Proceedings of the Combustion Institute, Volume 28, 2000/pp. 1305–1313

SCALING AND DEVELOPMENT OF LOW-SWIRL BURNERS FOR LOW-EMISSION FURNACES AND BOILERS

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A low-swirl burner (LSB) developed for laboratory research has been scaled to the thermal input levels of a small industrial burner. The purpose was to demonstrate its viability for commercial and industrial furnaces and boilers. The original 5.28 cm i.d. LSB using an air-jet swirler was scaled to 10.26 cm i.d. and investigated up to a firing rate of $Q = 586$ kW. The experiments were performed in water heater and furnace simulators. Subsequently, two LSBs (5.28 and 7.68 cm i.d.) configured to accept a novel vane-swirler design were evaluated up to $Q = 73$ kW and 280 kW, respectively. The larger vane-LSB was studied in a boiler simulator. The results show that a constant velocity criterion is valid for scaling the burner diameter to accept higher thermal inputs. However, the swirl number needed for stable operation should be scaled independently using a constant residence time criterion. NO_x emissions from all the LSBs were found to be independent of thermal input and were only a function of the equivalence ratio. However, emissions of CO and unburned hydrocarbons were strongly coupled to the combustion chamber size and can be extremely high at low thermal inputs. The emissions from a large vane-LSB were very encouraging. Between 210 and 280 kW and $0.8 < \phi < 0.9$, NO_x emissions of <15 ppm and CO emissions of <10 ppm were achieved. These results indicate that the LSB is a simple, low-cost, and promising environmental energy technology that can be further developed to meet future air-quality rules.

Introduction

Over the last decade, lean premixed combustion has become an important control technology option for reducing emissions of NO_x from natural gas heating and power systems [1–3]. However, the dynamic nature of premixed flames and their tendency to become unstable and blow off toward the lean limit presents technical and engineering challenges [4,5]. Commercial low-NO_x premixed burners available today are complex and relatively expensive to manufacture, operate, and maintain. At present, they are not yet economically feasible or technically acceptable for use in most small- to medium-sized furnaces and boilers.

Currently, the 25 ppm NO_x (corrected to 3% O_2) limit is considered a critical operational threshold. This is because burners offering <25 ppm NO_x can come with significant penalties in terms of cost increases and limitations in load flexibility. Lowering the emissions closer to 10 ppm NO_x raises safety issues that require expensive controls to mitigate. To achieve <10 ppm NO_x emissions, selective catalytic reduction is deemed to be the only practical option. Therefore, furnace and boiler manufacturers are very interested in new burner design concepts that will be much lower in capital, manufacturing, and operating costs but will match or exceed the NO_x performance of systems using flue gas recirculation and selective catalytic reduction.

The low-swirl burner (LSB), called the *weak-swirl burner* in some previous publications, is a new and promising lean premixed burner concept that is ripe for further research and development for commercial use [6]. Though the form of the LSB may show similarity to that of a conventional high-swirl burner, the LSB functions quite differently. Our previous laboratory investigations [6–8] have shown that the LSB exploits the propagating nature of a premixed turbulent flame and does not rely on flow recirculation to anchor the flame. Even under very intense turbulence [8], it stabilizes lean premixed flames very close to the flammability limit. In a previous study [9], we performed laboratory experiments to evaluate its feasibility for small heating appliances. Using a laboratory simulator of a spa heater (18 kW),

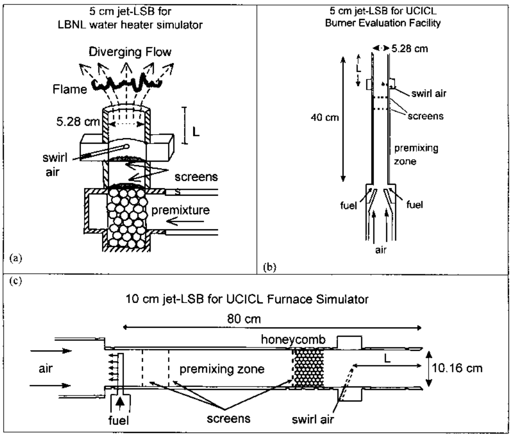

FIG. 1. Schematics of jet-LSB used at three different facilities.

it has been shown that the LSB adapts well to enclosures without generating flame oscillations. The emissions of NO_x can be controlled to below 15 ppm without significant effect on the thermal efficiency or CO emissions (which were <50 ppm).

Currently, southern California requires small industrial and commercial boilers, furnaces, and process heaters with thermal input, Q, of $0.56 < Q < 1.5$ MW to emit less than 30 ppm NO_x, and more stringent NO_x emissions requirements are being considered. The LSB is a viable option for these applications, but basic scaling information is needed for optimizing system efficiency and emissions. The purpose of this study was to scale the LSB up to the minimum Q for these applications and use the results to derive scaling guidelines. Our work consists of two aspects. First, the original version of the LSB that uses an air-jet swirler (jet-LSB) was scaled and investigated up to $Q = 0.6$ MW. Then a novel vane-swirler that has been developed for a small laboratory LSB (vane-LSB) was scaled to operate at $Q = 0.28$ MW. Our experiments provide information that burner engineers would need for adaptation of an LSB:

1. The minimum and maximum thermal input for different size LSBs
2. Variation of emissions and combustion efficiency with thermal input
3. Scaling laws deduced from the subscale prototype results

The results we obtained are very encouraging and show the LSB to be a simple, low-cost, and promising environmental energy technology that exceeds current emissions standards and can be further developed for even lower levels of emissions.

Low-Swirl Flame Stabilization Mechanism

The principle of flame stabilization in the LSB is shown in Fig. 1a. This burner is essentially an open tube fitted with an air swirler section consisting of four small inclined tangential air jets [9]. Reactants at a given ϕ are supplied through the bottom and interact with the swirling air jets. Because these jets have low angular momentum, they influence only the outer region of the reactant stream. A typical swirl number for this burner is $0.02 < S < 0.12$ compared to $0.5 < S < 1$ for conventional high-swirl burners. At these low-swirl levels, angular momentum is insufficient to cause the vortex breakdown process that leads to recirculation. Instead, the flow stream diverges when it exits the confines of the tube. For flame stabilization, the important feature is that the mean velocity decreases linearly downstream of the burner throat. This velocity "downramp" provides the flame stabilization mechanism. It allows the flame to propagate from the downstream side against this ramp and settle at the position where the local flow velocity is equal to the flame speed. The flame does not flash back because the flow velocity at the burner throat is higher than the flame speed. Neither does it blow off because the velocity downstream is lower than the flame speed.

Scaling of the Jet-LSB

For a premixed burner, a scaling formula for thermal input utilizes a reference flow velocity, $U_\infty = (\dot{m}_{\mathrm{air}}/\rho_{\mathrm{air}} + \dot{m}_{\mathrm{fuel}}/\rho_{\mathrm{fuel}})/A$, that is defined by the mass flow rates of air, $\dot{m}_{\mathrm{air}}$, and fuel, $\dot{m}_{\mathrm{fuel}}$, and the cross-sectional area of the burner, A. Thermal input is then calculated from $\dot{m}_{\mathrm{fuel}}$ by assuming a fixed heat release per unit mass. This is essentially the same scaling approach for non-premixed burners, (e.g. [10]). For simple burner designs, once the operating range of U_∞ is determined, a constant velocity criterion should apply, and the burner can be scaled to the desired thermal inputs by increasing its radius, R. In practice, R cannot be increased indefinitely because flow non-uniformity can develop inside the burner and restrict the operating range of large burners. For conventional high-swirl burners, a constant residence time criterion also applies. This residence time is often associated with the recirculation zone and is usually set to R/U_∞. Straub and Richards [11] have shown for a premixed, high-swirl gas turbine combustor that the transport time based on L/U_∞ (where L is the distance from the swirler to the throat) is an important parameter that controls the flame stability range. This is in accord with our previous investigation that showed that the operating swirl numbers of a jet-LSB are dependent on L. In scaling up to a larger size, all dimensions of the jet-LSB of Fig. 1a were doubled to infer which scaling criterion (or both) is relevant.

TABLE 1
Experimental conditions

	LBNL small water heater simulator, vertically fired $A_c/A_b + 15$	UCICL burner evaluation facility, vertically fired $A_c/A_b = 142$	UCICL furnace simulator, horizontally fired $A_c/A_b = 733$	A.D. Little boiler stimulator, vertically fired $A_c/A_b = 144$
Jet-LSB	Size: 5.28 cm i.d. 15–18 kW $0.7 < \phi < 0.95$	Size: 5.28 cm i.d. 18–106 kW $\phi = 0.8$	Size: 10.16 cm i.d. 146–585 kW $\phi = 0.8$	
Vane-LSB	Size: 5.28 cm i.d. 15–18 kW $0.7 < \phi < 0.95$	Size: 5.28 cm i.d. 14–73 kW $0.7 < \phi < 0.9$		Size: 7.68 cm i.d. 210–280 kW $0.58 < \phi < 0.95$

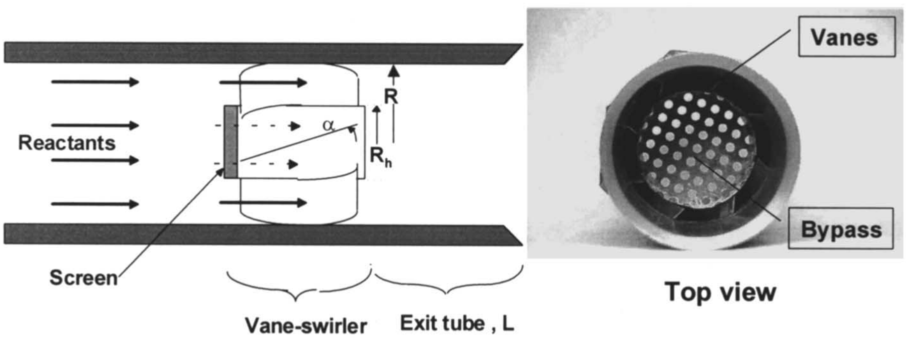

FIG. 2. Schematics and top view of a vane-LSB.

Schematics of three jet-LSBs are shown in Fig. 1. They were investigated at four different facilities (Table 1). The jet-LSBs of Fig. 1a and b are identical, with a swirl injector radius $R_\theta = 1.6$ mm, and an exit tube length of $L = 7$ cm. The only difference is the fuel supply hardware.

The schematic of the 10 cm jet-LSB is shown in Figure 1c. In increasing the diameter from 5.28 cm to 10.16 cm, the ratios R_θ/R (=0.06) and L/R (=2.7) are preserved by setting the swirl injector radius, R_θ, to 3.2 mm and the exit tube length, L, to 14 cm. The fuel injection point is also scaled to 80 cm upstream. The natural gas spoke is a small pipe with punctured holes pointing upstream. Two perforated plates enhance the mixing of the fuel and air. Immediately upstream of the swirler section, a 7 cm thick section of honeycomb material is used to remove large turbulence structures created in the premixing zone.

The swirl number, S, of jet-LSBs can be defined by the mass flow rate of the reactants, $\dot{m} = \dot{m}_{\text{air}} + \dot{m}_{\text{fuel}}$, the swirl air, $\dot{m}_\theta$, and the total swirl injector area, A_θ [12,13].

$$S \equiv \frac{R_\theta R \pi}{A_\theta} \left(\frac{\dot{m}_\theta}{\dot{m}}\right)^2 \qquad (1)$$

Vane-Swirler Development

The development of a vane-swirler is a critical step toward applying the LSB concept to practical use. This is because the separate main and swirl controls needed for the jet-LSBs are considered too complex and costly. Unfortunately, research on vane-swirlers has concentrated on high-swirl designs [14–16]. There is very little prior knowledge to support the design of a vane-swirler that generates the divergent flowfield needed for LSBs. Extensive experimentation led us to the design shown in Fig. 2 [17]. The key feature that distinguishes this vane-swirler from a conventional hub swirler is a cylindrical center bypass through which a portion of the reactants remains unswirled. The novelty of our design [18] is the use of screens with different blockage ratios to balance the pressure drops across the bypass and the swirl vanes. These screens also help to maintain a uniform radial flow distribution and generate turbulence.

In optimizing the vane-swirler design for lean premixed combustion, we used as benchmarks the nonreacting velocity profiles obtained previously for air-jet LSBs [6–9]. These measurements were made with a two-component laser Doppler anemometry

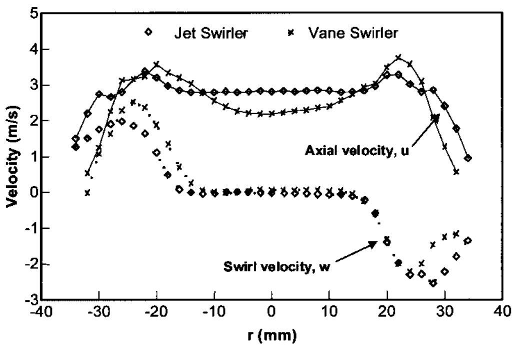

FIG. 3. Comparison of the non-reacting flowfield generated by a jet-LSB and a vane-LSB both with 5.28 cm i.d.

(LDA) system with differential frequencies of 5 MHz and 2 MHz to remove directional ambiguity from, respectively, the axial and the tangential components. This LDA system was also used to measure the velocity profiles at 5 mm above different vane-swirler prototypes fitted with an exit tube of $L = 7$ mm. The optimum configurations for an LSB with $R = 5.28$ cm i.d. were found to consist of a bypass radius of $R_h = 20.5$ mm, eight guide vanes angled at $37° < \alpha < 45°$, and a bypass screen blockage ratio of 60% to 75%. As shown in Fig. 3, mean velocity profiles above a vane-LSB fitted with 37° vanes and a screen with 65% blockage are almost identical to those measured in a jet-LSB. The slight dip in the U profile of the vane-LSB does not have a significant effect on flame stabilization. The only observable change is that the vane-LSB stabilizes a bowl-shaped flame, whereas the jet-LSB flame is more planar. The swirl velocity profiles show that the swirling motion does not penetrate to the center of the reactant stream.

In a previous paper, we reported the lean blow-off and flash-back limits for several 5.28 i.d. vane-LSBs with different screen blockages [17]. We also showed that the performance of a vane-LSB in an 18 kW water heater simulator was similar to that of a jet-LSB. For this study, a vane-LSB fitted with $\alpha = 37°$ vanes and a 75% blockage screen was investigated at firing rates up to 73 kW at the University of California, Irvine, Combustion Laboratory (UCICL) burner evaluation facility. In addition, the vane-LSB was also scaled to a larger size by increasing all the dimensions, except for the vane angle, α, by a factor of 1.5. The i.d. of the burner was 7.68 cm and the ratio $R_h/R = 0.776$ was preserved. The center bypass of this larger vane-swirler was fitted with a circular bock of 1.28 cm thick aluminum foam having an equivalent blockage ratio of about 80%. The large vane-swirler was investigated in a test furnace at Arthur D. Little, Inc.

In deriving the characteristic swirl number, S, for the vane-LSB, equation 1 does not apply. From the original definition based on the ratio of angular to axial flow momentum, S, for the new vane-swirler is

$$S = \int_0^R UWrdr \Big/ R\left(\int_{R_h}^R U^2rdr + \int_0^{R_h} U^2rdr\right) \quad (2)$$

which reduces to

$$S_v = \frac{2}{3} \tan \alpha \, \frac{1 - (R_h/R)^3}{1 + (R_h/R)^2((U_c/U_a)^2 - 1)} \quad (3)$$

U_c is the averaged axial velocity through the bypass, and U_a is the averaged axial velocity component in the outer annulus. U_c and U_a are not necessarily identical, because they are functions of the screen blockage.

For a fixed vane angle α, the functional dependence of S_v on U_c/U_a and R_h/R shows that it reduces to the proper physical limits in the extremes. For $U_c = 0$, equation 3 reduces to the definition of a hub swirler, and for $R_h \approx R$, S_v reduces to 0. Equation 3 also shows that S_v can be varied by changing either U_c/U_a or R_h/R. The difficulty in applying equation 3 is that it requires velocity data. Attempts to deduce S_v by integrating velocity profiles (e.g., Fig. 3) did not produce results that are consistent with the swirl number for a jet-LSB defined by equation 1 [17]. This is due to the large uncertainties associated with integrating velocities close to $r \approx R$, where large gradients exist. Though the exact definition of a swirl number for the vane-LSB does not present an impediment for the present study, this issue needs to be resolved for the future development of the LSB to even larger scales.

Facilities and Experimental Conditions

The facilities and experimental conditions are listed in Table 1. All experiments were performed using natural gas supplied at the different sites. The water heater simulator at the Lawrence Berkeley National Laboratory (LBNL) used a commercial heat exchanger of 15 kW [19]. It was rectangular (15 cm × 22 cm × 24 cm), with finned tubes mounted 4 cm below the top. Input flow measurements were made with electronic turbine meters and calibrated rotameters. Emissions were sampled 50 cm downstream of the heat exchanger in a 10 cm diameter exhaust flue.

The burner evaluation facility at UCICL was used to determine the turn-down of 5.28 cm i.d. jet-LSBs and the emissions of a 5.28 cm i.d. vane-LSB at higher thermal inputs. The facility had an octagonal-shaped enclosure 60 cm across and 175 cm in height. The bottom of the enclosure was fitted with eight high-temperature windows (25 cm × 30 cm), and the upper portion had eight water cooled panels (25 cm × 60 cm). Calibrated rotameters were used to independently measure the combustion air, gas, and

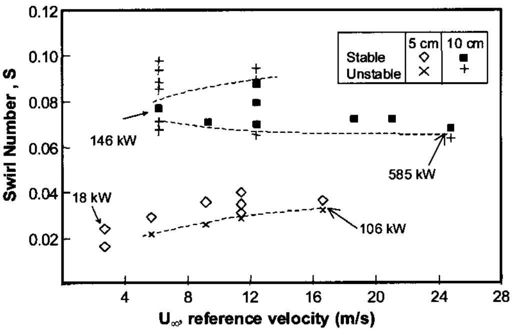

FIG. 4. Stability regimes for the 5 cm jet-LSB in the UCICL burner evaluation facility and for the 10 cm jet-LSB in the furnace simulator.

swirl air flow rates. Emissions were sampled 150 cm above the enclosure floor. The chamber to burner ratio, A_c/A_b, is an order of magnitude larger than that of the LBNL water heater simulator.

The 10 cm jet-LSB was mounted horizontally in the furnace simulator at UCICL. The furnace chamber was 2.4 m square by 3.0 m long and accepted thermal inputs up to 1.16 MW. The exhaust flue was at the wall opposite to the burner and emissions were sampled in the stack. Details of the facility can be found in Refs. [20,21].

The emission and stability of a 7.68 cm vane-LSB was investigated in a boiler simulator facility at Arthur D. Little, Inc. It had a vertical cylindrical chamber of 1.5 m i.d. and 3 m length and accepted a thermal input up to 0.75 MW. The burner was mounted at the bottom of the chamber, with natural gas supplied by a fuel distributor 30 cm upstream of the swirler. Emissions were sampled in the stack. The fuel to air ratios were computed based on the measured oxygen concentrations.

At all the facilities, stainless steel, water-cooled sampling probes were used. They were located in the exhaust stack, far downstream of the burner exit, in well-mixed regions of the exhaust flows. The samples were transported through heated lines to an NO_x converter, water dropout, and then to the emissions analyzers. NO_x concentrations were measured using chemiluminescence analyzers (Horiba model CLA-22 at UCICL, Thermo Electron Corp. Model 14A at LBNL). CO and CO_2 emissions were measured using non-dispersive infrared analyzers (Horiba model AIA-220 at UCICL, Bendix CO Analyzer at LBNL). Hydrocarbon and oxygen concentrations were measured using a flame ionization detector and paramagnetic analyzer, respectively (Horiba model FIA/PMA-220 at UCICL). The span gas concentrations were selected to coincide with the expected exhaust gas concentration range. The accuracy of all the analyzers was 1% full-scale of the range selected. The analyzers were calibrated at 50% to 80% of the full-scale range in the expected concentration range of the exhaust gas samples. The uncertainties of our emissions sampling systems were estimated to be ± 1 ppm for NO_x, ± 10 ppm for CO, and ± 10 ppm for unburned hydrocarbons (UHCs).

Results and Discussion

At different thermal inputs, the range between the minimum and maximum swirl numbers that support a stable flame defines the stability regime of an LSB. The stability regimes determined for the 5.28 cm and the 10.16 cm jet-LSB at $\phi = 0.8$ are compared in Fig. 4. The reference velocity, U_∞, is used as the independent variable to show the relevance of constant velocity scaling. The small jet-LSB was operated up to the maximum thermal input (106 kW) allowable at the burner evaluation facility. This corresponds to $2.7 < U_\infty < 16.6$ m/s and a 6:1 turndown. The boundary of minimum S shows a slight increase from 0.018 to 0.035 with increasing U_∞. This is consistent with previous work where a maximum $S = 0.15$ was also determined.

Successful firing of the 10 cm jet-LSB up to $Q = 585$ kW verifies the validity of constant velocity scaling. Though the furnace simulator can accept high thermal inputs, our test conditions were restricted to $Q < 585$ kW due to a limitation of compressed air for the swirler. At $Q = 585$ kW, the bowl-shaped flame was about 30 cm wide and 45 cm long. Fig. 4 also shows that the larger burner has a minimum U_∞ of 6.2 m/s that is higher than the minimum $U_\infty = 3.0$ m/s found for the smaller burner. Near the point of minimum thermal input, the operating range of S for the large burner is quite narrow. Two factors may contribute to this trend. First, flow uniformity across the larger burner may be more difficult to achieve due to the use of a longer tube length, L, that promotes transition to pipe flow distribution. Changes in the radial distribution of the mean axial velocity can affect the formation of flow divergence at the exit. Second, turbulence intensity may be higher and may result in a higher flame speed that could promote premature flashback.

The swirl number needed for the larger jet-LSB is almost constant at $S = 0.078$. This is a very important feature for future vane-swirler development because it implies that a variable-geometry vane-swirler is not needed for turn-down. The higher swirl numbers found for the larger burner also confirm the relevance of constant residence time scaling. The ratio between S for the large and small burner is approximately 2 and is the ratio of their exit tube length, L, downstream of the swirler. With a longer residence time, the swirling flow loses more of the angular momentum to the core reactants stream. Therefore, a higher swirl air rate is needed to compensate for the loss. This result shows the exit tube

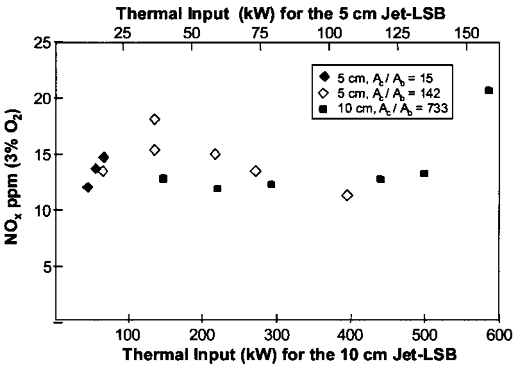

FIG. 5. NO_x emissions for three jet-LSBs at $\phi = 0.8$. The at upper and lower ordinates are scaled to constant U_∞.

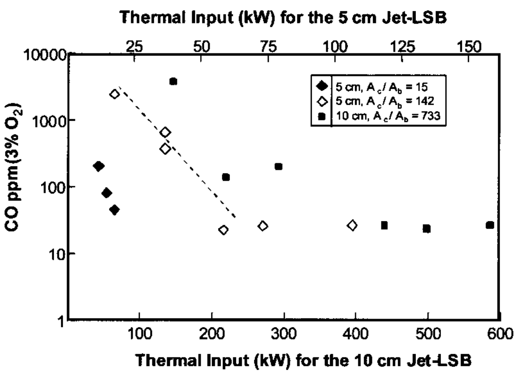

FIG. 6. CO emissions for three jet-LSBs at $\phi = 0.8$.

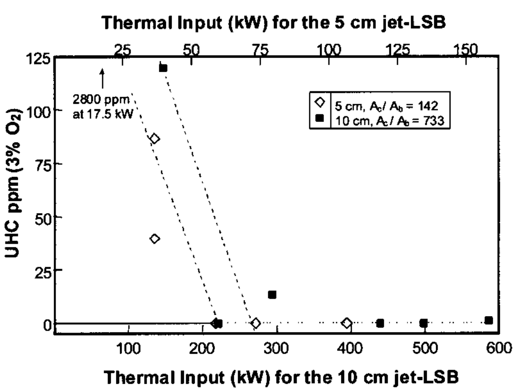

FIG. 7. UHC emissions for three jet-LSBs at $\phi = 0.8$.

length to be an important parameter for LSB that should be scaled independent of the burner radius.

Figures 5, 6, and 7 show, respectively, the NO_x, CO, and UHC emissions at $\phi = 0.8$ from the three facilities (LBNL water heater simulator, UCICL burner evaluation facility, and the UCICL furnace simulator). The upper and lower ordinates of these plots have been scaled to the same U_∞. As shown in Fig. 5, the NO_x emissions are independent of thermal input, U_∞, burner radius, and enclosure size. For the large jet-LSB, NO_x remains constant at 14 ppm up to $Q = 0.5$ MW. The slight increase to 21 ppm observed at 0.58 MW may be due to the fact that this experiment was performed under less than optimum conditions. Restricted by swirl air supply, we were only able to access a condition very close to the blow-off limit (Fig. 4). The flame was not as stable as those studied at low thermal inputs. Flame instability can effect the overall flame emissions.

For the small burners, NO_x emissions ranged between 12 and 17 ppm. These NO_x concentrations are similar to those reported for small laminar flames generated in flat flame burners. Considering system-to-system variations, our results strongly imply that in LSBs, flow velocity, turbulence, chamber environment, and flame sizes do not alter the basic NO_x formation mechanism. The key control parameter for NO_x is the equivalence ratio. This is very different from other premixed burners, where pulsing the recirculation zone behind a bluff-body flame stabilizer can affect NO_x emissions [5].

The corresponding CO emissions are shown in Fig. 6. A large disparity between the CO emissions measured in the LBNL water heater simulator (50 ppm) and in the UCICL burner evaluation facility (2500 ppm) at 18 kW demonstrates a strong influence of chamber size. CO emissions from the 10.16 cm i.d. burner were also very high for $100 < Q < 300$ kW. However, with increasing thermal input, CO emissions in both large and small jet-LSBs decreased rapidly and leveled out at CO = 25 ppm. The point at which CO emissions reach 25 ppm is, therefore, a practical limit for specifying the minimum thermal input for different systems.

In Fig. 7, UHC emissions also show strong burner-chamber coupling. The exceedingly high UHC emissions (2800 ppm) from the small jet-LSB at 18 kW indicates very poor combustion efficiency. Simultaneous high CO and UHC concentrations seem to be caused by a small flame burning in a large chamber, such that interaction with cooler furnace gases dilutes the reactants and quenches the flame at its periphery. The faster dilution rate in the plume can also promote rapid cooling of the combustion products to prevent CO oxidization. Significant decreases in both UHC and CO emissions at higher thermal input supports this argument. The undetectable UHC emissions measured at higher thermal input show

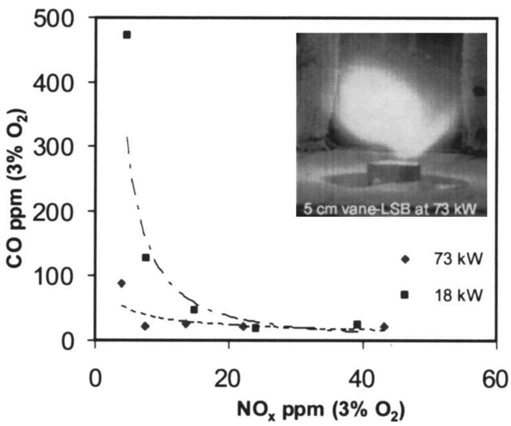

FIG. 8. NO_x and CO emissions of a 5.28 cm i.d. vane-LSB at 18 and 73 kW.

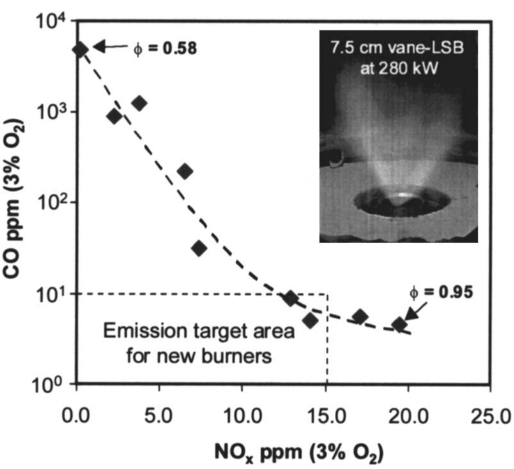

FIG. 9. NO_x and CO emissions from a 7.5 cm vane-LSB at $210 < Q < 280$ kW and $0.58 < \phi < 0.95$.

that the LSB can perform with high combustion efficiency. These results illustrate that controlling CO emissions and increasing combustion efficiency are system optimization issues.

The 5.28 cm vane-LSB was investigated at 18 kW and 73 kW with $0.7 < \phi < 0.95$. NO_x, and CO emissions are compared in Fig. 8. The flame at 73 kW is stable, and the lean blow-off limits remained unchanged. Separate tests performed at the facility of one of our industrial collaborators have shown that this 5.28 cm vane-LSB can be fired up to 150 kW. This 10:1 turn-down can be achieved because the swirl number for flame stabilization is independent of U_∞ (see Fig. 4). As shown in the inset in Fig. 8, the vane-LSB produces a compact flame. Its width is about 12 cm, and it is relatively short. In Fig. 8, the emissions data trends are typical of those measured in lean premixed flames. The reduction of NO_x from 43 to 4 ppm is due to changing ϕ from 0.95 to 0.7. Differences in the trends of CO emissions for the two sets of data (Q = 18 and 73 kW) show again the influence of chamber size. Under the leanest condition we have investigated (ϕ = 0.7), CO emissions differ by a factor of 5. But the disparity disappears at $\phi > 0.85$. The emission of UHCs was also measured but is not shown and indicated the same trend as in Fig. 7.

Experimental conditions at Arthur D. Little's boiler simulator were $210 < Q < 280$ kW and $0.58 < \phi < 0.95$. These thermal inputs correspond to an average U_∞ of 20 m/s. Success in firing the vane-swirler under these conditions confirms that the vane-swirler can be scaled by the constant velocity criterion. Furthermore, a larger-diameter vane-swirler does not affect lean blow-off, thus preserving the most significant feature of an LSB. The photograph in Fig. 9 shows the flame to be more elongated than the one shown in Fig. 8. This is due to the use of aluminum foam in the center bypass. Though the blockage ratio of the perforated plate used in the 5 cm vane-LSB is identical to that of the aluminum foam, turbulence intensities produced downstream are different. The aluminum foam generates lower turbulence and therefore a less compact flame. This shows that the vane-swirler design can be further exploited for flame shaping. In Fig. 9, the relative change in NO_x and CO emissions is associated with changes in ϕ. Close to stoichiometric conditions, NO_x is about 20 ppm and CO is 8 ppm. These emissions are already below the current air-quality rules for southern California of less than 30 ppm NO_x, and it is the manufacturers' preference to limit CO to less than 50 ppm. Close to the blow-off limit ϕ = 0.58, NO_x is below a detectable level, but the CO emission is unacceptably high. However, it is the regime of stable operation conditions $0.8 < \phi < 0.9$ where NO_x is less than 15 ppm and CO less than 10 ppm that should be exploited for practical applications.

Conclusions

A low-swirl burner (LSB) has been scaled to the thermal input levels of small industrial size to investigate its viability for use in commercial and industrial furnaces and boilers. The purpose of this study was to conduct experiments to derive scaling laws and to determine if scaling affects the performance in terms of combustion efficiency, lean blow-off limit, and emissions of NO_x and CO. First, the original 5.28 cm i.d. LSB that used an air-jet swirler was scaled to 10.26 cm i.d. and investigated up to a firing rate of Q = 586 kW. Then two LSBs (5.28 and 7.68 cm i.d.) configured to accept a novel vane-swirler design were evaluated up to $Q = 73$ kW and 280 kW, respectively.

Following are our main conclusions:

1. A constant velocity criterion is valid for scaling the burner diameter to accept higher thermal inputs.
2. The swirler should be scaled independently by using a constant residence time criterion.
3. Increasing burner diameter increases the minimum flow velocity for stable operation.
4. Maximum thermal input has yet to be found because our test conditions have reached the maximum thermal input allowable by the test facilities.
5. Swirl numbers of large jet-LSBs remain constant with increasing thermal input.
6. NO_x emissions are independent of thermal input and are only a function of the equivalence ratio.
7. Emissions of CO and UHCs are strongly coupled to chamber size and are extremely high at low thermal inputs.
8. The vane swirler can be scaled to larger sizes without affecting lean blow-off.
9. The emissions of the vane-LSB measured between 210 and 280 kW output for $0.8 < \phi < 0.9$ ($NO_x < 15$ ppm and CO < 10 ppm), indicating a strong potential for applying LSBs to practical applications.

Acknowledgments

This work was supported by the California Institute of Energy Efficiency through the U.S. Department of Energy under contract no. DE-AC03-76F00098. Work performed at A. D. Little, Inc., was supported by in-kind contribution.

REFERENCES

1. Keller, J. O., Bramlette, T. T., Barr, P. K., and Alvarez, J. R., *Combust. Flame* 99:460 (1994).
2. Bradley, D., Gaskell, P. H., Gu, X. J., Lawes, M., and Scott, M. J., *Combust. Flame* 115:515 (1998).
3. Brewster, B. S., Cannon, S. M., Farmer, J. R., and Meng, F. L., *Prog. Energy Combust. Sci.* 25:353 (1999).
4. Richards, G. A., Janus, M., and Robey, E. H., *J. Prop. Power* 15:232 (1999).
5. Poppe, C., Sivasegaram, S., and Whitelaw, J. H., *Combust. Flame* 113:13 (1998).
6. Chan, C. K., Lau, K. S., Chin, W. K., and Cheng, R. K., *Proc. Combust. Inst.* 24:511 (1992).
7. Cheng, R. K., *Combust. Flame* 101:1 (1995).
8. Bedat, B., and Cheng, R. K., *Combust. Flame* 100:485 (1995).
9. Yegian, D. T., and Cheng, R. K., *Combust. Sci. Technol.* 139:207 (1998).
10. Weber, R., and Breussin, F., *Proc. Combust. Inst.* 27:2957 (1998).
11. Straub, D., and Richards, G., "Effects of Axial Swirl Vane Location on Combustion Dynamics," ASME paper 99-GT-109, ASME/IGTI Turbo Expo, Indianapolis, IN, June 7–9, 1999.
12. Claypole, T. C., and Syred, N., *Proc. Combust. Inst.* 18:81 (1980).
13. Feikema, D., Chen, R. H., and Driscoll, J. F., *Combust. Flame* 80:183 (1990).
14. Syred, N., and Beér, J. M., *Combust. Flame* 23:143 (1974).
15. Beér, J. M., and Chigier, N. A., *Combustion Aerodynamics,* Applied Science Publishers, London, 1972, p. 100.
16. Lilley, D. G., *AIAA J.* 15:1063 (1977).
17. Yegian, D. T., and Cheng, R. K., "Development of a Vane-Swirler for Use in a Low NO_x Weak-Swirl Burner," American Flame Research Committee International Symposium, Baltimore, MD, Sept. 30–Oct. 2, 1996.
18. Cheng, R. K., and Yegian, D. T., *Mechanical Swirler for a Low-NO_x Weak-Swirl Burner,* U.S. Patent 5879148, 1999.
19. Yegian, D. T., and Cheng, R. K., "Laboratory Study of a Low NO_x Water Heater with a Weak-Swirl Burner," Symposium of Fire and Combustion Systems, ASME IMECE, San Francisco, Nov. 12–17, 1995.
20. Miyasato, M. M., and Samuelsen, G. S., "Near-Burner Flow-Field Characterization and Its Relation to Performance in a Model, Industrial, Natural-Gas Fixed Burner," AFRC Fall International Symposium, Monterey, CA, Oct. 15–18, 1995.
21. Weakley, C. K., and Samuelsen, G. S., "Parametric Characterization of a Full-Scale, High Temperature Industrial Burner in a Controlled Simulation of a Thermal Oxidizer for VOC Emission Control," AFRC Fall International Symposium, Baltimore, MD, Sept. 2–Oct. 2, 1996.

COMMENTS

J. M. Beér, MIT, USA. This is an elegant solution to the problem of reducing the pressure drop across a low NO_x burner. Boiler applications require the use of preheated air (~550 K) and to burn natural gas close to the stoichiometric ratio (O ~ 0.98). How would the NO_x emission develop with these parameters?

Author's Reply. As in all premixed burners, we expect that NO_x emissions will increase when firing with preheated air at near stoichiometric conditions. There are several approaches that can be used in conjunction with the LSB concept to counter this increase. We have tested LSBs with recirculated flue gas and obtained very promising results. Another option is to combine the basic LSB design with some form of fuel or air staging. Incorporation of these auxiliary methods to LSB will be an integral part of the burner/boiler optimization process that is system specific and involves other practical considerations such as energy efficiency/emissions trade-off, reliability, and cost.

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Philip C. Malte, University of Washington, USA. The low NO_x emissions of your burner are impressive. In this regard, it would be interesting to know the temperature of the flame in your experiments. Low emission of NO_x is typically associated with flame-formed NO_x rather the post-flame thermal NO_x, especially for lean combustion. Under low load, there might be heat loss from your flame (and thus reduced flame temperature) sufficient to account for the very low NO_x emission of about a few ppm (3% O_2) NO_x reported.

Author's Reply. This question refers to our recent results that were presented at the Symposium but are not included in the paper. The results show that for $\phi = 0.86$ NO_x emission is 8.1 ppm (3% O_2) at 1 MW and 28.9 ppm (3% O_2) at 0.18 MW. This trend cannot be explained by the heat loss effect. We suspect that at high load, the high burner exit velocity (approaching 60 m/s) promotes internal flue gas recirculation within the furnace to further reduce NO_x emissions. We plan to perform further studies to investigate this phenomenon.

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Kozo Saito, University of Kentucky, USA. This is practical and useful work. Could you let me know what is the minimum scale (size) that can simulate the full scale system and why?

Author's Reply. Our largest LSB (10.16 cm ID) can be considered full scale for small industrial applications and about quarter-scale for large utility systems. As our results show, this larger burner can be simulated by our smallest unit (5.28 cm ID). This is because the turbulent flame speed (at least in this configuration) seems to be a linear function of turbulence intensity and the swirl number needed for flame stabilization is independent of U_∞.