Scalar Measurements in Bluff Body Stabilized Flames using Cars Diagnostics

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Abstract

Measurements of mean and rms temperature fluctuations were performed in confined turbulent premixed methane-air flames, stabilized on a conical flameholder. A CARS system was used for these measurements. These tests employed flameholders of different blockage ratios (13% and 25%), and mixtures with different equivalence ratios (0.56, 0.65, 0.8, and 0.9) and approach turbulence intensity (2%, 17%, and 22%).

It was found that the recirculation zone closely resembles a perfectly well-stirred reactor. Blockage ratio, equivalence ratio, or approach turbulence intensity did not alter the scalar field. The turbulent flame structure enveloping the recirculation zone comprises: (i) an ignition/thin flame region in the vicinity of the flameholder base, (ii) a reacting shear layer region of large-scale coherent structures, and (iii) a thick flame region where entrainment is the dominant mechanism. Finally, analysis suggests that the scalar gradient-diffusion relationship is valid and areas of non-gradient diffusion, if any, are probably small.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>BR</td>
<td>blockage ratio</td>
</tr>
<tr>
<td>C</td>
<td>reaction progress variable $\left( T - T_u \right)$</td>
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<tr>
<td>$C_t$</td>
<td>rms temperature $\left( \frac{T - T_t}{T_u - T_t} \right)$</td>
</tr>
<tr>
<td>$d^t$</td>
<td>base diameter of conical stabilizer</td>
</tr>
<tr>
<td>I</td>
<td>approach axial turbulence intensity $u^a / U_a$</td>
</tr>
<tr>
<td>L</td>
<td>length of the recirculation zone</td>
</tr>
<tr>
<td>$r^t$</td>
<td>radial direction</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
</tr>
<tr>
<td>U, V</td>
<td>mean velocities in axial and radial directions</td>
</tr>
<tr>
<td>$u, v$</td>
<td>fluctuating velocities in axial and radial directions</td>
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Superscripts

- mean value
- rms value

Subscripts

- annular flow
- flame
- unburned
- total, turbulent

Introduction

In designing afterburner systems and ramjet combustors, provision must be made to initiate and sustain effective flameholding in highly turbulent combustible mixtures. A bluff body is commonly used to create a recirculation zone. This zone exchanges mass and momentum with the flame surrounding it and also provides the necessary heat flux to ignite the incoming reactants. In this type of flowfield, the magnitude and nature of the scalar transport depend upon mean temperature gradients, temperature fluctuations, velocity-temperature correlations, and properties of the premixed reactants such as equivalence ratio and burning velocity. Also, knowledge of scalar transport allows accurate computation of mean reaction rate and therefore heat release, flame stability, and production of unburned hydrocarbons (UHC) and NOX.
Many years ago Longwell et al. (1953) proposed that the recirculation zone may be viewed as a perfectly-stirred reactor. However, in practical combustors, the situation of perfect homogeneity does not exist. To simulate the practical combustion process more closely, Swithenbank et al. (1980) and Pratt (1980) proposed models of "partially-stirred reactor" and "imperfect micromixing". To evaluate these models and to understand the mechanism of flame stabilization require data on turbulent scalar properties.

Measurement of flame temperature in highly turbulent, confined, recirculatory flows is an extremely difficult task. Comparatively few results are available in the literature. Lewis and Moss (1979), Shephard and Moss (1982), and Shephard et al. (1982) reported heat flux measurements in a weakly sheared unconfined and confined premixed flames. Heitor et al. (1987, 1988) measured temperature fluctuations in disk-stabilized open and confined flames. Sivasegaram and Whitelaw (1983) and Taylor and Whitelaw (1980) have presented temperature data in a step-stabilized premixed flame, and in an axisymmetric combustor respectively.

Almost all the temperature measurement reported above employed either uncompensated or compensated fine-wire thermocouples. Hence, these measurements suffer from many deficiencies as follows: (i) uncertainty in mean and rms temperatures of 120 K or more due to large wire-size (e. g., Shephard and Moss (1982) and Shephard et al., 1982), (ii) uncompensated thermocouple or one with a large time constant (100 ms or more) of the compensation circuit introduces errors in pdf measurements (e. g., Lewis and Moss 1979), (iii) uncertainty in radiation correction, catalytic effects of coatings, and heat loss to thermocouple prongs can result in the underestimation of temperature by 150 K or more (e. g., Heitor et al. 1987), (iv) flow disturbances produced by inserting the thermocouple within the flame can significantly alter the flame structure, e. g., thermocouple can act as a flameholder.

To overcome the uncertainties of thermocouple temperature measurements, we employed a Coherent Anti-Stokes Raman Spectroscopy (CARS) system. This system offers several advantages such as non-intrusive probing, high spatial and temporal resolution, good accessibility to confined flames, insensitivity to soot and particulates, and good reproducibility.

The objectives of our work were to (i) measure temperature fluctuations in and around a confined recirculation zone, (ii) study the influence of blockage ratio, equivalence ratio, and approach turbulence intensity on the scalar distribution within and around the recirculation zone, and (iii) develop an understanding of the turbulent flame structure surrounding the recirculation zone.

Experimental Work

1 Test Rig. Figure 1 shows the test rig employed for these experiments. Several stainless steel conical flame stabilizers were manufactured including two base diameters, \( d = 4.44 \text{ cm} \) and \( 3.18 \text{ cm} \) corresponding to the blockage ratios \( BR = 25\% \) and \( 13\% \) respectively. Each stabilizer was mounted coaxially inside an 8 cm x 8 cm x 28.4 cm test section with rounded corners which has four 5.64 cm x 25.4 cm cut-outs for quartz windows. This test section was mounted on a vertical combustion tunnel with a three-axis traversing mechanism. Different turbulence grids could be inserted at 5.8 cm upstream of the base of the conical bluff body. Measurements of turbulence quantities and mean wall-static pressure, which are reported by Pan et al. (1990, 1991), were performed by using a two-component Laser Doppler Anemometer (LDA) and a precision micromanometer respectively. A CARS system was used to perform independent temperature measurements.

2 Test Condition. In these experiments, premixed methane-air flames were studied. The mean annular velocity \( u = 15 \text{ m/s} \) and the Reynolds number varied between \( Re_d = 3x10^4 \) to \( 4.2x10^4 \). Zukoski and Marble (1955) have pointed out that the bluff body wake region becomes fully turbulent when \( Re_d = U d / v \geq 10^4 \). Four different equivalence ratios, \( 0.56, 0.65, 0.8, 0.9 \) were tested, corresponding to adiabatic flame temperatures of 1590 K, 1755 K, 1990 K, and 2130 K respectively. The inlet turbulence intensity level was varied from 2\% to 22\% by using different grids.

![Fig. 1 Schematic diagram of the confined flame stabilizer test facility.](image-url)
3 CARS System. The CARS optics layout is shown in Fig. 2. The laser source is provided by a Nd:YAG pulse laser with 10 ns time resolution. The frequency-doubled source green beam (532 nm) is equally divided into four parts. Two of these serve as the pump beams, while the other two pump a dye laser oscillator and amplifier. The dye laser is tuned to provide a red broad-band Stokes beam (110 FWHM) centered at 607 nm. The red Stokes beam and the two green pump beams are then focused together by a 25-cm focal length lens in a BOXCARS configuration. A 25-µm-x-250-µm measuring spot size is achieved. The CARS signal is collected by a Spex 1702 spectrometer, 1024 element DARSS camera, and Tracor-Northern multichannel analyzer. The raw data are processed by a MODCOMP minicomputer.

From the raw data, the temperatures are determined by comparing the actual nitrogen spectra to the calculated spectra, using a least square fit. The calculation of a nitrogen CARS spectrum requires knowledge of the instrument slit function. This slit function is normally determined at a known temperature and then assumed to be the applicable function at all temperatures, independent of the optical path which varies with density or temperature gradients. However, the constant slit function assumption can lead to serious error in temperature determination. Heneghan et al. (1991) have developed a simple method of determining the slit function from the collected data at the actual temperature and turbulence level by applying the principle of local thermodynamic equilibrium. In general, the mean temperature is measured for two different curve-fit weighting schemes and two different slit widths. The actual mean temperature and slit width are calculated by finding the intersection of the two lines (T vs. slit width at constant weighting). This method yields improvement in the precision of the CARS measurement.

4 Error Analysis. Both fuel flow and air flow were monitored by separate electronic flow control units to within ± 0.5% and ± 1.5% respectively. The combined error produced an uncertainty of ± 1.5% in equivalence ratio, or ± 30 K in temperature. Usually, 500 samples were taken for each CARS measurement to ensure that the error in the rms temperature was less than 10 K, while 1500 samples were taken in the flame region where the rms values were expected to be large. As shown by Heneghan and Vangsness (1990), the rms temperature is susceptible to CARS instrument noise. However, in combusting flow, the temperature fluctuations are much greater than the instrument noise and thus the measurement precision (reproducibility) is good. Overall, we estimated the CARS mean temperature measurement accuracy to be within 50 K, while the precision is well within 20 K. Unlike the LDA, CARS temperature measurements are time-averaged, without density biasing effects.

Results and Discussion

In this section we present and discuss three principal features of the temperature field, namely (i) influence of parametric variations on the temperature field, (ii) nature of temperature pdfs, and (iii) structure of the turbulent reacting shear layer. All the temperature data were made non-dimensional and plotted in the form of reaction progress variable C and C, which are relevant in developing theories of premixed turbulent combustion (for example, see Bray, 1980). In all the figures, the approach turbulence intensity I = 2% unless otherwise stated.

1 Influence of Parametric Variations. Figures 3a-b show axial and radial distributions of the reaction progress variable C and C, for BR = 25% and 13% respectively. In Figs. 3a-b, we observe that within the recirculation zone (r/d < 0.5) and near the metal base of the bluff body (x/d = 0.1), C = 0.90-0.87. Further downstream, the mean temperature within the recirculation zone is lower than the adiabatic flame temperature by approximately 5%. Also, the rms temperature fluctuation is around 5% and constant throughout. These results suggest that the recirculation zone (i) loses about 5% (or less) heat to the environment, (ii) loses approximately 5%-8% heat to the metal base of the bluff body, and (iii) is almost, but not perfectly well-stirred. These observations are also generally valid for the rest of the data presented in Figs. 4 and 5. Now, effects of parametric variations on scalar field are discussed.

(a) Blockage Ratio: Figures 3a-b show the influence of approximately doubling the blockage ratio on mean and rms temperature fluctuations. It is observed that the blockage ratio does not affect either the mean or the rms temperature. Since Pan et al. (1991) have reported no significant change in the size of the recirculation zone, it is clear that the flame position, and therefore the scalar field, remain unaltered. In practical afterburner systems, the blockage ratio mainly influences the drag of the bluff body. For the same annular velocity, a large bluff body confined in a combustor has less mass flow of reactants taking part in combustion. This increases residence time for complete combustion, but also decreases the total heat released downstream of the recirculation zone. Clearly, combustor pressure loss, reactant mass flow,
Fig. 3 Radial profiles of non-dimensional mean temperature (reaction progress variable) and rms temperature plotted to illustrate the influence of blockage ratio on scalar fluctuations. These measurements are for a 45 degree conical-body, at \( U = 15 \text{ m/s} \) and \( \phi = 0.65 \), (a) \( \text{BR} = 25\% \), \( L / d = 2 \), (b) \( \text{BR} = 13\% \), \( L / d = 2.37 \).

Fig. 4 Axial and radial profiles of non-dimensional mean temperature (reaction progress variable) and rms temperature plotted to illustrate the influence of equivalence ratio on scalar fluctuations. These measurements are for a 45 degree conical-body, \( \text{BR} = 25\% \), \( U = 15 \text{ m/s} \), (a) centerline profiles (b) radial profiles for \( \phi = 0.8 \), \( L / d = 1.4 \), (c) radial profiles for \( \phi = 0.56 \), \( L / d = 2.37 \).

and combustor size are just some of the factors that determine a suitable value of the blockage ratio for use in a given practical application.

(b) Equivalence Ratio: Figures 4a-c illustrate the effects of equivalence ratio on mean and rms temperatures. In Fig. 4a, the centerline temperatures are plotted. These data show that the rms temperature fluctuation is nearly constant at 5%, but the mean temperature within the recirculation zone gradually increases with downstream distance. Also the reaction progress variable \( C \) increases with decreasing equivalence ratio from 0.90 to 0.56. At least two factors contribute to this trend: (i) a decrease in the heat loss to the metal base of the bluff body with decreasing temperature difference from 1870 K to 1500 K, and (ii) a complete conversion of entrained reactants to hot products within the recirculation zone.

In Figs. 4b-c radial temperature profiles are shown for various axial planes. The results of Fig. 4b are almost identical to those of Fig. 3a and the same explanations are valid here also. Figure 4c illustrates the results of experiments at the lean extinction limit of methane-air mixture. Specifically, we observe a rapid growth in the temperature fluctuations (\( C \) rises from 5% to 30%) for \( r/d > 0.3 \) and \( x/d = 2 \), i.e., upstream of the rear stagnation.
Fig. 5 Axial and radial profiles of non-dimensional mean temperature (reaction progress variable) and rms temperature plotted to illustrate the influence of approach turbulence intensity on scalar fluctuations. These measurements are for a 45 degree conical-body, BR = 25%, U = 15 m/s, and φ = 0.65, (a) centerline profiles (b) radial profiles for I = 22%, Lr/d = 1.1, (c) radial profiles for I = 17%, Lr/d = 1.3.

In summary, increasing the equivalence ratio (i) strongly affects the size (and specifically the length) of the recirculation zone and this modifies the velocity flowfield (Pan et al. 1991), but (ii) the scalar field is not altered in any dramatic manner for a stable flame, except through changes in the magnitude of heat losses stated above. However, at the lean extinction limit, the turbulent burning velocity of the flame is not fast enough to consume the reactants completely. This allows entrainment of fresh or partially burned reactants into the region around the stagnation point and increases the scalar fluctuations.

(c) Approach Turbulence Intensity: Figures 5a-c demonstrate the influence of increasing the approach turbulence intensity from 2% to 17% to 22%. In Fig. 5a, centerline axial distribution of temperature is shown. Within the length of the recirculation zone (x/Ls ≤ 1), increasing the approach turbulence intensity increases mean temperature but does not change rms temperature fluctuations. This can be explained by noting that Pan et al. (1991) have reported a dramatic decrease in the size, and hence also the surface area, of the recirculation zone with increasing reactant turbulence intensity and this must contribute to reducing the heat loss from the recirculation zone. Further downstream of the rear-stagnation point (x/L > 1), increasing turbulence reduces mean temperature and increases rms temperature fluctuations, both the result of accelerated exchange of mass and heat transfer between cold reactants and hot products.

Figures 5b-c show radial profiles of mean and rms temperatures. It should be noted that within the recirculation zone (r/d ≤ 0.3) values of C and C remain fairly constant. However, outside the zone (r/d > 0.3), the mean value gradually falls and the rms value rapidly increases within the vicinity of the flame. Clearly, increasing the turbulence level of the reactants increases both the heat transfer between cold and hot gases (which decreases mean temperature) and turbulent burning velocity of the flame (which increases temperature fluctuations). Again, these results appear consistent with the heat loss arguments invoked earlier.
2 Temperature Pdfs. From the radial temperature profiles of Figs. 3-5, we can calculate the mean temperature gradient \( \frac{\partial C}{\partial r} \) and the flame thickness \( \delta \). Two types of flame thickness were defined: (i) total thickness, \( \delta \), spanning the value \( C = 0-1 \), and (ii) flame front thickness, \( \delta_f \) corresponding to the range \( C = 0.5-1 \) (note: \( C = 0.5 \) implies that combustion products are present half the time and reactants are present the rest of the time at this location, i.e., this represents the mean flame position).

Figure 6 shows plots of \( \frac{\partial C}{\partial r} \), \( \delta \), and \( \delta_f \) for a bluff body with \( BR = 13\% \), over the axial distance covering the length of the recirculation zone. It is observed that the radial temperature gradient \( \frac{\partial C}{\partial r} \), which is negative throughout, rises steeply within \( x/L = 0-0.12 \) (corresponding to \( \delta = 0.54 \) mm and \( \delta_f = 0.29 \) mm) and then maintains a fairly constant value. This result shows that the ignition of reactants and the establishment of the flame by the heat flux transported from the recirculation zone are achieved within 12% of the length of the recirculation zone. Also, the flame front is extremely thin (< 1 mm). Downstream of this ignition/thin flame region, the mean temperature gradient remains fairly flat but the flame thickness continues to increase eventually to \( \delta = 7.1 \) mm and \( \delta_f = 4.5 \) mm. This suggests that entrainment is the dominant mechanism in this region and is responsible for producing the thick flame front.

Figures 7a-e show typical CARS temperature pdfs measured in the reacting shear layer around the bluff body at three different axial locations, (i) within the ignition zone, \( x/d = 0.1 \), (ii) near the vortex center, \( x/d = 0.8 \), and (iii) within the thick flame region, \( x/d = 1.5 \). These data are for a 45 degree conical-body, \( BR = 13\% \), \( U_a = 15 \) m/s, and \( \phi = 0.65 \).

In Figs. 7a-b, the two radial locations differ from one another by only 0.2 mm. These results show only one skewed peak in each pdf; (i) in Fig. 7a, the peak corresponds to the product gas temperature of 1070 K (\( C = 0.5 \)) on the hot side, and (ii) in Fig. 7b, the peak corresponds to the reactant temperature of 470 K on the cold side. This dramatic shift in the pdf confirms that the flame front is extremely thin at this axial location.

The temperature pdf shown in Fig. 7c shows a bimodal distribution with approximately equal weighting on each of the cold and hot peaks (\( C = 0.5 \)). The cold gas peak is centered corresponding to gas temperatures in the preheat zone, somewhat higher than...
the room temperature and the hot gas peak is centered near the adiabatic flame temperature. The bimodal nature of the scalar pdf indicates the presence of large-scale coherent structures within the reacting shear layer. As Spalding (1976) has suggested, these structures form as folds around the flame edge, and then grow in size downstream, entraining reactants and products and thickening the reacting shear layer.

Finally, Figs. 7d-e show temperature pdfs within the thick flame region separated radially by 1.6 mm. Both pdfs show a skewed-bimodal type of distribution with one dominant peak. The hot gas peak found in Fig. 7d is much higher than the one found in Fig. 7e, while the cold gas peak of Fig. 7e is very close to the room temperature. A finite probability of intermediate temperatures also exists in both the temperature pdfs which suggests the presence of gas in the partially burned-unburned state. Thus, the flame front structure is extremely complex comprising large-scale structures, entrainment, and stretching produced due to the necking-down of mean streamlines in the vicinity of the rear stagnation point. In such instances, the Bray-Moss-Libby model (Bray, 1980) which describes the statistics of the thin flame front, cannot be applied.

3 Turbulent Flame Structure. From the above experimental observations, a model of the turbulent flame structure enveloping the recirculation zone was developed. A schematic diagram of this model is shown in Fig. 8 and it is described below.

Turbulent combustion in the reacting shear layer is a three-stage preheat-ignition-propagation process. Near the base of the bluff body and along its edge, the flowing reactants are preheated and ignited by the heat flux transported radially outward from the recirculation zone. Within the region x/L_r = 0-0.12, ignition of the incoming reactants takes place and a thin flame that conforms to the "fast-chemistry" assumptions sits slightly oblique to the oncoming reactants. This type of flame can be successfully modeled by the Bray-Moss-Libby theory (Bray, 1980).

Downstream of this ignition-thin flame region, (x/L_r > 0.12), the temperature remains either fairly constant or decreases slightly, i.e., \( \partial C/\partial r < 0 \). This suggests that no radial heat flux is transported, and only entrainment of reactants and products is taking place downstream. In this region, large-scale coherent structures begin to grow within the reacting shear layer. These structures form as folds around the flame edge and then grow in size downstream, producing a convoluted reaction zone with many isolated pockets of hot product and cold reactant gas. These coherent bodies of gas are squeezed and stretched during their travel through the flame and the entrainment process causes their growth downstream thereby thickening the flame.

Further downstream, and in the vicinity of the rear stagnation point, the flame front is thick (~ 4.5 mm) and mass entrainment of fresh reactants is the dominant mechanism at work. In this region, large temperature fluctuations (C \( = 25\%-35\% \)) are measured as observed in Figs. 3b, 4c, and 5b-c. Such fluctuations may acoustically couple with a sufficiently long duct and produce combustion instability or rumble in practical combustors. Clearly, the relatively simple statistical description of the wrinkled thin flame front is inadequate here. Rather, the "eddy-entrainment, combustion-in-depth" process of Ballal and Lefebvre (1974) is at work. Thus, the instantaneous region of combustion is distributed throughout the time average of the combustion zone rather than being confined to a thin wrinkled laminar flame. Also, since an intermediate state of gas exists, neither the perfect-stirred reactor theory of Longwell et al. (1953) nor the characteristic time theory of Zukoski and Marble (1955) can fully describe the bluff body flame stabilization mechanism accurately. More work is required to examine these issues in detail.

Finally, within the reverse flow region of the recirculation zone, the axial heat flux is directed towards the bluff body because hot products (T > 0) are moving axially towards the bluff body (u = -ve) and cold reactants are moving axially downstream, i.e., the axial heat flux \( \mu T \) is negative. In this same region, the axial temperature gradient \( \partial C/\partial x \) is generally positive as evident from Figs. 4a and 5a. These observations support the scalar gradient-diffusion relationship of the form \( -\mu T = D_T (\partial C/\partial x) \). Outside of the recirculation zone (r/d > 0.5) and within the flame, hot products (T > 0) are moving axially downstream (+ u), i.e. the axial heat flux \( \mu T \) is positive and the axial temperature gradient \( \partial C/\partial x \) is \( < 0 \). Again this lends credence to the validity of the above scalar
gradient-diffusion relationship. Now, the radial heat flux \( \overline{\nu T} \) is always positive because reactants are preheated and ignited by the heat flux transported radially outward from the recirculation zone. Also, Fig. 6 shows that \( \partial C/\partial r \) is negative throughout. Therefore, it appears that the conventional scalar gradient-diffusion relationship of the form \( \overline{\nu T} = -D_h (\partial T/\partial r) \) is valid in this type of reactive flow-field.

Our above arguments suggesting the validity of the scalar gradient-diffusion relationship are in conflict with the scalar measurements of Shephard et al. (1982) in confined premixed flames, those of Heitor et al. (1987) in open baffle-stabilized flames, and the analysis of Libby and Bray (1981). These authors found counter-gradient diffusion effects. However, they used thermocouples with relatively large-wire sizes and it is possible that their measurements of flame temperature could have suffered from relatively large experimental uncertainties or errors discussed earlier. On the other hand, direct, laser-diagnostics-based, non-intrusive measurements of axial and radial turbulent heat fluxes are required in the future to examine in an unambiguous manner if counter-gradient diffusion exists within these type of flows. Currently, the LDA-CARS systems are being integrated in our laboratory for meeting this goal.

Conclusions

Using a CARS system, mean and rms temperatures were measured within and outside the recirculation zone produced by a conical flameholder confined in a test section and supplied with turbulent premixed methane-air mixtures. The following conclusions emerged.

(1) Measurements reveal that the recirculation zone loses about 5% heat to outside and about 5-8% heat to the flameholder base. Also, low rms temperatures (< 5%) suggest that a perfectly well-stirred reactor description of the recirculation zone is very close to valid.

(2) Blockage ratio does not affect either the mean or rms temperature fluctuations. Increasing the equivalence ratio or approach turbulence intensity increases heat losses from the recirculation zone, but does not alter the scalar field in any dramatic way.

(3) Near the flameholder base, temperature pdfs reveal an extremely thin flame front. Downstream of this, temperature pdf is bimodal and suggests the presence of large-scale coherent structures within the reacting shear layer. Further downstream, a thick flame consisting of partially burned-unburned gas states develops.

(4) The turbulent flame structure enveloping the recirculation zone comprises an ignition/thin flame region, a reacting shear layer which has large-scale coherent structure, and finally, a thick flame region where entrainment is the dominant mechanism. Analysis suggests that the gradient-diffusion relationship is valid and areas of non-gradient diffusion, if any, are probably small.

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