GOMES, JONATHAN NICHOLAS. Stability Limits of Jet Flames in Oblique Air Flows. (Under the direction of Dr. Kevin Lyons.)

The stability limits of a jet flame can play an important role in the design of burners and combustors. This study details an experiment conducted to determine the liftoff and blowout velocities of oblique-angle methane jet flames under various coflow velocities. A nozzle is mounted on a telescoping boom to allow for an adjustable burner angle. Twenty-four flow configurations are established using six burner nozzle angles and four coflow velocities. Measurements of the fuel supply velocity during liftoff and blowout are compared against two parameters: nozzle angle and coflow velocity. The resulting correlations indicate that flames at more oblique angles have a greater upper stability limit and are more resistant to changes in coflow velocity. This behavior occurs due to a lower effective coflow velocity at angles more oblique to the coflow direction. Additionally, stability limits are determined for flames in crossflow and mild counterflow configurations. For these flames, the stability limits are higher. Further studies may include more angle and coflow combinations, as well as the effect of diluents or different fuel types.
Stability and Blowout Behavior of Jet Flames in Oblique Air Flows

by
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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science

Mechanical Engineering

Raleigh, North Carolina

2011

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DEDICATION

To my amazing parents,

for all the sacrifices they made so that I can chase my crazy dreams.

I love you.
Jonathan (Jon) Nicolas Gomes is a graduate student in North Carolina. Born and raised in El Monte, California, his family relocated to Raleigh, North Carolina in 2000, when Jon was eleven years old. He attended Leesville Road High School, where he graduated as salutatorian of the Class of 2006. Jon chose to attend North Carolina State University to pursue an undergraduate degree in Mechanical Engineering.

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ACKNOWLEDGEMENTS

The author would like to extend his gratitude towards the following individuals who have contributed in some capacity to this work:

- Dr. Kevin Lyons, for his invaluable guidance and enthusiasm

- Dr. Tiegang Fang and Dr. Alexei Saveliev for their time and support

- James Kribs, for all the assistance, informal education, and the laughs

- Tamir Hasan, for the fun job of holding the velocimeter

Finally, a thank you goes out to the reader. Please enjoy.
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1. INTRODUCTION

1.1 Background

Previously, a multitude of studies have been performed on lifted jet flames and their behavior in various air flow configurations. In such partially-premixed flames, the characteristics of the surrounding air flow (velocity, temperature) impact the overall combustion process and the stability parameters. As fuel flows out of a jet nozzle and mixes with the air, the fuel and oxidizer concentrations vary throughout space and time. The extent of mixing due to turbulence also changes depending on the surrounding flow. The perpetually varying concentrations determine the overall behavior of a flame: its shape, velocity, size, color, temperature, and composition.

In particular, two important behavioral parameters are liftoff and blowout velocity. Initially, a jet flame will remain attached to the nozzle at low fuel velocities. However, at a critical jet velocity, the flame will lift off from the nozzle and stabilize at a position downstream due to the inability of the flame to remain anchored on the burner [1]. While there is in general a regime where the flame can stabilize, increasing the jet velocity will ultimately lead to blowout, in which the flame is extinguished. This behavior occurs at some critical blowout velocity. Together, the liftoff and blowout velocities essentially define the stability limits of a lifted jet flame.

Typically, past experiments on liftoff and blowout have focused on coaxial flow. In this arrangement, the jet nozzle is parallel to a surrounding air flow (coflow). Another common arrangement is transverse flow, in which the nozzle is perpendicular to the air flow...
(crossflow). Jet diffusion flames behave differently in both arrangements, as previously-performed experiments have demonstrated.

1.2 Purpose

Compared to jets in coflow and crossflow, the behavior of intermediate oblique jets has not been studied to the same extent. Instead of a parallel (0°) or perpendicular angle (90°) between the fuel and oxidizer streamlines (i.e., the nozzle and concentric air flow), an oblique angle may also be utilized in the design of combustors. Angled fuel injectors or nozzles can possibly yield more desirable flame behavior in terms of stability under various flow velocities, thereby enhancing combustor performance. In most cases, flames used in industry often lift off due to high velocities [1]. The location of the lifted flame must be taken into consideration when designing a combustor. While lifted flames in coflow and crossflow have been studied extensively, little attention has been devoted to angled jet flames.

Oblique jet flames can also occur in petrochemical flaring operations when wind blows against a large flare flame. In this case, the stability of the jet can change dramatically with wind direction and speed. Despite a much smaller scale, understanding the behavior of angled flames in an experimental setting can aid in the proper design of flaring towers and burners that account for varying wind conditions.

Ultimately, the purpose of this experiment is to delineate flame stability and blowout behavior at several oblique angles under various flow velocity ratios. By consolidating the overall results, an optimal burner configuration may be chosen based on desired stability and blowout parameters.
1.3 Stability of Jets in Coflow

Early major experiments involving flame stability in coflow were conducted by Wohl et al around 1950 [2]. They determined that the liftoff and blowout velocities (stability limits) are functions of the supply (jet) velocity and fuel concentration. When the supply velocity is less than the flame velocity, then the flame will flash back into the burner. In contrast, the flame will lift off from the burner and equilibrate downstream when the supply velocity exceeds a critical value.

Later, Vanquickenbourne and van Tiggelen [3] expanded on Wohl by suggesting that the liftoff height occurs where the mean incoming fuel velocity equals the turbulent burning velocity of the flame (induced under coflow). Their work has served as the foundation for other experiments involving the modeling of jet diffusion flames.

Another major development occurred in 1984 with the work of Kalghatgi [4], who built on the previous work of Vanquickenbourne and Tiggelen. He observed that the flame liftoff height for hydrogen, propane, methane, and ethylene depends on several physical parameters—and strongly on the jet exit velocity. A linear correlation exists between the two variables, regardless of the burner diameter. After performing a nondimensional analysis of his data, Kalghatgi concluded that diffusion flames blow out at a height that is 0.65-0.75 times the height of the stoichiometric contour. According to his findings, the height is also inversely proportional to the square of the laminar burning velocity.

Brown et al have studied the effect of jet exit velocity and coflow velocity on liftoff height [5]. They discovered that the former has a minimal effect on lifted flames that are significantly downstream from the burner exit (i.e., in the far field). In this area, the turbulent
burning velocity equals the flame stabilization velocity. However, in the near field relative to the burner, findings reveal that the stabilization velocity is approximately equal to three times the laminar burning velocity.

The work of Vanquickenbourne and van Tiggelen formed the basis for a study by Tieszen et al which explored blowout mechanisms [6]. Their results confirmed the theory proposed by Vanquickenbourne and van Tiggelen: blowout occurs when the local flow velocity exceeds the turbulent burning speed of the flame. However, they also investigated the role of large-scale eddies, concluding that they are responsible for flame propagation in the interior of the jet.

Burgess and Lawn [7] have expanded on the work of Vanquickenbourne and van Tiggelen by including the effects of large eddy structures and locations where the flame is relatively stable. Imaging and direct numerical simulations revealed that flames tend to propagate near large eddies, but away from the center where the mixture is too rich. In addition, Navarro-Martinez and Kronenburg [8] have consolidated results from large eddy simulations (LES) for multiple lifted flame configurations. They assert that the conditional moment closure approach can accurately predict stability conditions based on experimental behavior. Recently, more studies have focused on modeling and simulating jet flames using LES and other techniques.

1.3 Stability of Jets in Crossflow

While jet behavior in coflow has been extensively studied, less attention has been devoted to jets in crossflow. In a recent publication, Bandaru and Turns included a
comprehensive list of all major crossflow research to date [9]. Many of the works relevant to this study were observation-based experiments performed by Kalghatgi, who is well known for his work with lifted flames in coflow. His crossflow flame experiments were conducted in a wind tunnel and involved propane, methane, and ethylene fuels.

At the same time as his research on flame liftoff height in coflow, Kalghatgi investigated flames in a cross-wind normal to the burner axis [10]. His findings revealed two distinct blowout limits for flames in a moderate cross-wind: a lower limit in which the incident wind extinguishes the flame and an upper limit in which the flame blows itself out. At the lower limit, the jet velocity is much lower than the blowout velocity of a jet in still air. However, at the upper limit, the blowout mechanism is similar to that of a flame in still air. The upper blowout limit is usually greater than the blowout velocity in still air due to greater levels of turbulence caused by the cross-wind. Kalghatgi’s experimental results demonstrated that a lifted, stable flame can exist between the upper and lower blowout limits.

Kalghatgi also investigated the effect of burner orientation to wind direction [11]. Burner diameters ranged from 4 mm to 20 mm, while the angle between the wind direction and burner axis varied between 45°, 66°, 90°, 114°, and 135°. By measuring the jet velocity at which blowout occurs (at the lower limit), Kalghatgi concluded that jet flames are less prone to blowout as the burner angle increases from 0° to 180°. He also discovered that the lower blowout limit does not always exist under low wind speeds. In such conditions, a flame will stabilize in the wake of the burner and the wind cannot extinguish it, especially at angles greater than 90°. Thus, flame behavior is difficult to predict in these conditions.
In another study, Han and Mungal observed the mixing and combustion processes of jet flames injected at -45°, 0°, and 45° [12]. Using particle image velocimetry (PIV) and CH PLIF imaging techniques, they concluded that flame length increases with injection angle due to reduced entrainment. They also attempted to model the dilation behavior of the stoichiometric contour, which they suggest occurs due to the premixed characteristics of deflected jet flames. Hasselbrink and Mungal performed a similar study in which the velocity fields of transverse (0°) jet flames was measured using PIV [13]. Overall, they noted greater flame/flow interaction near the base of the lifted flame than at downstream locations.
2. EFFECTS OF ANGLE ON BLOWOUT CONDITIONS

2.1 Experimental Setup

Figure 1 depicts the apparatus used for angled jet experiments. This apparatus was used for previous experiments involving flame stability behavior in coflow [14] [15].

![Burner apparatus for angled jet experiments.](image)

The burner consists of a 3 mm fuel nozzle that is concentric with a large annulus for air coflow. However, this nozzle was not used for angled jet flames. Instead, an appropriate nozzle was devised from 0.25” (6.35 mm) stainless steel tubing mounted on a telescoping boom with an adjustable angle, as shown in Figure 2. To determine the angle of the nozzle, a protractor was mounted on the boom. Using a string with a weight at the end (which provided a vertical line of reference), the angle could be read off the protractor. The nozzle is oriented such that it is in the uniform velocity region of the coflow, away from the edges. A
vertical distance of 11 inches is maintained between the nozzle and the top of the burner to avoid any irregularities in the air coflow.

The coflow air is pumped by a Magnetek model 9467 centrifugal blower, controlled with a potentiometer to allow for variable operation speeds. The coflow then travels through flexible hose (5 inches in diameter) to the burner. The air travels through a 90° tee before entering a 2.54-mm thick honeycomb screen. The screen makes the coflow velocity profile more uniform and straight. After the screen, the coflow air enters a diffuser section with a greater cross-section area. The diffuser section contains four wire mesh screens which serve to eliminate flow irregularities and further refine the coflow velocity profile into a “top-hat” shape. Finally, the coflow air exits the burner through a contraction section with a terminating diameter of 150 mm.

The coflow air velocity is measured using a TSI Veloci-calc model 8345 hot-wire anemometer, which displayed values in meters per second with a precision of 0.01 m/s and
an accuracy of ±3% of the reading. For each coflow velocity measurement, the tip of the wand (containing the sensing element) is placed horizontally on the burner exit, perpendicular to the coflow direction. The potentiometer controlling the blower motor is then adjusted to achieve the desired coflow velocities of 0, 0.25, 0.40, and 0.60 m/s.

The fuel volumetric flow rate is measured using an Advance Series 150 flowmeter, calibrated for use with methane. The flowmeter consists of a stainless steel ball in a graduated cylinder. Readings are taken from the bottom of the ball and converted into units of scfh (standard cubic feet per hour) using the manufacturer’s charts. The jet velocity can then be calculated based on the volumetric flow rate and cross-sectional area of the burner. The gas is supplied from a pressurized cylindrical tank and regulated through a MicroLine UHP Gas Panel controller.

### 2.2 Results at Various Configurations

For this experiment, six different angles were chosen: 20°, 30°, 40°, 50°, 60°, and 70°. The 10° and 80° angles were not chosen due to their closeness to the 0° (coflow) and 90° (crossflow) orientations. At each angle, liftoff and blowout jet velocities were measured under four ambient flow velocities: 0 (still air), 0.25, 0.4, and 0.6 m/s. (Note: the velocity of 0.25 was chosen due to physical limitations of the blower motor.) Thus, twenty-four flow configurations are established. Table 1 contains the raw data collected for each configuration, along with the calculated values for liftoff and blowout velocity.
To determine any correlations between nozzle angle, coflow velocity, and the liftoff and blowout velocities, the data from Table 1 can be examined in several manners. First, the liftoff and blowout velocities are plotted against coflow velocity for each angle. Figures 3 through 8 depict these plots.
Figure 3: Stability limits vs. coflow velocity (20° angle).

Figure 4: Stability limits vs. coflow velocity (30° angle).
Figure 5: Stability limits vs. coflow velocity (40° angle).

Figure 6: Stability limits vs. coflow velocity (50° angle).
Figure 7: Stability limits vs. coflow velocity (60° angle).

Figure 8: Stability limits vs. coflow velocity (70° angle).
The data obtained involved two independent variables: angle and coflow velocity. Alternatively, the liftoff and blowout velocities can be plotted as a function of angle under the four different co-flow settings: 0, 0.25, 0.40, and 0.60 m/s. These plots are shown in Figures 9 through 12.

Figure 9: Stability limits vs. angle (0 m/s coflow).
Figure 10: Stability limits vs. angle (0.25 m/s coflow).

Figure 11: Stability limits vs. angle (0.40 m/s coflow).
As expected, the flame shape varied with the angle, with the flame front conforming to the direction of the coflow. The photographs in Figure 13 depict a flame at a 20° (less oblique) angle with a coflow velocity of 0.4 m/s. Three states are shown: the attached flame, the lifted flame, and the hysteresis flame just prior to blowout. Likewise, Figures 14 and 15 show flames at 50° and 70° angles under the same coflow velocity of 0.4 m/s.

Figure 13: Flame states at 20°.
The overall data from Table 1 and Figures 3 through 8 can be combined to form a general stability chart based on the angle between the burner nozzle and coflow air, as shown in Figure 16. Similarly, Figures 9 through 12 can be consolidated into a general chart based on coflow velocity, as shown in Figure 17.
Figure 16: Stability limits vs. coflow velocity for all angles.
Figure 17: Stability limits vs. angle for all coflow velocities.
Based on Figure 16, it can be seen that the flame liftoff velocity is largely resistant to changes in the nozzle angle. The greatest deviation occurs at a coflow velocity of 0.4 m/s. At each angle, liftoff velocity generally decreases with greater coflow velocity. This behavior can be attributed to the component of the coflow velocity vector that lies parallel to the flame direction. Thus, at greater coflow velocities, a lower fuel supply speed (liftoff velocity) is required for the flame to detach from the burner.

In contrast, the blowout velocities in Figure 16 exhibit greater deviation with increasing coflow velocities. The nozzle angle has a more pronounced effect on blowout velocity under high coflow velocities—namely at 0.40 and 0.60 m/s. Figure 16 suggests that the blowout velocity increases for higher angles. For the 60° and 70° angles, the blowout velocity is over 70 m/s; however, for the 40°, 30°, and 20° angles, the blowout velocity is between 60-65 m/s. Since the nozzle angle has a minimal effect on the liftoff velocity, it can be concluded that flames have a greater upper stability limit (blowout threshold) at more oblique nozzle angles, namely 60° and 70°.

The data in Figure 17 exhibits behavior that conforms to the trends shown in Figure 16. Again, it can be observed that liftoff velocity generally decreases under higher coflow velocities for the full range of nozzle angles (but with slightly less deviation at 70°). The blowout velocities demonstrate much more variation at smaller angles, with the greatest deviations at 20° and 40°. However, at 50°, 60°, and 70°, the blowout velocities show relatively less deviation. This result indicates that the nozzle angle has a stronger effect on blowout velocity than the coflow velocity, thus following the behavior shown in Figure 16.
Overall, it can be concluded that flames at more oblique angles (50°-70°) have a greater upper stability limit that is also more resistant to changes in coflow velocity. This behavior is due to a reduced coflow velocity component that approaches zero as the nozzle angle approaches 90°. The effective coflow velocity is the component of the overall coflow velocity vector that lies along the flame/nozzle direction. With the coflow remaining vertical, this component diminishes as the nozzle angle increases towards the horizontal—that is, less of the coflow blows along the flame and contributes to liftoff/blowout behavior. The effective coflow velocity follows the equation below, as presented originally by Kalghatgi and recently by Moore et al [11] [16]. The effective velocity depends on the fuel and air densities, as well as the ambient and coflow velocities:

\[ U_{\text{eff}} = U_0 + C \sqrt{\frac{\rho_f}{\rho_0}} U_{\text{cf}} \]

Lastly, the relationship between the liftoff and blowout velocities under different flow configurations can be examined. The two stability limits can be plotted against each other, as shown in Figure 18 (ignoring coflow velocity). To determine the effect of nozzle angle on the flame stability limit ratio, non-dimensional analysis can be applied to the liftoff and blowout velocities. For each flow configuration, the coflow velocity is divided by the liftoff and blowout velocities to produce a dimensionless ratio. Figure 19 shows the liftoff and blowout velocity ratios plotted against each other. A strong linear relationship exists, suggesting that these two values remain in proportion to each other regardless of coflow velocity.
Figure 18: Blowout velocity vs. liftoff velocity.
2.3 Additional Results for Crossflow and Counterflow

As the results of Figures 16 suggest, there is not a strong correlation between the liftoff velocity (lower stability limit) and flame angle. However, the angle seems to have an effect on the blowout velocity (upper stability limit) under high coflow velocities. Figure 17 supports this notion, showing generally lower values for both liftoff and blowout velocities for higher coflow velocities. For the liftoff velocity, the effect is uniform throughout all angles. However, for the blowout velocity, the effect is more pronounced at smaller angles, namely from 20° to 40°. The most deviation occurs at these points.
To gain further insight, liftoff and blowout velocities are determined for flames at 90° (crossflow) and 110° (mild counterflow). As with the previous angles, four coflow velocities are used, resulting in eight additional flow configurations. Table 2 contains the data obtained for these configurations, as well as calculated values for the liftoff and blowout velocities. Also, Figures 20 and 21 show the crossflow and counterflow flames in their three main states: attached, lifted, and pre-blowout hysteresis.

Table 2: Liftoff and blowout velocities for 90° and 110° flow configurations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Liftoff</th>
<th>Blowout</th>
</tr>
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<td>Meter Readings</td>
<td>Chart Value (ft³/h)</td>
</tr>
<tr>
<td>Angle (°)</td>
<td>Coflow Velocity (m/s)</td>
<td>Liftoff</td>
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<td>48</td>
</tr>
<tr>
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</tr>
<tr>
<td>110</td>
<td>0.60</td>
<td>57</td>
</tr>
</tbody>
</table>

Figure 20: Flame states at 90°.
Figure 21: Flame states at 110°.

Compared with the original data in Table 1, the liftoff and blowout velocities at 90° and 110° are greater than those for oblique angles from 20° to 70°. These velocities can be plotted against the original data as shown in Figures 22 and 23.

Figure 22: Stability limits vs. coflow velocity including 90° and 110°.
Note that the blowout velocity in Figure 2 is a constant 72.80 m/s for all eight flow configurations. This limitation occurred due to high fuel flow rates that were beyond the indicating range of the flowmeter used in this experiment. Thus, the actual blowout velocity is beyond the 72.80 m/s reading used in Table 2 and Figure 2. Regardless, this value is still sufficient in showing that the flame upper stability limit is generally higher for the 90° and 110° nozzle angles. Though the blowout velocity data is indeterminate, the liftoff velocities vary to a minimal degree with changing coflow velocities. Thus, the lower stability limit of flames in crossflow and mild counterflow is largely unaffected by coflow velocity.

Regarding Figure 23, the lower stability limit (liftoff velocity) deviates much less for the 90° and 110° nozzle angles. This result also indicates that coflow velocity has an
inconsequential effect on crossflow and mild counterflow flames. There is an overall increase—notably at the 110° nozzle angle—suggesting better stability behavior. (Again, in this case the blowout velocities remain at a maximum of 72.80 m/s due to the limitations of the flowmeter used; the true blowout velocity is greater than this value.)

Previously, it was shown that flames at high oblique angles (50°-70°) have higher blowout velocities that are not affected much by coflow velocity. This conclusion applies to an even greater degree for the liftoff velocities of flames at 90° and 110° angles, which are higher and remain nearly constant regardless of coflow velocity. Though changes in blowout velocity could not be determined, the actual values exceed the velocities for oblique flames in the 20°-70° range. Thus, flames in crossflow and mild counterflow have higher stability limits than those in an oblique configuration.
3. SUMMARY

3.1 Conclusions

Based on the results obtained from this experiment, a number of conclusions may be drawn regarding the stability of oblique jet flames in coflow:

1) Flame liftoff velocity is largely unaffected by the nozzle angle. However, the liftoff velocity generally decreases with increasing coflow velocity. This phenomenon is due to the coflow air contributing to the lifting of the flame, which results in a lower required fuel supply velocity (i.e., liftoff velocity).

2) Flames at more oblique angles (50°-70°) have a greater blowout velocity that is also more resistant to changes in coflow velocity. This behavior is due to a reduced effective coflow velocity that occurs at these angles. Overall, flames in these configurations are the most consistent in terms of upper and lower stability limits.

3) A strong linear relationship exists between the non-dimensional liftoff and blowout velocity ratios, which incorporate the coflow velocity. Thus, the actual liftoff and blowout velocities remain proportional to each other regardless of the coflow velocity.

4) The blowout behavior for flames in crossflow (90°) and mild counterflow (110°) cannot be determined from the data obtained. However, the same data shows that the liftoff velocity of flames in crossflow and mild counterflow is largely unaffected by coflow velocity. In general, the lower stability limits (liftoff velocities) are higher than those for oblique flames in the 20°-70° range.
3.2 Future Work

This experiment served as a basic observation of how the angle between a jet flame and its surrounding flow can affect the flame stability limits. A more extensive study would be required in order to fully understand the relation between these two factors. With more measurements at different ambient flow velocities, it may be possible for a mathematical model to be developed (perhaps based on the previous work of Kalghatgi). A stronger correlation may exist under flow configurations not used in this experiment. Higher coflow velocities may be achieved with the use of a wind tunnel.

The data obtained revealed that an oblique flame in counterflow (i.e., at 110°) behaves differently than an oblique flame in coflow (between 0° and 90°). Further experiments can be performed to study flames at more extreme angles, such as those between 90° and 180°. Such work would help determine if counterflow flames can be utilized in efficient burner designs. Horizontal coflow orientations may also be investigated.

Additionally, this experiment only considered methane as the fuel source. Future experiments may be performed with propane, ethylene, hydrogen, or other commonly-used hydrocarbon fuel sources. Non-reacting diluents such as nitrogen can also be introduced in the fuel. Furthermore, the stabilizing effect of high coflow temperatures can be studied [17]. The combustion equivalence ratio may be introduced as yet another parameter that can influence flame stability.
REFERENCES


