Radiation Emissions from Turbulent Premixed Jet-A/Air Flames Diluted with Combustion Products

by
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A THESIS

submitted to
Oregon State University
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Honors Baccalaureate of Science in Mechanical Engineering
(Honors Associate)

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Heat flux measurements of radiation emissions from turbulent premixed flames diluted with N₂ and CO₂ were taken to identify sensitivities of radiation heat loss to diluent fraction and species. This work is motivated by the desire to better characterise radiant heat transfer in the presence of combustion products, which can influence engine component lifetime and exhaust gas composition. A Medtherm radiometer (model 64-0.2-20) was used to measure radiation heat flux from undiluted, CO₂ diluted and N₂ diluted jet-A/air flames at two concentrations of diluent. The equivalence ratio, turbulence intensity, and Reynolds number were held constant at 1, 10%, and 10000, respectively. Flames diluted with CO₂ were found to radiate more than their N₂ diluted counterparts, with total heat fluxes 50% higher at the extreme. Radiation intensity measurements were acquired using a FLIR SC6700 infrared camera to investigate fluctuations in flame emissions. To characterize the relative stability of each flame, standard deviations of each flame’s fluctuations in emissions were normalized by the average intensity. It was found that flame fluctuations increased rapidly with increasing diluent fraction, indicating changes in radiation emissions were caused by changes in both peak temperatures and combustion behavior.

Key Words: turbulent, premixed, jet-A, radiation, combustion

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

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Zohar Hoter, Author
I. Introduction

Flames burning fuel in the presence of combustion products are of significant interest in gas turbine engines. Primary applications of this type of combustion are afterburners, interturbine burners, and exhaust gas recirculation systems [1]. There is a need to characterize radiation emissions from flames because radiation can be a dominant mode of heat transfer in a combustion environment. Radiation heat transfer can influence engine component temperatures, potentially reducing hardware longevity [2], and can influence exhaust composition. There is a need for greater characterization of radiation heat transfer from turbulent premixed jet-A/air flames in the presence of combustion products, as radiation emissions from turbulent premixed flames are still relatively unquantified.

The composition of reactants and products, as well as the locations within flames of different species can have consequences for the radiation emissions. Diffusion flames burning large hydrocarbon fuels have been previously investigated by Zeuthen and Blunck [3], and the radiation intensity from CO₂, H₂O, and soot in those flames were reported. Soot and hydrocarbons radiated mainly in the flame sheet and varied with fuel composition, while CO₂ emissions were relatively consistent and distributed in the flame. Spectral intensity measurements by Brooks and Moss [4] found that CO₂ and H₂O were the strongest radiators of a methane/air flame, but that a significant contribution from soot could be expected at higher combustion pressures.

Turbulence in the flame can influence radiation heat loss, in addition to flame composition. Frank and Barlow [5] investigated CH₄/air flames with conditions varying from laminar to turbulent and collected measurements of temperature and several major combustion products. Mass fractions of CO₂ and H₂O, both strong radiators, increased with increasing turbulence. Zheng et. al. [6] investigated radiation intensities emitted from non-premixed and partially premixed turbulent flames. They found that radiation intensities were higher further from the axis of the flame where turbulent fluctuations were more prominent. Accompanying numerical calculations had difficulty predicting this behavior.

Radiation heat losses are sensitive to fuel dilution. Liquid fuels diluted with gaseous fuels showed a reduction in radiant fraction with increasing gaseous fuel dilution [7]. Frank et. al. [8] reported that when CH₄ flames were diluted with H₂, which burns with a high radiant fraction, the radiant fraction of the mixture increased. The results from Dutta et. al. and Frank et. al. indicate that dilution with other fuels can change the radiant fraction of an otherwise undiluted fuel.

Many applications exist in which combustion can occur in environments where dilution by combustion products exists. In addition to changes in flame structure and temperature through chemical kinetics [9], combustion product dilution can also change the radiation emissions from a flame, especially when CO₂ [10] and H₂O [11] are diluents. Reductions in flame temperatures due to radiant heat loss initiated by CO₂ dilution in particular was observed to reduce NOx production in diffusion flames [12]. Radiant fraction is a parameter defined as the radiation heat loss of a flame normalized by its total heat release. Frank et. al. [8] reported radiant fractions of H₂ flames with and without dilution. Hydrogen flames diluted with N₂, He, and CO were found to have radiant fractions equal to approximately 50% of their undiluted counterparts. The influence of combustion product diluents on the radiant fraction of premixed, large hydrocarbon fuel flames, however, is relatively unknown. This is significant because such measurements can be used to determine heat loss terms in numerical models, and large hydrocarbon fuels are widely used in practical systems.

With this background and motivation, the objective of this study was to identify sensitivities of the radiant fraction of a premixed, turbulent, jet-A/air flame to the level of dilution with a combustion product (i.e. CO₂) and an
inert diluent (i.e. N\textsubscript{2}). A time-averaged multi-point measurement technique was used to measure the total radiation heat loss. Mixtures of reactants and diluents were evaluated in such a way as to highlight the thermal and chemical effects of the diluent species on the radiant fraction. An infrared camera was used to evaluate the global structure of the flame and evaluate stability and fluctuations in radiation emissions due to turbulent fluctuations.

II. Experimental Arrangement

IIA. Burner

A turbulent Bunsen burner is used in this study to control the Reynolds number, turbulence intensity, and equivalence ratio of the flame. The burner was modeled after a design reported previously [13]. An overall schematic is shown in Fig. 1. Fuel (jet-A) is provided by two syringe pumps and injected through an air-assist atomizing nozzle into a pre-heated mixture of air and diluent gas. Air is preheated to ~475K. Air and diluent flow rates are controlled with thermal mass flow controllers (MKS GE250a and M100B-2000, respectively). The fuel/air/diluent mixture is maintained at ~475 K between the vaporizer and burner using rope heaters and fiberglass insulation on the plumbing. The mass flow controllers and syringe pumps have an accuracy of ±1%, and the temperatures are maintained within 10 K of the setpoint. Flow rate setpoints for each condition, along with the corresponding adiabatic flame temperature and diluent mole fraction, are shown in Table 1.

The flow passes through a layer of ball bearings for flow conditioning, then a turbulence generator to trip the flow, and finally into an annular nozzle with a methane-air pilot flame at the exit of the nozzle. The nozzle is smoothly contoured and intended to reduce boundary layer growth. It has an exit diameter of 12mm.

<table>
<thead>
<tr>
<th>Flame</th>
<th>Adiabatic Temperature (K)</th>
<th>Diluent Mole Fraction</th>
<th>Fuel Flow Rate (ml/min)</th>
<th>Air Flow Rate (slm)</th>
<th>Diluent Flow Rate (slm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No diluent</td>
<td>2352</td>
<td>0</td>
<td>8.348</td>
<td>91.7</td>
<td>None</td>
</tr>
<tr>
<td>CO\textsubscript{2} Low Condition</td>
<td>2310</td>
<td>0.041</td>
<td>8.005</td>
<td>87.9</td>
<td>2.187</td>
</tr>
<tr>
<td>CO\textsubscript{2} High Condition</td>
<td>2239</td>
<td>0.107</td>
<td>7.454</td>
<td>81.9</td>
<td>5.709</td>
</tr>
<tr>
<td>N\textsubscript{2} Low Condition</td>
<td>2311</td>
<td>0.05</td>
<td>7.930</td>
<td>87.1</td>
<td>3.965</td>
</tr>
<tr>
<td>N\textsubscript{2} High Condition</td>
<td>2216</td>
<td>0.125</td>
<td>7.095</td>
<td>77.9</td>
<td>12.650</td>
</tr>
</tbody>
</table>

A pilot flame ignites the flow as it exits the nozzle. For the pilot flame, a methane-air mixture of equivalence ratio 1 is passed through a porous medium with an average pore diameter of 20 \textmu{}m. Pilot air is supplied at 15.35 slm and methane is supplied at 1.322 slm to achieve an equivalence ratio of 1, with a heat release roughly 20\% that of the jet-A flame. The porous medium anchors the pilot flame to the nozzle exit plane. Pilot flame conditions were fixed through all experiments.
The mixtures of fuel, diluent, and air were selected with the goal of isolating chemical and thermal effects on the radiation heat release from the flames. Both undiluted and diluted flames had an equivalence ratio of 1. The quantities of $\text{N}_2$ and $\text{CO}_2$ added to two of the diluted mixtures were originally specified such that the adiabatic flame temperatures of the diluted mixtures were equivalent. Two additional mixtures of $\text{N}_2$ and $\text{CO}_2$ at higher diluent concentration were also investigated.

Figure 1: Overall schematic of turbulent Bunsen burner reproduced, with permission, from reference [14]. All units are in mm.

IIB. Heat Flux Measurements and Radiant Fraction Calculations

Radiation heat flux measurements were acquired at several locations around the flame. Corresponding measurements of the pilot flame and ambient radiation were then subtracted in order to characterize the total radiation heat transfer. The radiometer used was a Medtherm model 64-0.2-20, a Schmidt-Boelter type radiometer with a 150° viewing angle and a BaF$_2$ window. The instrument is sensitive to infrared radiation between 0.2 and 20 microns. Transmission losses through the window are accounted for in the calibration for the radiometer. The radiometer was water cooled by a closed flow loop kept at ~295 K. The radiometer was sampled at 95 Hz for 60-90 seconds. The sampling time was chosen by taking means at progressively longer sample times until that mean was consistent, indicating that fluctuations in the flame were being adequately captured.

The location of the heat flux measurements was such that they define a control volume in the shape of a cylinder. Axially, measurements are collected at a radius of 15.8 cm, and at heights every 10 cm starting at 5 cm below the nozzle exit plane and climbing six increments to 55 cm above the nozzle exit plane. Radial measurements are taken 5 cm and 15 cm from the centerline of the nozzle. A schematic of this arrangement is shown in Fig. 2.
The heat flux measurements acquired at each location are time-averaged to account for fluctuations in the flame. The measurements acquired at axial locations are then curve fitted using a smoothing spline fit. Radial points, which are only collected on one side of the flame (Fig. 2), are first mirrored about the axis of the cylinder to allow curve fitting using a one degree Fourier fit. A curve of heat flux measurements generated from measurements of the background, mainly the pilot flame and any ambient radiation, is subtracted from the curves generated from each flame obtaining a characterization of only the flame being investigated. An example of this process is shown in Fig. 3. For each flame a Riemann sum is obtained from the curve fit of the axial measurements, and multiplied by the radiometer’s calibration factor to convert from millivolts to Watts. The Riemann sum is integrated around the circumference of the control surface, giving the radiation heat transfer through the walls of the control surface. To repeat this process for the top of the cylinder, a Riemann sum is obtained from the curve fitted to the radial points and the background is subtracted as before. The resulting curve is the background subtracted radiation heat flux along the diameter of the cylinder top. One-half of this curve, representing the profile along the radius of the top, must then be integrated about a disc to obtain the radiation heat transfer through the top of the cylinder. The resulting radiation heat transfer through the top of the cylinder is then multiplied by two as the top and bottom are assumed symmetric. The true heat transfer may be higher than the value we calculated due to the fact that the bottom is significantly closer to the flame than the top. The radiation heat transfer for the top and bottom is added to the radiation heat transfer through the walls found earlier and a value for the net radiation heat transfer from the flame is obtained.
The total radiation heat transfer, $Q_r$, is then also normalized by the chemical heat release of the flame, $Q_c$, giving the radiant fraction, $X_r$. The chemical heat release of the flame is calculated as the mass flow rate of the fuel, $\dot{m}$, multiplied by its lower heating value (LHV), $LHV$,

$$X_r = \frac{Q_r}{Q_c} = \frac{Q_r}{\dot{m}LHV} \quad \text{Eq. 1}$$

Standard errors are obtained through dividing standard deviations by the square root of the number of observations. These values were found to be between 6% and 21% of the spread. A Kline-McClintock uncertainty propagation analysis was conducted and applied to the radiant fraction. Instrument uncertainty was found to be insignificant compared to precision error.

IIIC. Spatially Resolved Radiation Emissions

Spatially resolved radiation intensity data is collected using a FLIR SC6700 infrared camera. This enables comparisons of flame stability and structure between diluent conditions. Both broadband and filtered (2700 nm) radiation intensity data is collected. The 2700 nm (120 nm bandwidth) bandpass filter was selected to focus on radiation emissions from hydrocarbons in the flame. The camera collected 1000 frames at 283 Hz. The integration time was set to 0.00308 $\mu$s for broadband images and 1.2 $\mu$s for filtered images. The window was cropped to 208 x 512 pixels (roughly 120mm x 310mm) which is sufficient to capture the entirety of the flame and most of the plume. Spatial calibration was achieved by taking the interior of the pilot flame and correlating that to the diameter of the
interior nozzle (12.5 mm). The FLIR SC6700 is specified to be accurate within 1% of the reading. Once applied to the normalized values of this investigation it was determined that this (instrument error) was negligible.

III. Results

III.A. Heat Flux Measurements

The results of the radiation heat flux measurements are shown in Fig. 4, and corresponding radiant fractions are shown in Fig. 5. The undiluted flame radiated about 160W of heat energy. Dilution with 5% N₂ reduced this value by 13% and dilution with 12.5% N₂ reduced radiation emissions by 38%. CO₂ dilution of 4.2% actually raises the net radiative heat transfer by almost 4%. Radiation emissions were reduced by 6% at 10.7% CO₂ dilution. A relatively large variation in repeated measurements of each flame was observed. The spread in radiation emissions for repeated measurements of each flame was at most 30W.

There are two primary findings in these results. The first is that as N₂ diluent fraction increases, a reduction in radiation and radiant fractions are observed. This reduction is statistically significant and due to the reduction in adiabatic flame temperature. The second observation is that as dilution with CO₂ increases, an initial rise in radiation is observed. This is not a statistically significant observation, but still worth noting, and is discussed further.

A possible explanation for the increase in radiation at the lower CO₂ concentration of 4.2% stems from the interaction of CO₂ as a strong radiator and the reduced fuel flow rate with increasing diluent fraction. As CO₂ is added to the burning mixture, the fuel flow rate is reduced and adiabatic flame temperature decreases by 42K to 2310K. However, at lower diluent fractions the increase in radiation due to the presence of CO₂ is greater than the loss in radiant emissions due to the reduced adiabatic flame temperature.

The trends seen in Fig. 4, of radiation decreasing with N₂ dilution and increasing with CO₂ dilution, are also observed in Fig. 5. Radiant fraction of the undiluted flame is 0.032, which is consistent with previously reported values [15-16], and reduces to 0.029, and then 0.023 with increasing N₂ dilution. The rise with low CO₂ dilution, to \( X_r \) of 0.034, is more pronounced. At the higher CO₂ concentration the \( X_r \) value remains greater than the undiluted flame at 0.033.

Further investigation into these results, especially the increase in radiant fraction with CO₂ dilution, was desired. The products of the diluted flames were calculated using NASA CEA [17], given the adiabatic flame temperature and reactants shown in Table 1. The radiance of these products at the specified adiabatic temperature was then estimated using RadCal 2.0 [18]. RadCal estimates spectral radiation emissions of a mixture at a temperature assuming a specified homogenous path length of the mixture. This allows for more detailed investigations into species contributions to radiation, but does not account for all of the complexities in the flame. The results are shown in Fig. 6. The most prominent difference between the different mixtures is found in the CO₂ band of the spectrum. Increasing CO₂ dilution increases the radianc in this band as expected because of the strong radiating characteristics of CO₂. This is supported by our experimental results. Increasing N₂ dilution decreases radianc across the spectrum broadly, but not by the same amount that CO₂ dilution increased radianc. The higher CO₂ concentration radiates more strongly across the spectrum than any other condition, while the lower CO₂ condition is higher across the spectrum than the remaining three conditions.
Figure 4: Radiation heat flux from turbulent premixed jet-A/air flames as a function of $N_2$ equivalent diluent mole fraction, the mole fraction of $N_2$ necessary to achieve the given adiabatic flame temperature.

Figure 5: Radiant fraction as a function of diluent mole fraction.
IIIB. Radiation Emission Intensity

To evaluate flame stability, a finer increment in diluent concentration was desired. Seven concentrations of N₂ dilution and eight concentrations of CO₂ dilution were investigated. Flame stability was evaluated using the local standard deviation and average, both with respect to time. Representative averages and standard deviation images are shown in Fig. 7. The maximum standard deviation along the centerline of each flame was then normalized by the maximum average intensity along the center of each flame. Normalized fluctuations in the radiation intensity emitted by the flame are shown in Fig. 8.

The undiluted flames show higher peak radiation intensities than their diluted counterparts, about 40% higher than with CO₂ dilution and 50% higher than with N₂ dilution. The maximum average intensity and standard deviation values of the CO₂ diluted flame are about 50% greater than the N₂ diluted flame. The undiluted flames appear to have a shorter length, and appear closer to the burner exit than the diluted flames. The undiluted flames also show higher fluctuations further from the centerline than the diluted flames.
Figure 7: Images of averaged intensities and standard deviations for several different flames
Flames with no dilution have normalized fluctuations near 0.17. There is no increase at N\textsubscript{2} equivalent dilution of 0.021. Normalized fluctuations increase roughly linearly from N\textsubscript{2} equivalent dilution of 0.021 to about 0.3 at N\textsubscript{2} equivalent dilution of 0.18. The CO\textsubscript{2} diluted flames show slightly higher normalized standard deviations. Note that increasing diluent fraction has a strong effect on the normalized standard deviation. The most diluted flames had normalized standard deviations twice as great as the undiluted flame.

These results indicate that there are significantly greater normalized fluctuations in the radiation intensity emitted by a flame with a high diluent concentration than a flame with lower diluent concentration or no dilution. The similarity of the normalized values, despite the differences in radiation emissions between CO\textsubscript{2} diluted flames and N\textsubscript{2} diluted flames is interesting as it shows that the fluctuations depend more on the diluent concentration than the diluent. This is attributed to the flames becoming less stable, and as a result larger fluctuations between air, fuel, and diluent are present. Continued increasing diluent concentration could possibly lead to instabilities in the flame and ultimately tip quenching.

**IV. Summary and Conclusions**

Measurements of radiation emissions from turbulent premixed jet-A/air/diluent Bunsen flames were conducted using a radiometer and an infrared camera. The effect of dilution with CO\textsubscript{2} and N\textsubscript{2}, two gases commonly found in exhaust products, were investigated at different concentrations of dilution. Discrete radiometer measurements were extrapolated and integrated over a control surface to obtain a total radiative heat flux of the
flame at an undiluted condition and two mass fractions of dilution. Radiation intensity measurements of emissions from the flame were acquired. Average intensity normalized standard deviations of fluctuations were compared over a wide range of diluent fractions to investigate fluctuations within the flame.

The primary results of the heat flux measurements are that \( N_2 \) diluted flames were found to radiate significantly less than their \( CO_2 \) diluted counterparts, as expected. Changes in radiative heat transfer were also found to be more sensitive to increasing dilution with \( N_2 \) than \( CO_2 \). Variations up to 30W (19%) were observed in repeated measurements of the flame under the same diluent condition. \( N_2 \) diluted flames were also found to have lower radiant fractions than their \( CO_2 \) diluted counterparts. Notably, there is evidence that flames diluted with low levels of \( CO_2 \) (0.041 mole fraction) radiate more than their undiluted counterparts, and these findings are supported by calculations. Radiation intensity measurements of the flames found little difference in the intensity normalized standard deviations of the flames with respect to diluent. It was observed that normalized standard deviations increased with increasing diluent fraction.

V. Acknowledgments

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VI. References


