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Scaling and Performance of Dump Combustors with Transverse Gas Jets

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Small gas jets, in the role of a fluid amplifier, can be used for vortex amplification and swirl generation in small laboratory scale dump combustors using premixed propane-air mixtures. Typically these tests are performed in a low temperature, low pressure environment with unchoked nozzles. The objective of this study was to determine if the results of laboratory burners can be used for predicting the performance of larger combustors operating under realistic conditions typical of ramjets. Analysis of the experiments performed at the University of Southern California and the Air Force Aero Propulsion Laboratory shows that geometric scaling is possible. Also, under certain operating conditions the use of transverse gas jets is a convenient method of increasing the combustion efficiency of a burner.

Nomenclature

A = area
D = chamber diameter
d = diameter
h = step height
L = chamber length
M = Mach number
m = mass flow rate
N = number
p = stagnation pressure
T = temperature
x = location upstream of the step

Subscripts

a = pertaining to primary
j = pertaining to jet

Introduction

SUDDEN expansion burners (dump combustors) are being investigated as possible candidates for advanced air-breathing propulsion systems which are compact, smooth burning and highly efficient.[1] Unfortunately, except for the side dump concept, most sudden expansion burners have rather low flame spreading rates. Also, when the characteristic length of the burner is reduced, the combustible mixture becomes stratified due to an insufficient time for evaporation of the fuel droplets. In many instances, fuel stratification and geometric constraint in a compact, volume-limited dump burner cause rough burning.[2]

In order to remove some of the deficiencies of the basic dump burner concept, a slight modification has been proposed.[2] In the modified burner, small gas jets located upstream of the dump plane are used for vortex amplification. The vortices induced by the gas jets and the sudden expansion step interact and, thereby, amplify the size of the recirculation zone. If the location and the momentum flux of the jet system are chosen properly, a significant increase in the size of the recirculation zone downstream of the sudden expansion step can be achieved. On the whole, the jet system helps increase the flame spreading and the characteristic residence time,[3] and decrease the effect of fuel stratification. Thus, the use of gas jets gives rise to a variable strength flame holder[4] where the strength of flame holding could be modulated over the entire flight path as the need arose. In addition to the gas jets in the radial direction, swirl can be induced in the burner by means of proper orientation of the jets.[5]

Most of the studies of the interaction of gas jets in a dump burner were conducted in both two-dimensional and axisymmetric laboratory burners with low inlet stagnation pressure and temperature. Unlike realistic ramjet burners, premixed propane-air mixtures were used in the laboratory burners and the nozzles were not choked. Because of these operating differences questions can be raised regarding the usefulness of the jet systems in a liquid fuel injected burner operating at higher pressures and temperatures with choked nozzles.

This paper describes a series of experiments at higher pressures and temperatures in a 15.2-cm-diam burner with a 2.5-cm step conducted at the Air Force Aero Propulsion Laboratory (AFAPL), Dayton, Ohio. The ranges of pressure and temperature were consistent with a typical ramjet application, and the burner nozzle was always choked. The first objective was to determine if the jet system could perform effectively in a high temperature, high pressure environment with a choked burner nozzle. The second objective was to ascertain if it would be possible to predict the performance of a larger burner operating at higher pressures and temperatures from known behavior of smaller laboratory scale burners at lower pressures and temperatures.

Experimental Apparatus

Premixed propane air mixtures at slightly over 1 atm of pressure and inlet temperature of 327 K were used both in two-dimensional and axisymmetric combustors. Three different sizes of two-dimensional channel burners (20.3 × 2.5 cm, 7.5 × 2.5 cm, and 5.1 × 3.8 cm) and two axisymmetric burners (10.2 and 7.6 cm diam) with unchoked nozzles were studied. Pressure, temperature, location, diameter, number of holes, and the momentum flux of the jet system as well as the step height were varied. A typical transverse jet system was located 1.3 cm upstream of the step and consisted of 36 equally spaced 1-2-mm-diam holes. The jet mass flow rate

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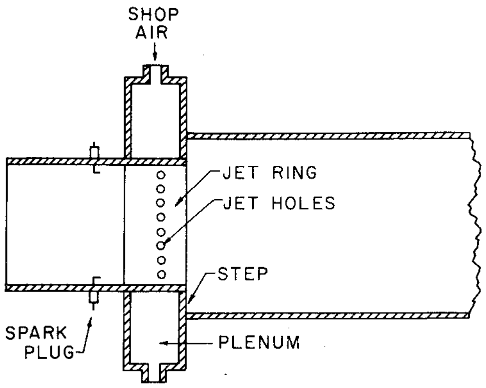

Fig. 1 Sketch of an axisymmetric dump burner with a jet system (USC).

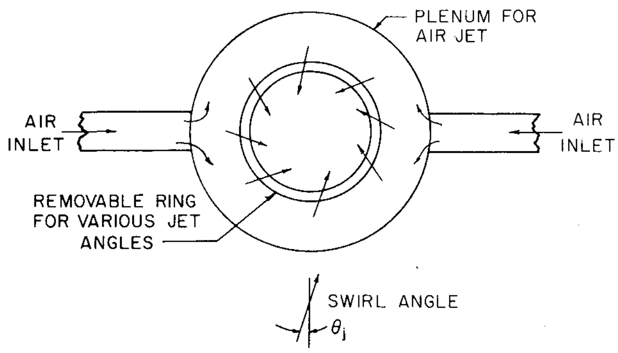

Fig. 2 Plenum chamber of the jet system (USC).

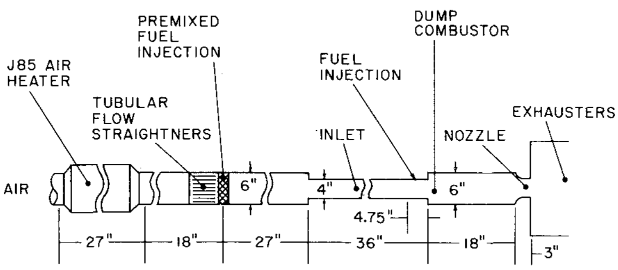

Fig. 3 Sketch of the AFAPL combustion tunnel.

was approximately 3-4% of the primary air flow rate. Figure 1 is a sketch of an axisymmetric dump combustor with a jet system upstream of the sudden expansion step. Figure 2 shows the plenum chamber of the jet system of a swirl jet with a swirl angle θ_j. When $\theta_j = 0$, the jet flows in the radial direction and no swirl is introduced in the burner. The angle θ_j has been varied parametrically from 0 to 60 deg. Shop air at room temperature was used in the jets both at USC and AFAPL. In order to reduce the number of variables no attempt was made to use heated air, oxygen, or fuel in the jet and thereby increase the performance of the burner.

Figure 3 is a sketch of the AFAPL combustion tunnel. A J85 air heater was used to heat the inlet air to two preselected temperatures in the neighborhood of 550 and 720 K. Also, as shown in the figure, two different locations could be chosen for injecting fuel in the burner. When the fuel was injected far upstream (about 1.6 m) the mixture was assumed to be uniformly mixed and the term "premixed fuel injection" was used to describe this injection system. On the other hand, when the fuel was injected 12 cm upstream of the dump plane, the fuel air mixture was no longer homogeneous. This type of injection in the AFAPL test was referred to as "wall injection." Choked flow was maintained in the burner nozzle for all the tests by means of an exhaust system downstream of the burner. It was possible to measure the engine thrust in the AFAPL facility. From the measured thrust, the average stagnation temperature in the burner and, thus, the increase in stagnation temperature across the burner could be calculated. The ratio of the temperature rise from thrust measurement to that calculated from equilibrium thermodynamics was defined as the combustion efficiency.

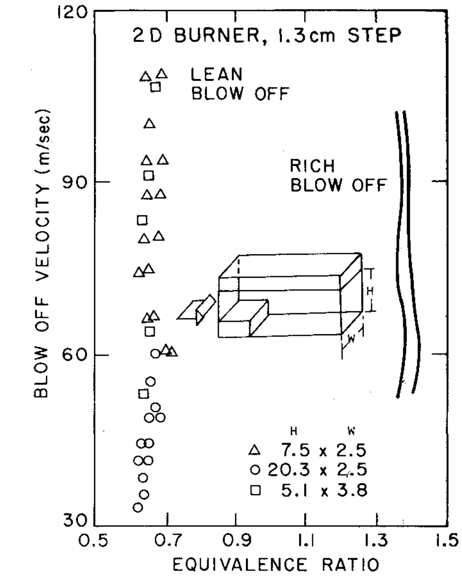

Fig. 4 Blowoff limits for channel burners; propane-air mixtures, $P_a = 1$ atm, $T = 327$ K.

The AFAPL combustor was 15.2 cm in diameter with a 2.5-cm step. Oxygen was introduced in the flow system to counteract the vitiation due to the J85 burner. Therefore, the primary flow stream can be considered "air like." Table 1 lists the range of jet variables considered at AFAPL.

Except for the jet stagnation pressure, the selection of the variables was based upon the tests performed at USC. The shop air at AFAPL had to be maintained at a higher pressure so that enough flow of air could be established through the jet. Therefore, it was not possible to vary the jet pressure parametrically to determine its effect on the burner performance.

Results and Discussion

Lean blowoff limits for three different two-dimensional channel burners are shown in Fig. 4. Also shown are the rich blowoff limits for a 7.5×2.5 cm burner. Only a limited number of experiments were performed with rich mixtures. In spite of the differences in chamber size, all lean blowoff data points seem to follow a trend which is independent of the size of the system. Earlier observation, both in axisymmetric and two-dimensional systems with different step heights, indicated that flame blowoff in dump burners was a local phenomenon and was independent of the burner size as long as the step height was sufficiently large to provide an adequate recirculation zone volume.[6]

Table 1 Range of jet variables at AFAPL

Jet variables	Range
P_j	6.7-10 atm
m_j/m_a	0-6%
x_j	1.3 cm
N	36
d_j	1, 1.3, and 2 mm
θ_j	0, 20, and 45 deg

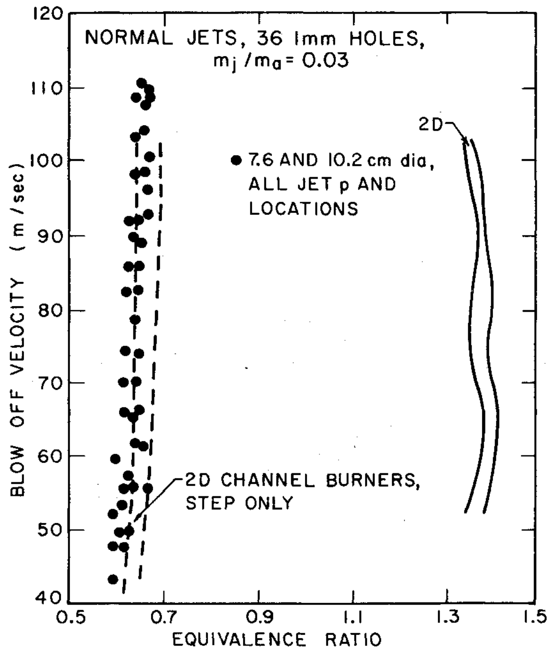

Fig. 5 Blowoff limits of axisymmetric burners with air jets; $P_j = 1.3$–4 atm, $x_j = 0.3$–2.3 cm, $h = 1.3$ cm.

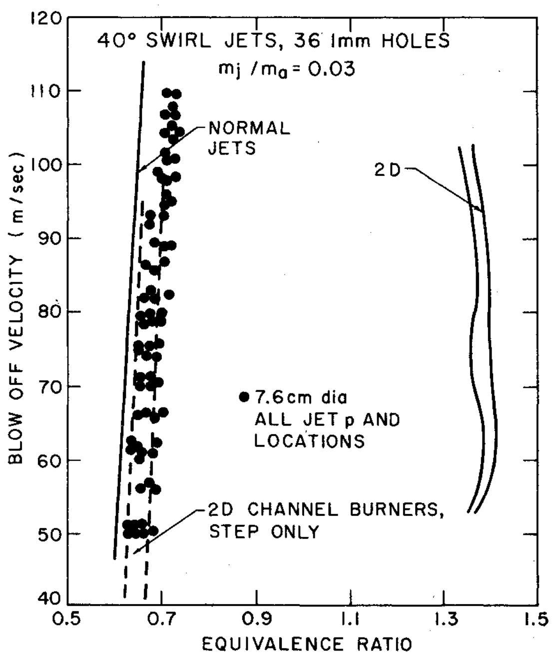

Fig. 6 Blowoff limits with 40 deg swirl jets; $p_j = 1.3$–4 atm, $x_j = 0.3$–2.3 cm, $h = 1.3$ cm.

Figure 5 shows the lean blowoff data for both 10.2 and 7.6 cm diam burners with a 1.3 cm step. The data points represent jet pressures from 1.3 to 4 atm and jet locations from 0.3 to 2.3 cm upstream of the step. There were between 18 and 36 jets with diameters in the range of 0.76–1.3 mm. Additional experiments also showed that within the range of the jet variables, the blowoff limit was independent of the location, number of holes, hole diameter, and jet pressure as long as the jet mass flow rate relative to the primary flow rate was kept constant. The range of blowoff limits of the channel burners is also shown in the figure by means of lines. The difference in the equivalence ratio at lean blowoff between the axisymmetric and the two-dimensional burners can be attributed to the difference in size of the recirculation zone downstream of the step.

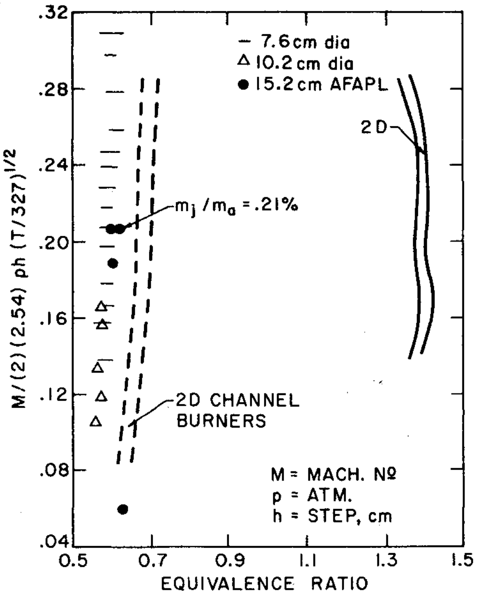

Fig. 7 Comparison of lean blowoff data—USC: $h = 13$ cm, AFAPL: $h = 2.5$ cm.

The insensitivity of lean blowoff to the variation of jet pressure, jet location, etc., applies also to the case of swirl jets. Figure 6 shows the lean blowoff points for 40-deg swirl jet system in a 7.6 cm burner with 1.3 cm step. Also shown are the data for normal jets in an axisymmetric chamber and a channel burner without any jet. The equivalence ratio at blowoff was larger for the 40-deg swirl angle than for the normal jets. Additional study showed that the difference was the largest for the 45-deg swirl angle and decreased for both smaller and larger angles. No perceptible difference in the equivalence ratio at lean blowoff was observed for swirl angles between 0 and 20 deg. The difference in equivalence ratio at blowoff with and without the jet system was probably caused by the local dilution of the combustible mixture by the cold air. Since the degree of penetration of the swirl jets can not be predicted, it was not possible to determine exactly why a 45-deg swirl jet would cause more local dilution than, for example, a 60-deg swirl jet. The burner performance was degraded to some extent due to the quenching action and dilution of the combustible mixture by the cold air jets. It is possible to use heated air, oxygen, or even fuel in the jet system and improve the burner performance. No attempt was made to use any gas other than air at room temperature during the course of this investigation. It was felt that the feasibility of the concept of using gas jets for vortex amplification and swirl generation can be demonstrated adequately with the use of shop air at room temperature.

The lean blowoff performance of the USC system was correlated with that of the AFAPL burner using a homogeneous reactor parameter for a second-order reaction.[7] The homogeneous reactor parameter has been used successfully in the past for correlating flame blowoff in bluff body flame holders operating under different pressure and temperature environments. In the present work the reactor parameter is expressed in terms of Mach number and step height rather than the velocity and the dimension of the flame holder. Figure 7 shows that in spite of large differences in pressure and temperature the lean blowoff data of the test programs can be correlated for the case of "premixed fuel injection." It did not seem to make any difference whether the burner nozzle was choked or not. The blowoff limits of the USC channel burners are also shown in the figure for comparison. The blowoff performance was independent of burner size in the range of 7.6–15.2 cm. The constants used in the homogeneous reactor parameter were chosen for the convenience of data reduction. For example, the inlet tem-

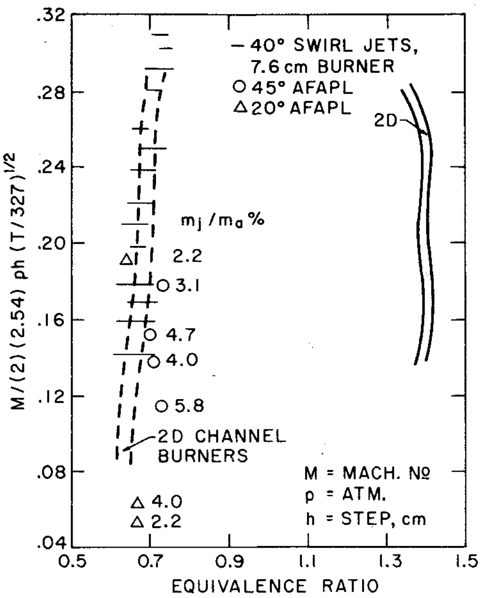

Fig. 8 Comparison of lean blowoff data with jet systems—USC: $m_j/m_a = 0.03$, 40 deg swirl; AFAPL: 45 deg swirl.

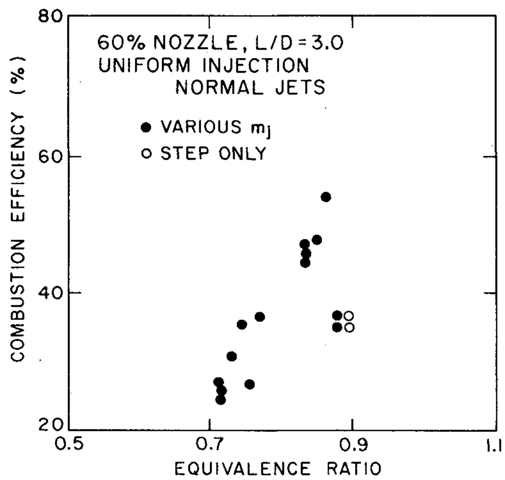

Fig. 9 Combustion efficiency; 60% nozzle, uniform injection, $T = 556$ K, $\theta_j = 0$ deg.

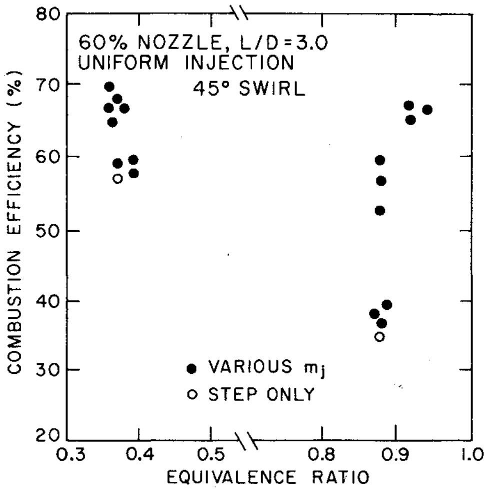

Fig. 10 Combustion efficiency; 60% nozzle, uniform injection, $T = 556$ K, $\theta_j = 45°$ deg.

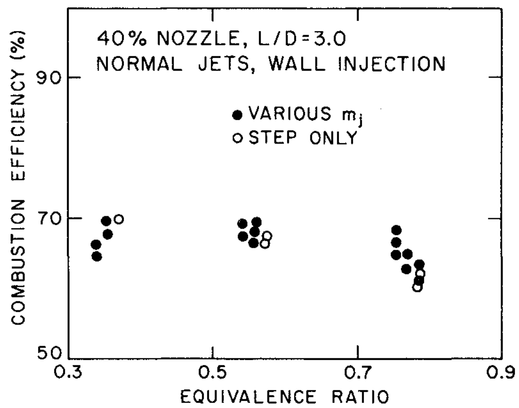

Fig. 11 Combustion efficiency; 40% nozzle, wall injection, $T = 556$ K, $\theta_j = 0$ deg.

perature for the USC tests was 327 K and this value was used for normalizing the temperature. Also the use of inlet Mach number instead of the velocity made it possible to compare the two test results over a reasonable range of values of the reactor parameter. Figure 8 compares the lean blowoff limits with both normal and swirl air jets. Since the inlet temperature in the AFAPL burners was rather high, quenching due to the jet air had a greater effect on the burner performance. The correlation of Fig. 7 and 8 shows that the lean blowoff performance of larger burners with choked nozzle can be predicted from the data of smaller laboratory scale burners at lower pressures and temperatures. This is true for the case of "premixed fuel injection." It was not possible to duplicate the condition of "wall injection" at USC. Therefore, flame blowoff with "wall injection" was not attempted at AFAPL during the course of this investigation.

Because of the low chamber pressure in the USC burner the nozzle was not choked and no attempt was made to measure the thrust. However, both thrust and combustion efficiency data were available for the AFAPL tests. At USC the improvement in burner performance with the jet system was ascertained in a qualitative manner from observation. The AFAPL tests showed quantitatively that the combustion efficiency can indeed increase for either the normal or the swirl jet system. Figures 9 and 10 show the variation of the combustion efficiency for a normal and a 45-deg swirl jet system. The fuel injection was "uniform" and the nozzle was large. With increasing jet momentum flux a large increase in combustion efficiency was observed particularly for relatively rich mixtures. For very lean mixtures the increase in combustion efficiency was not so spectacular. The chamber length to diameter ratio L/D for these and all of the tests conducted at AFAPL was 3. Generally, when larger nozzles ($A_{\text{throat}}/A_{\text{chamber}} = 0.6$) and "uniform" fuel injection (injection point 1.6 m upstream of the step) were used, the jet system helped increase the combustion efficiency. A combination of smaller nozzle (40%), leaner mixtures, and "wall injection" (injection point 12 cm upstream of the step) can actually degrade the combustion efficiency when jet air is used. Figures 11 and 12 show such a trend when normal and swirl jets are used. Even though the cooling effect of the cold air jet was accounted for in the calculation of the equilibrium reaction temperature, its influence on the chemical kinetics was not considered in the calculation of the combustion efficiency. Also the effect of cold air jets on the evaporation rate of the droplets was not taken into account in calculating the equivalence ratio.

Figure 13 is a composite figure for the combustion efficiency of a burner with two different nozzles, gas jet system and "wall" and "uniform" injections. It shows the maximum value of combustion efficiency as a function of the swirl angle. The use of gas jets, even without the swirl, can increase the combustion efficiency of a dump burner with the larger

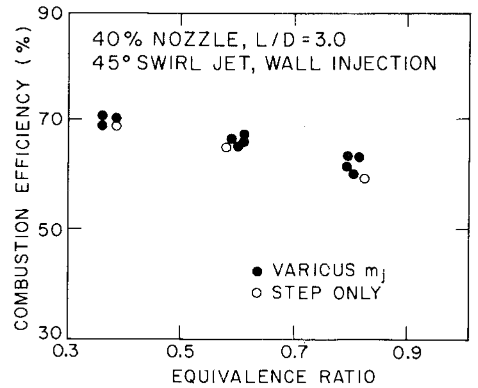

Fig. 12 Combustion efficiency; 40% nozzle, wall injection, $T = 556$ K, $\theta_j = 45$ deg.

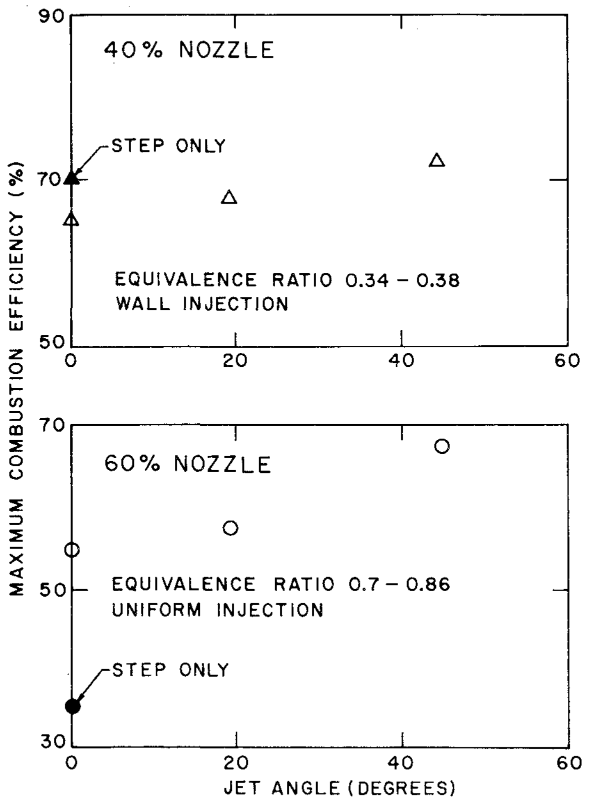

Fig. 13 Maximum combustion efficiency vs swirl angle.

nozzle. The performance can be further increased if, instead of using cold air, it is heated to the inlet condition. This would help eliminate the chemical and thermal penalties imposed upon the burner due to the quenching effect at regions of flame stabilization. Two extreme cases of fuel injection systems, equivalence ratios, and two nozzle sizes were used in Fig. 13 to illustrate the ranges of combustion efficiency to be expected. In an actual case, the nozzle is not as small as 40% and the fuel injection is not as restrictive as "wall injection." Therefore, the data in Figs. 11-13 show only the limiting behavior of the system. A realistic configuration is expected to have larger increases in combustion efficiencies.

A series of tests with "wall injection" showed that the change in combustion efficiency with the gas jet system was sensitive to the mixture equivalence ratio for both the nozzles. For very lean mixtures the combustion efficiency was reduced with air jets for both nozzles. With air jets, the combustion efficiency increased when the equivalence ratio was between 0.7 and 0.9. The increase, however, was not as large with the smaller nozzle.

The overall effect of the gas jets on the flowfield is to increase the size of the recirculation zone. The amplification of the recirculation zone due to the interaction of the two flowfields is believed to be the primary cause of the increase in combustion efficiency.

Conclusions

Results of the two experimental programs show that

1) Small scale tests at low temperature can be used to predict the blowoff performance of a larger burner operating in a more realistic environment. Thus, geometric scaling is possible for the case of uniform injection.

2) Swirl induced by gas jets is a convenient method of increasing the combustion efficiency of a burner.

3) Normal jets, even without the swirl, are able to increase the combustion efficiency.

4) A jet system with cold air can degrade the burner performance when lean mixtures and smaller nozzles are used.

Acknowledgments

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