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Thin Filament Pyrometry of Bio-fuels on a Counter-Flow Burner

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Abstract :

As a result of increasing greenhouse gases and decreasing petroleum supplies, new fuel sources such as bio-fuels have emerged with the potential to partially replace fossil fuels. The goal of this study is to characterize and verify the combustion and emission properties of different bio-fuels such as ethanol and propanol at different equivalence ratios. Using an electric pre-heater, the fuel is vaporized and premixed with air leading to combustion in a counter-flow tubular flat flame burner at atmospheric pressure and under laminar conditions. Thin filament pyrometry technique has been used to measure the temperature profiles across the flame. In this technique, silicon carbide fibers with the diameter of 15 μm have been used along with a blue color Schott glass filter and custom white balance to yield similar red, green, and blue intensities along the fibers. Calibration of the pyrometer was accomplished using B-type thermocouple measurements. The pyrometer calibration is valid between 1350 and 1500 °C.

Introduction :

The increase of energy demand and decrease availability of petroleum based fuels lead to alternative energy development. The use of bio-fuels arise from the need to extend energy security and diminish greenhouse gas emissions. Currently bio-fuels are used in mixtures with fossil fuels in various applications. The combustion of bio-fuels requires optimized characterization that may be used in the current and future development of chemical kinetics models, burners, combustors, and engines. In this study a laminar counter-flow burner is used to measure the temperature profile of the combustion from bio-fuel at different equivalence ratios. There are different techniques for measuring the temperature of a flame, which can be intrusive and non-intrusive. The objective of this research is to use a less intrusive optical method called thin filament pyrometry (TFP) for measuring the temperature profile. The temperature of a blackbody behaved media located in a flame was measured, using pyrometry technique in the visible field spectrum. This goal was accomplished by calibrating the pyrometer with a B-type thermocouple in certain temperature range.

Experimental Method :

a. Experimental Setup :

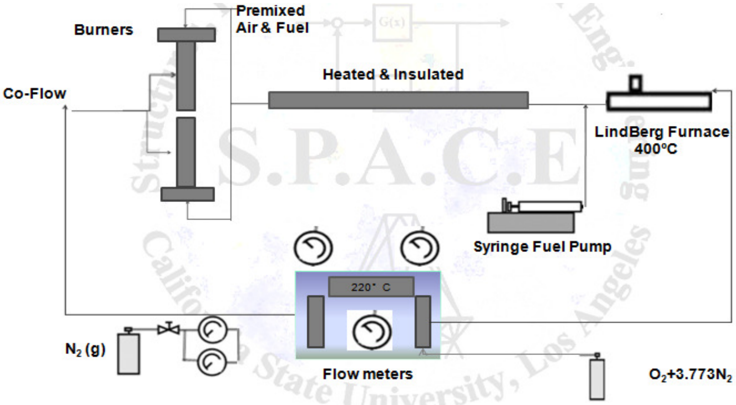

Figure 1 - Schematic diagram of the experimental setup.

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A two dimensional, axisymmetric, laminar, premixed flame was established in a counter-flow burner. A counter-flow burner was designed and built for this study where fuel and air are premixed prior to combustion. At the initial state of the experimental set up flow meters have been placed in order to control the volumetric flow rate of the air, and nitrogen (Co-flow) entering into the system. In addition, pressure gauges have been placed downstream of these flow meters in order to obtain the operating pressure of the flow meters. The flow meters were calibrated at 10 psi.

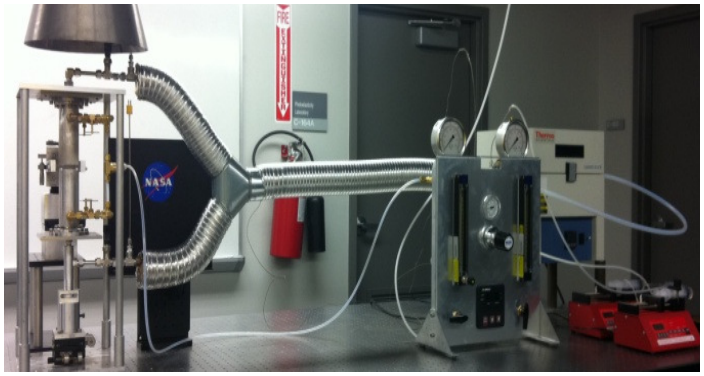

Figure 2 - Experimental set up.

The fuel injection system incorporated in the experiment includes two NE-300 syringe pumps along with a 3-way switch valve between the two pumps to achieve continuous testing.

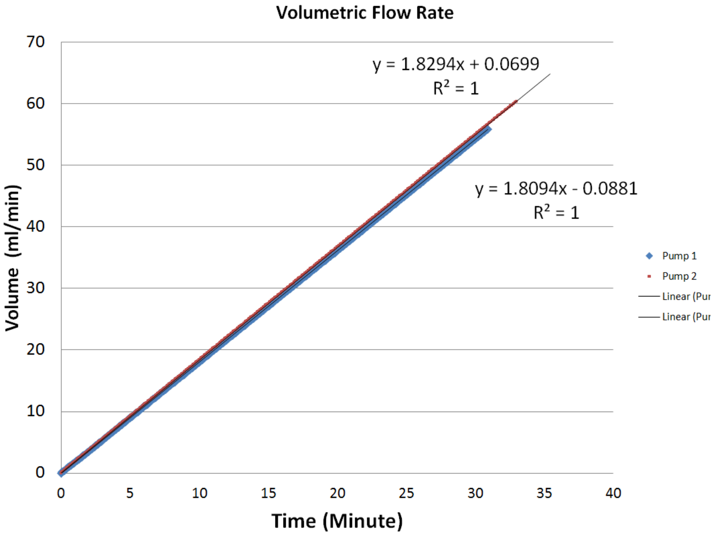

Figure 3 - Pump calibration result.

As it is shown in Figure 3, the two syringe pumps have been tested and calibrated to ensure a steady flow rate of fuel supply during the experimental process. The slope of the graph represents the volumetric fuel flow rate. The air flow rate during test is kept constant at 28.1 standard cubic feet per hour (SCFH), while the fuel flow rate was adjusted in order to obtain the desired equivalence ratio. For the calibration process, propanol was used as a fuel and the fuel flow rate was set to 1.5 ml/min.

An electric tube furnace preheats the air prior to entry into the system. The temperature of the furnace is kept at 400 °C. The hot air exiting the tube furnace vaporizes the fuel injected by the syringe pumps. The vaporization line's heat loss is minimized by high temperature resistant insulation. Taking into account that an adiabatic system is unrealistic, a heating element was incorporated in the vaporization line. This heating element is directly connected to an Omega CN2110 temperature controller. The Omega CN2110 controller has an on/off proportional integral control, a 20 amp mechanical relay. The controller receives feedback through a thermocouple input that is connected to a K-type surface thermocouple measuring the temperature of the vaporization line. By successfully fine-tuning the temperature controller the vaporization line is heated to a desired temperature with negligible temperature variation during the experiment. The temperature controller is kept at 220 °C. In order to monitor the temperature at all times during experiments, three K-type thermocouples have been added to the system. One K-type thermocouple upstream, and two downstream of the vaporization line respectively. The two thermocouples located downstream give temperature readings near the entrance of the upper and lower burners. The thermocouple located upstream gives the temperature of the air at the point at which fuel is initially introduced to our system. With the temperature recorded at the specified location, the temperature controller can be adjusted to ensure that the temperature in the system stays above the condensation point of the fuel. Thermocouple readings show that at steady state conditions, directly downstream from the furnace the temperature is 141°C, and directly upstream form the top and bottom burners the temperatures are 101°C and 94°C respectively.

High precision needle valves with an attached micrometer have been incorporated prior to both inlets of each burner. This permits precise control of the inlet flow in each burner. Aluminum housings surround each burner to ensure the flow of nitrogen in order to prevent reaction with the ambient air. This housing is termed the co-flow housing, and nitrogen is termed the co-flow gas. The co-flow connection consists of ¼ inch stainless steel tubing and elbows. Needle valves have been placed prior to the inlet of each co-flow connection to ensure a symmetric distribution of flow throughout the housing. A design that would ensure leveling at all times with the option of approximately 2 ½ inch displacement vertically has been designed for the bottom burner. Although leveling was achieved through this design, alignment was still an issue. The counter flow stand was modified by adding a 2-D linear stage, which was attached to the bottom side of the stand. This grants precise control over the positioning of the bottom burner with respect to the top burner, which in essence allows for perfect alignment.

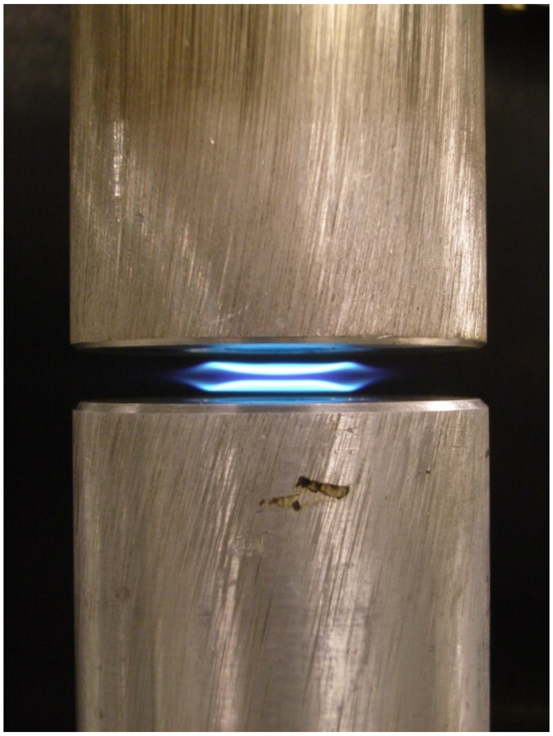

Figure 4 – Counter-flow flame

b. Thin filament pyrometry :

In this study, the method of thin filament pyrometry was chosen for measuring the flame temperature. This method provides better spatial and temporal resolution and fewer disturbances with respect to the thermocouple. In this technique, radiative emissions from the filament can be correlated with filament temperature. This technique involves a color digital still camera with a charged-couple device sensor to determine the local gas temperature from the intensity of inserted fibers glowing in a flame. In this study, a Nikon D70 camera with 3000 × 2000 pixels and 8 bits per color plane is used.

Thermocouples provide very accurate temperatures, but they are not useful in this study due to the fact that they measure temperature at only one location at a time, and it causes disturbance to the flame. A high temperature exposed junction B-type thermocouple is used for the calibration of pyrometer. Temperatures are measured in the same flame in the absence of fibers using the thermocouple. The thermocouple in this study has a diameter of approximately 200 microns. The operating temperature of this thermocouple is up to 2100 K, which is close to the adiabatic flame temperature of selected fuel. According to a study done by Maun et. al. [1, 2] raw thermocouple temperature has an uncertainty of ± 20 K. Also uncertainties in the thermocouple-derived fiber temperatures are estimated to be up to ±30 K.

The thermocouple wires were positioned perpendicular to temperature gradient in order to minimize heat conduction along the thermocouple wire. The positions of the SICO and thermocouple wire are controlled using a linear stage. A holder was designed that attaches to the linear stage and holds the SICO and thermocouple in a specific position which allows us to obtain its exact location in reference to each burner. Since the red and green intensities were greater than blue intensities in a glowing fiber, a blue color Schott glass filter was used to yield similar red, green, and blue intensities along the fibers. The International Organization for Standardization (ISO) film speed was set at 200. All automatic camera settings were disabled. Images were taken in raw format and saved in uncompressed 12 bit Nikon electronic image (NEF) format. The images were converted to tagged image file (TIF) format using IrfanView software. A MATLAB code was developed to extract the color data. Separate images were recorded with fibers and without fibers present. The MATLAB code subtracts the image without the fibers from the image with the fibers. If a color value was negative it was set to zero.

Results :

Figure 5 shows temperature measurements with a B-type thermocouple at three different equivalence ratios of 0.51, 0.74, and 0.88 for ethanol. As it is shown in Figure 5, the temperature profile is a function of the equivalence ratio. As the fuel/air mixture gets leaner (more air/less fuel), the temperature gets lower. In all three cases, the temperature profiles become flat in region between the two flames.

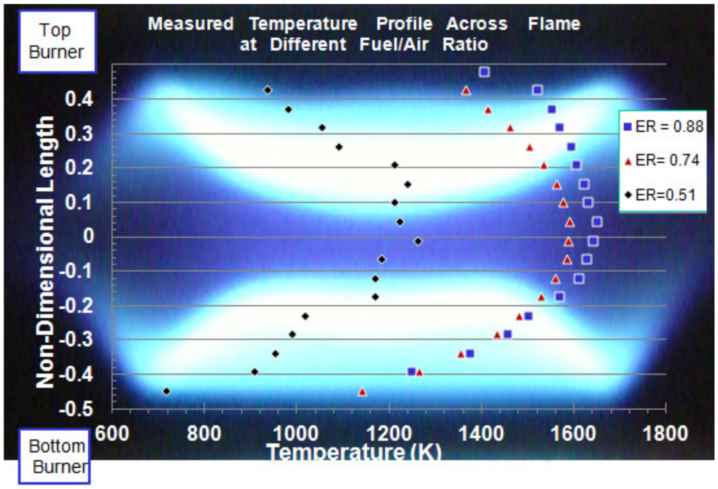

Figure 5 – Measured temperature profile across the flame. Equivalence ratios = 0.51, 0.74 ,and 0.88 .

Since it is a premixed flame the soot deposition on the thermocouple and SICO fiber is minimal.

Figure 6, 7, and 8 are the thin filament pyrometry calibration plots. It shows the measured color ratio at different temperatures. The results are shown for 1/400 and 1/640 second exposure time. Using a B-type thermocouple, temperature was measured at the same position. Thermocouple temperatures were corrected for radiative losses in order to obtain the gas temperatures and the fiber temperatures. This calibration is used to convert the fiber intensities to fiber temperatures to which radiative corrections were made to obtain the gas temperatures. The fiber intensities were obtained after image subtraction.

The thermocouple derived fiber temperature versus color ratio of Figure 6, 7, and 8 were fitted with a linear equation using the least squares approach. These linear equations are used to associate the fiber color ratios with the thermocouple derived fiber temperatures. These linear equations are expected to be valid only for the range of calibration (1350-1500 °C).

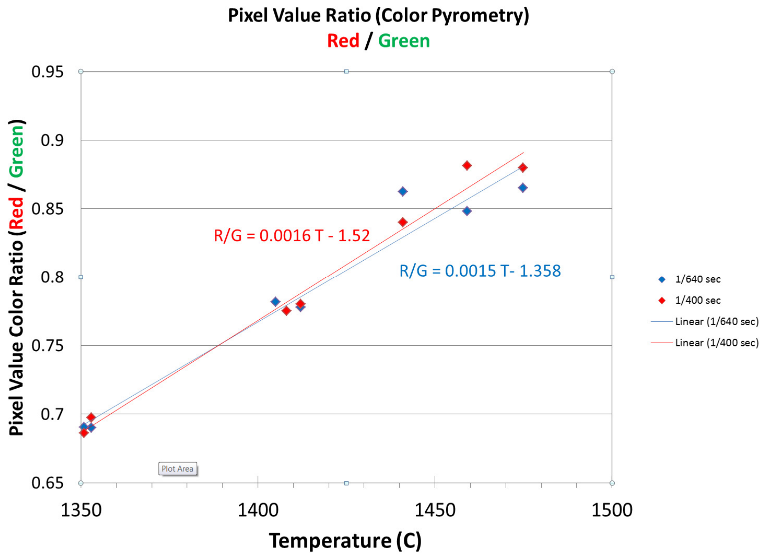

Figure 6- Thin filament pyrometry calibration (Red/Green).

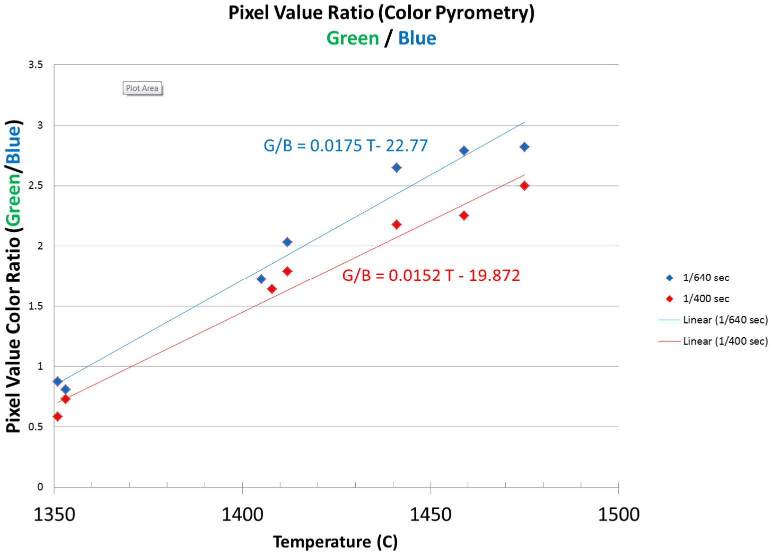

Figure 7-Thin filament pyrometry calibration (Green/Blue).

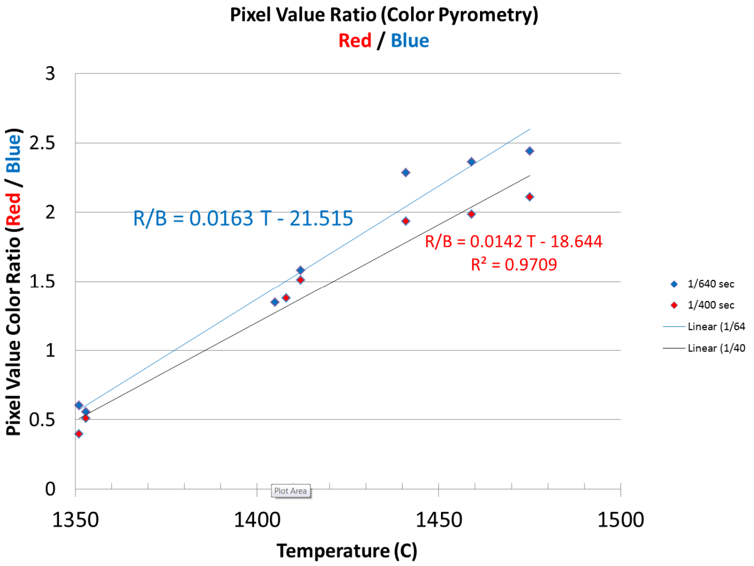

Figure 8 -Thin filament pyrometry calibration (Red/Blue).

Conclusion :

Thin-filament pyrometry was conducted in a premixed propanol–air laminar flat flame using a digital still camera. A pyrometer (Nikon D70 digital camera) was calibrated for measuring the temperature of a radiant body (SICO) behaving as a blackbody emitter in the visible spectrum.

The provided equations are expected to be valid only for the range of calibration (1350-1500 °C). Initial images of glowing fibers revealed that red and green intensities were far greater than blue intensities. Hence two color channels are outside the dynamic range of the sensor. In order to be able to use this method for higher temperatures a blue color Schott glass filter and custom white balance was used to yield similar red, green, and blue intensities along the fibers.

Work in progress:

Efforts currently underway to further validate the calibration equations include:

- Measuring SICO intensity and temperature at different equivalence ratio to validate calibration equations for wider temperature range.
- Using smaller diameter thermocouple wire to lessen disturbance of chemical reaction zone and flow field and reduce radiation loss.

Acknowledgements :

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Refrences :

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2. J.D. Maun, P.B. Sunderland, D.L. Urban Appl. Opt., 46 (2007), pp. 483–488.