study of soot formation

over a pressure range of 1 to 80 *atm* in an ethylene diffusion flame. The burner has been built and preliminary measurements are provided here.

The ISSE diagnostic will allow a much faster characterization of the soot volume fraction and temperature which is integral to the soot formation study proposed. Initial measurements using the ISSE system are encouraging, despite uncertainties with the measurements at the edges of the soot region of the flame. Further study of the system is required as well as comparison with the SSE diagnostic and the 2D light attenuation by soot diagnostic.

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