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A Study of the Global Differences between Axisymmetric Turbulent Free Jet Flames from a Smooth Contraction and a Pipe with Well Defined Boundary Conditions

A.S. Langman[1], G.J. Nathan[1] and P.J. Ashman[2]

[1]School of Mechanical Engineering, [2]School of Chemical Engineering
The University of Adelaide, Adelaide, SA, 5005, AUSTRALIA

Abstract

A quantitative assessment is undertaken of the global differences between axisymmetric turbulent free jet flames from a smooth contraction and pipe nozzle by measurement of the radiant fraction, mean flame length, lift-off height and blow-off. The results show that the differences in these parameters are significant. The smooth contraction nozzle produces a flame less radiant, longer and more stable flame than the pipe. It resists lift-off at higher velocities and is self-sustaining at velocities 17% greater than that for the pipe. Similarly, lift-off is prevented till a velocity 40% higher compared to the pipe. The 25% higher radiant fraction of the smooth contraction is also significant.

These results show that the trends found in previous studies [4,5] in non-reacting jets, where differences in the initial flow conditions are found to propagate throughout the flow, also apply for reacting flows. Thus the accepted approach of normalising global parameters based solely on bulk mean velocity and nozzle diameter is inadequate.

Introduction

The general behaviour of simple round jets is well established. Hawthorne *et al.* [2] developed a formula to describe flame length for all round jets employing the classical assumption of universal similarity in their mixing characteristics. Similar assumptions were employed more than 30 years later by Becker and Liang [1] who proposed refined models which also unify the behaviour of round jets. Likewise, the pioneering measurements of Kalghatgi [3] of lift-off and blow-off employ similar assumptions in their normalisation, which are reproduced in many text books, e.g. Turns [9]. All of these measurements have been performed with a single set of initial conditions, as have measurements of global emissions [8] and radiant fraction [7]. In each the tacit assumption is that the same results will occur for any round nozzle of the same diameter, e.g. for a pipe and a smooth contraction. However this assumption is yet to be tested.

Recent works [4,5] found both near and far field differences in three non-reacting round jets with different initial conditions. The existence of these far field differences suggested the possibility of global differences in reacting jets. The aim of the present study is therefore to compare the global characteristics of flames from straight pipe and smooth contraction nozzles.

Experimental Method

Global performance is assessed here by measurements of radiant fraction, flame length and lift-off height. The stability limits and the heat transfer characteristics of a flame are significant indicators of performance. Measurements of the flame width and area, axial radiant profiles and emissions of CO, CO_2, NO and NO_2 were taken but are not presented here.

Burner Arrangement

To provide consistent ambient flow for both nozzles, which have different *external* shapes, the burner tips were set into a 450 mm round metal plate. The presence of the plate also avoids having an unknown co-flow, since any ambient flow at the nozzle tip must be radial. It is noted that this configuration will provide a more stable flame than most studies in the literature that do not have such a plate.

Careful control of the initial conditions is of key importance in the present comparison. Both nozzles had an exit diameter of 5.00mm. The pipe nozzle had a length of 500mm and was attached in-line to a series of 8 honeycomb sections and mesh screens to ensure symmetrical initial flow without swirl (Figure 1). This satisfies the criteria that *l/d* exceed 100 for fully-developed turbulent pipe flow [6]. The smooth contraction was mounted to the end of a 20mm ID × 1000mm long supply pipe fitted to the same flow conditioning system. The initial velocity profile of the smooth contraction approximates a “top hat” profile in contrast to that of the of the pipe with its fully-developed turbulent flow.

Fire retardant curtains were used to both limit the ingress of light into the laboratory area and to minimise the effect of draughts.

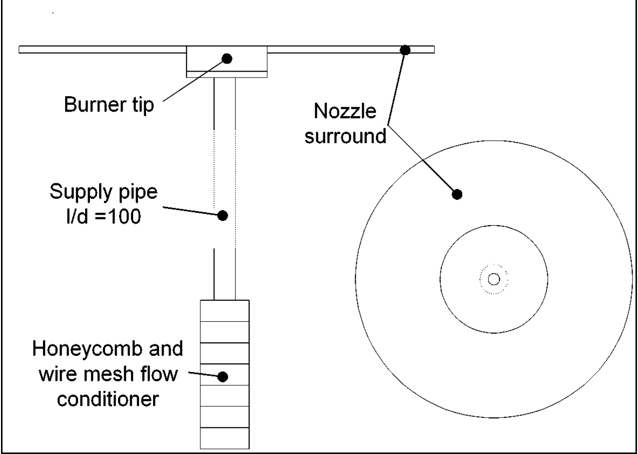

Figure 1: Burner and supply pipe arrangement.

Radiant Heat Flux

A radiant heat flux transducer (Medtherm, 64P-0.5-24-T) was mounted to an automated vertical traverse with a 2.3-metre span via a support frame. This provides good resolution of the axial heat flux profile for flame lengths of up to approximately 1.2 metres. This method is to be preferred over the single point measurement techniques developed by Sivathanu & Gore [7] for the present study, since single point measurements rely on the assumption that the flames are self-similar.

The signal from the transducer is transferred to an amplifier via shielded, low-impedance cabling. The signal then enters a data acquisition card in a PC (National Instruments, Lab-PC-1200). The experimental layout is shown in Figure 2.

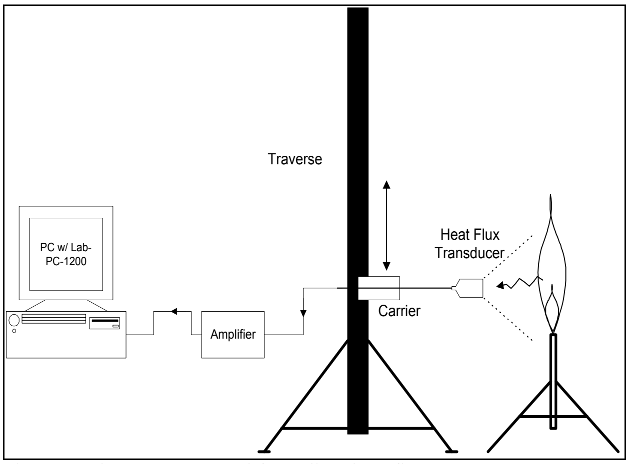

Figure 2: The apparatus used for radiant heat flux measurements.

Purpose written software is used to control the traverse, to capture data and to synchronise these processes.

A statistical study was used to determine the number of measurements required for reliable measurement of the mean and rms at each height along the axis of the flame. This showed that 400 measurements, sampled for 2 minutes at 3.33 Hz, provides convergence of the rms to within 2%.

The axial radiant profile was typically measured at 20 heights. The transducer was initially placed in a position where it registered only background radiation (i.e. below the burner exit plane) and was then traversed along the flame axis until, again, only background radiation was detected (typically 1.2-1.5 times the flame height).

As discussed by previous studies [7], the total radiant emission is assumed to be dominated by the axial radiant profile (for these long, thin flames) and thus the radial profile is ignored. The temperature of the flat plate surrounding the burner tip (Figure 1) was measured but never exceeded the ambient temperature by more than 10^{o}C during any test and its influence has been neglected.

Flame Size Measurements

A time series of visual images has been recorded with a digital video camera (Sony, DCR-TRV900E). The camera has a three colour (RGB) CCD recording system with manual control of exposure setting and is capable of shutter speeds of up to 1/10000th of a second, allowing instantaneous flame images to be captured without blurring. The camera is operated in progressive scan mode to eliminate image interlacing.

To allow direct comparisons of different flames a series of video clips was recorded at standard exposures, shutter speeds and frame sizes. The amount of background light was sufficiently reduced using blackout curtains to allow for a valid comparison of intensity. Each flame was recorded for 30-40 seconds (750-1000 frames) to ensure statistically significant results.

To determine flame dimensions the video footage was imported and processed by computer. Edge determination from time-lapse images has always been a contentious issue due to low intensity gradients. With this in mind, video footage is recorded at fast shutter speeds and analysed frame by frame. The instantaneous images are clear and importantly have very sharp edge definition. Typically, image intensity at the flame edge increases from a background intensity of approximately zero to over 80% of the maximum intensity in the space of 2-4 pixels (~0.2-8mm actual distance). Thus an overall spatial accuracy of better than 1.1%, ignoring errors associated with parallax, can be achieved using this technique. The mean flame length and mean lift-off height are defined as the arithmetic average of the instantaneous positions, with reference to the burner exit planes.

The use of a frame-by-frame approach means that the arbitrary threshold value used in determining the edge position is of minor importance. For footage with a high overall exposure, such as in Figure 3, varying the threshold value between 30 and 200 resulted in only a 3% change in the calculated flame tip position.

Using this frame-by-frame approach, flame length, width and lift-off height detection was unambiguous. Since each frame is analysed individually it is also possible to obtain a histogram of flame position, as opposed to only a mean value, as shown in Figure 3 & Figure 4.

Figure 3: Example of instantaneous flame length measurement performed by software using frame-by-frame approach.

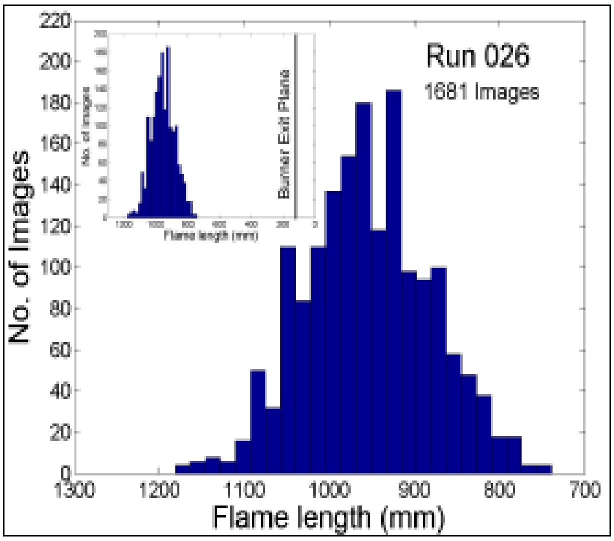

Figure 4: Histogram of flame tip position using frame-by-frame approach. Inset, histogram of flame tip position, showing burner exit plane at 122 mm.

The computer analysis calculates the flame tip position for each of the three colour channels independently. The red channel is used to measure the length of yellow-to-red radiant flames. Whereas footage of flames which are predominately blue in colour, such as lifted flames, are analysed using the blue channel. This approach maximises the signal to noise ratio in the video data, which is an important consideration when processing footage taken at high shutter speeds of flames with low luminosity.

Results & Discussion

Radiant Fraction

A comparison of the radiant fraction for the two burners is presented in Figure 5. The trends are similar for both nozzles. An increase in jet velocity causes in initial rapid drop in radiant intensity as the flame lifts off, before converging asymptotically to their ultimate valve. The effect of lift-off correlates with the visual observation of less yellow/orange colour in the flame associated with the presence of soot. At their respective blow-off velocities the relative difference in the radiant energy emitted from the two flames is 36%. The maximum velocity used for each of the nozzles was the largest velocity sustainable for the duration of the measurements (typically 45 minutes per flame). These maximum velocities are expected to be slightly smaller that the minimum blow-off velocities.

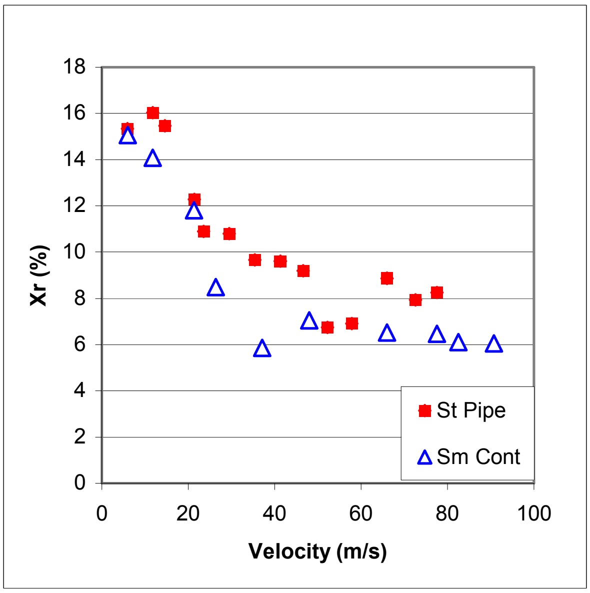

Figure 5: Radiant fraction (Xr) vs. nozzle exit velocity.

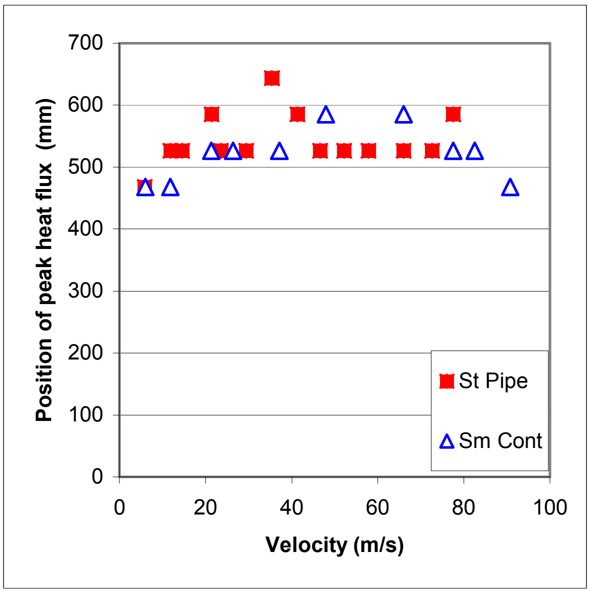

Figure 6: Position of the peak heat flux height vs. velocity.

Figure 6 shows that there is little difference in the position of the peak heat flux relative to the exit plane for the two burners. Previous work [7] suggests a method to approximate the total heat flux of a flame from a single point measurement at axial and radial positions equal to half the flame height, which is to coincide with the position of maximum heat flux. This single point measurement technique has since become prevalent in research, notably, [8]. The results of Fig. 6, when viewed with the flame length data in Figure 8, can not be reconciled with these finding and indeed lend support to the method used in this study. The position of maximum radiant heat release is relatively constant across the range of heights measured that differ by up to 27%. Figure 7 shows that the positions of the peak heat flux for both flames is neither equal to 0.5 nor constant. Further, some of the data points are outside of the 0.5-0.7 range quoted as typical for the single point method.

The accuracy of the single point method was assessed to be 20% [7]. It can be seen that this level of accuracy is insufficient for this study.

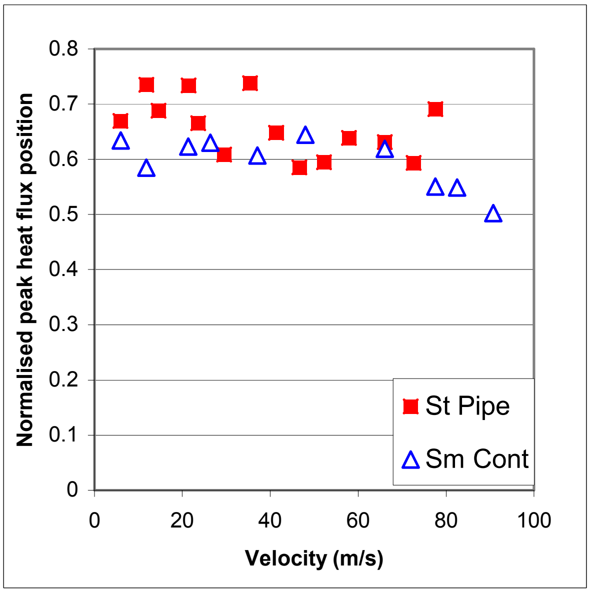

Figure 7: Normalised position of peak heat flux vs. velocity.

Flame Length

The flame lengths from the two burners are shown in Figure 8. The mean flame length from the smooth contraction burner have a maximum length 17% longer than those from the pipe. The burners can be seen to yield a similar trend up to a velocity of 50 m/s. The straight pipe then converges to a constant length, while the smooth contraction nozzle flames continue to lengthen. In general, the length of the straight pipe flame is shorter than that from the contraction. This result conflicts with expectation based on the cold flow measurements [4,5], since the pipe jet has a lower rate of centre-line decay.

It is possible that the unexpected differences in flame length arise from slight differences in buoyancy. A possible explanation for this effect could be due to the difference in the radiant heat released from the two flames (Figure 5). Due to the lower radiation emitted from the smooth contraction nozzle it can be expected that higher flame temperatures will be experienced. The higher temperatures will result in a larger degree of gas expansion and hence, a potential increase in flame size. However, further investigations are required to confirm this effect and explanation. In any case it is clear that the presence of the flame changes the behaviour of the system from what may be expected from cold flow tests.

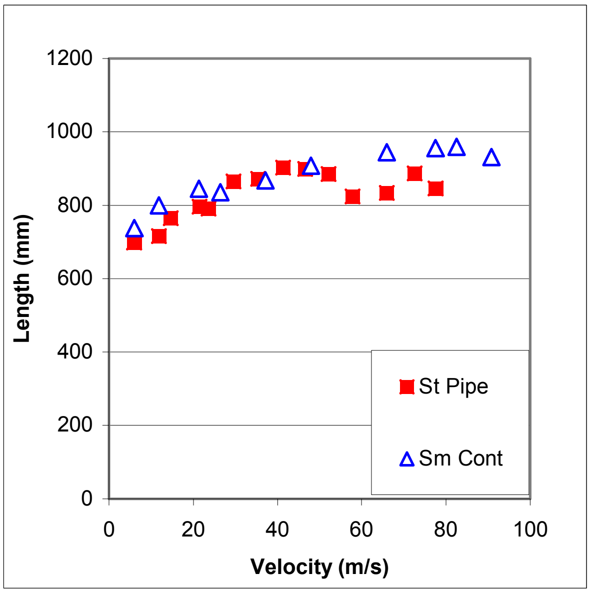

Figure 8: Mean flame length vs. velocity.

Flame Lift-off Height

A clear difference in lift-off and blow-off behaviour can be seen in Figure 9. The smooth contraction burner is shown to exhibit a greater degree of stability in terms of initial lift-off velocity and lift-off height achieved before blow-off. The lift-off velocity was measured by starting with an attached flame and slowly increasing the flow rate. This was repeated ten times and the results averaged. The same method was used to determine blow-off. Due to the susceptibility of the flames to minor external disturbances at the point of blow-off this may not be an ideal method. Differences in the rate at which the flowrate is increased, as well as fluctuations in the lift-off height with time, are probably significant. However, an advantage is that the method is repeatable and uncomplicated.

The difference in the lift-off velocities is 40%, with the smooth contraction flame remaining attached at higher velocities. The blow-off velocity of the smooth contraction burner was found to be 17% greater.

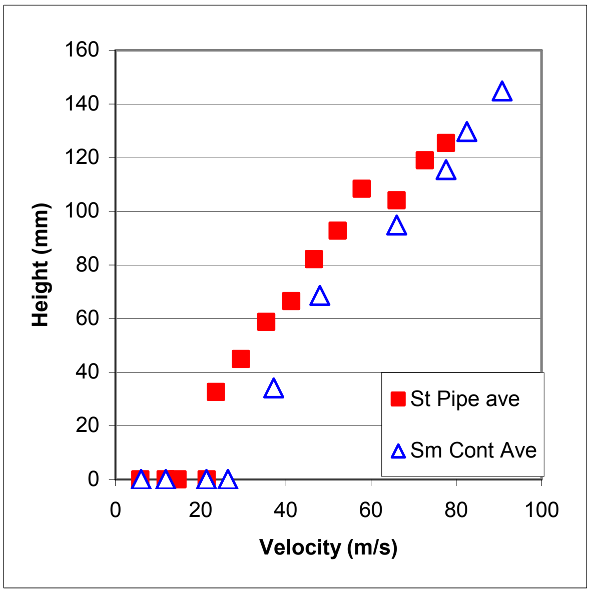

Figure 9: Lift-off height vs. velocity.

The present values of lift-off and blow-off are lower than previously reported data due to the flat plate surrounding the nozzles.

Conclusion

This study has found that there are non-negligible differences between the flames from a smooth contraction and a straight pipe with the same exit diameter.

The following differences were found between the two burners:

1. The blow-off velocity of the smooth contraction nozzle exceeds that of the straight pipe by 17%
2. The smooth contraction nozzle has a mean flame length 13% longer than the straight pipe
3. The maximum stable lift-off height of the smooth contraction nozzle is 17% greater than the straight pipe.
4. The lift-off velocity of the smooth contraction exceed that for the pipe by 40%
5. The radiant energy released for a give fuel flow was always lower for the smooth contraction nozzle. This resulted in approximately a 36% difference at blow-off conditions.

This work is consistent with previous findings [4,5] that found both near and far field differences in their cold flow experiments with the same nozzles used in this study. It supports the idea that far field differences influence global performance. This work also has implications for combustion modelling as it is becoming apparent that circular burners can not be seen a being globally self similar.

Further work will be done to assess the impact of initial conditions on other aspects of global performance, such as emissions of CO, CO_2, NO and NO_2.

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