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ABSTRACT

This paper reports a study of the velocity and scalar characteristics of the weak-swirl burner in enclosures. WSB utilizes a unique aerodynamic mechanism to stabilize lean burning premixed combustion over a wide range of equivalence ratios ($\phi$) and power inputs. As the WSB was developed for fundamental research, previous works focused only on open WSBs. Recent success in adapting the WSB to practical use suggests that a better understanding of the WSB in enclosures is required for further development. Laser Doppler anemometry (LDA), and Mie scattering of oil droplets (MSOD), are used to measure the flame flowfields and flame crossing spectra of the WSB with an open flame, enclosed within a quartz cylinder and within a cylinder with a restricted exit. The flame of the enclosed WSB remained extremely stable and did not develop recirculation zones or audible characteristics. The only change observed was a greater divergence of the flowfield upstream of the reaction zone. Neither lengthening the enclosure nor restricting the flow downstream caused any noticeable difference in the operation of the WSB. This work has demonstrated that the WSB should be amenable for adaptation to a wide variety of low NOX applications.

INTRODUCTION

Since its recent inception, the premixed weak-swirl burner (WSB) [1-5] has demonstrated to be an important tool to both fundamental combustion research and commercial applications. The main advantage of the WSB for research is that it offers a wide range of operating conditions. The flame brush is stationary and detached from the burner for easy access by laser diagnostics. Bedat & Cheng [2] designed a WSB to infer detailed premixed flame structures
under intense turbulence. Their density statistics showed no evidence that indicated significant
deviation from flamelet characteristics. Cheng [3] used the WSB to investigate the evolution of
velocity statistics with decreasing equivalence ratios and found that the lean flames have very
little influence on the velocity statistics. Recently, the WSB has been used for examining scalar
dissipation in premixed turbulent flames [6].

Commercial interest on the WSB stems from its lean burn capability. As conventional
natural gas burners utilize rich flames, the high flame temperatures contribute to the production
of unacceptable levels of NO\textsubscript{x} emission. To meet proposed tougher legislation (NO\textsubscript{x} < 50 ppm
or 25 ppm), lean premixed burners are emerging as attractive and less costly alternatives to
conventional approaches such as staged combustion, product gas recirculation and catalysts.
Lean-burning lowers the flame temperatures, thus reducing the formation of NO\textsubscript{x} through
thermal generation. To assess the use of WSB in water heaters, Teledyne Laars of Moorpark CA
is collaborating with LBNL to conduct laboratory feasibility studies of a WSB hot water heater.
The results we have obtained thus far are most encouraging and show that the laboratory WSB
system can easily meet possible future NO\textsubscript{x} emissions standards of < 25 ppm (at \(\phi < 0.85\)) over a
range of power levels [4,5]. More importantly, the low NO\textsubscript{x} emission is achieved without
sacrificing thermal efficiency nor increasing CO emission over the permissible limit.

For use in water heaters, the WSB needs to be enclosed within the casing of a heat
exchanger. Although our experiments have shown that the WSB remains stable in an enclosure,
a better understanding of how an enclosure affects the WSB’s flowfield is necessary. Questions
on whether or not flow recirculation develops, how mean stretch rates are influenced, if acoustic
coupling arises, and how velocity patterns differ between the open and enclosed situations need
to be addressed. The knowledge gained by these studies is necessary to guide the design for
scaling up the burner and for accommodating different heat exchanger geometries. Moreover,
characterizing the WSB in enclosure will provide the fundamental information to evaluate if it
can be applied in more stringent environments such as those of large furnaces, boilers and
perhaps gas turbines.
APPARATUS AND DIAGNOSTICS

As details of the WSB and laser diagnostics are described previously [1,2,5], only a brief summary is included here. Figure 1 shows a schematic of the WSB, the enclosure geometry and the laser diagnostics. The WSB used here is the second generation design with 52 mm inner tube diameter and it does not have co-flow [2,4,5]. The burner is mounted on top of a large settling chamber which supplies the premixture. The premixture exits the settling chamber through a converging nozzle that produces a laminar flowfield in the WSB tube. The two screens on either end of the burner tube not only act as flashback arrestors, but also as generators of uniform turbulence of about 8%. The amount of swirl air provided through each of the four tangentially mounted jets can be adjusted independently to produce a uniform divergent flowfield as the premixture leaves the exit tube. To quantify the amount of swirl, Claypole and Syred [7] have shown that the swirl number $S$ can be obtained from the burner geometry and the ratio of tangential mass flow rate to the axial flux

$$S = \frac{\pi r_0 R}{A_0} \left(\frac{m_\theta}{m_\theta + m_a}\right)^2$$

where $r_0$ (1.6 mm) and $R$ (26 mm) are the radius of the tangential air injectors and burner respectively, $A_0$ (32.2 mm$^2$) is the total area of the injectors, and $m_\theta$ and $m_a$ are the total mass flows in the tangential and axial directions. However, slight flame asymmetry is unavoidable under some conditions. Both the inclined angle (20°) of the swirl jets and the exit tube length (7 cm) were chosen through earlier testing of the WSB's stability limits and performance.

The length of the enclosure, $L$, and its exit configuration are altered to examine their effects on the WSB's performance and flowfield (see Fig. 1). The enclosures are two 156 mm diameter quartz cylinders with $L$ = 200 or 300 mm. They are placed on top of the swirler section such that the exit tube extends 50 mm into the cylinder. The enclosure area is nine times as large as the exit tube and is approximately the same area as the interior of a heat exchanger used in the water heater test station [5]. The quartz cylinder eliminates disturbances to the flowfield due to interaction with the cool ambient air. The "open-channel" (Fig. 1 insert bottom left) case is typical of burner arrangements found in large boilers and furnaces where the flame is directed into a large combustion chamber through a burner tube. The effects of restrictive exit is evaluated by the "restricted-channel" case (Fig. 1 insert bottom right). Restriction is created by
capping the quartz cylinder with a stainless steel plate that has a 52 mm opening centered directly above the burner exit tube. This configuration simulates water heaters with an exhaust chimney and also the combustor geometry of gas turbines. The reduction in our exhaust area (11%) is more severe than that found in commercial water heaters (46%). It was chosen to bring-out any effects downstream restrictions might have on the flowfield of the WSB.

**FIGURE 1:** Basic schematic of test station for laser diagnostics (LDA and MSOD) and the WSB with diagrams of cylinder and restricted cylinder configurations.
Flow velocities are measured by a two-component, four beam LDA system consisting of two TSI frequency counters, two photomultipliers, and a 4W Spectra Physics argon ion laser. All four beams are frequency shifted to remove directional ambiguity, with the two 488 nm beams shifted by 5 MHz, and 2 MHz differential shifting frequency for the two 514 nm beams. The LDA system is arranged to measure the axial velocity component, \( U \), with the two 488 nm beams and the radial component, \( V \), with the two 514 nm beams. As shown previously [1], the circumferential component, \( W \), is effectively zero within the central core of the premixture (\( r \approx 20 \text{ mm} \)), therefore this component will not be examined. Mean velocities, RMS velocities, and flowlines are deduced from 1024 validated velocity pairs obtained using 0.05 micron Al\(_2\)O\(_3\) particles.

The flame crossing frequency spectra are measured by the Mie scattering from oil droplets (MSOD) method [8]. This is a convenient method to measure time and length scales of premixed turbulent flames. It is used here to infer if the enclosure and downstream restriction induces regular flame motion that may lead to flame/acoustic coupling. The optics are relatively simple as our system uses the same 488 nm beams produced by the LDA transmitting optics. This enables us to switch conveniently between LDA and Mie scattering measurements. Mie scattering intensities at the beam waist are collected by a photomultiplier tube arranged perpendicular to the beam direction. As the oil aerosol burns and evaporates at the flame zone, the output Mie signal resembles that of a telegraph. For frequency spectra the Mie scattering output was sampled at 4 kHz with 2 Hz bandwidth.

**TEST RESULTS AND DISCUSSION**

Figure 2 displays the centerline velocities for three equivalence ratios (\( \phi = 0.7, 0.8, 0.9 \)) in three different configuration; open flame, open-channel, and restricted-channel. As centerline distance was measured from the WSB exit tube rim that extends 50 mm into the quartz cylinder, the end of the \( L = 200 \text{ mm} \) enclosure is at \( x = 150 \text{ mm} \). With power being held constant at 18 kW for all cases, the axial velocity, \( U \), without swirl, \( U_\infty \), increases slightly from 2.4 m/s at \( \phi = 0.9 \), to 2.7 m/s at \( \phi = 0.8 \), and 3.0 m/s at \( \phi = 0.7 \). Since \( S \) varies only slightly, one would expect \( U \) at the burner exit to be slightly greater for lower \( \phi \) as is the case.
FIGURE 2: Centerline velocities for $\phi = 0.7, 0.8, 0.9$ for open/cylinder/restricted cases for power = 18 kW and $L = 200$ mm.
By comparing the local peak $U$ at the trailing edge of the reaction zone ($x \approx 40 - 50$ mm), one can see that the acceleration due to combustion is greater the closer $\phi$ is to stoichiometric. This result has been seen before [3] and arises due to higher flame temperatures, and thus lower density and increased velocities. An interesting trend is the rather flat $U$ profiles for the open cases immediately following the reaction zone. Only a mild decrease is seen until $x \approx 70 - 80$ mm, followed by slight increase for the length of the record. As there is no enclosure separating the hot combustion gases from the cool ambient air, buoyancy induced acceleration and contraction of the hot products plume could be the explanation for such an increase. Once an enclosure is placed around the reaction zone, this increase disappears and $U$ drops steadily from its peak velocity until leveling out around $x \approx 100$ mm. By then, the combustion products have uniformly spread to the edges of the enclosure and, as they can no longer diverge, travel downstream at the same velocity. Most importantly, none of the velocity profiles dip below zero which would have suggested flow recirculation.

Placing the downstream restriction on the enclosure has two noticeable effects. First, the leading edge of the reaction zone (as defined by the minimum $U$) is pushed upstream 5 mm from its earlier position at $x \approx 20-25$ mm. The most probable cause is an increase in backpressure causing greater divergence of the premixture, thus allowing the flame brush to stabilize itself closer to the burner exit. Visually, the flame brush becomes slightly flatter and thinner when the restriction is placed on the quartz cylinder, supporting the above explanation. Again, no evidence of recirculation is found for the restricted-channel cases. The only significant difference in $U$ between the open and restricted channel begins at $x = 80$ mm. As the restriction decreases the enclosure area by 88%, the products must converge to exit the enclosure and thus $U$ increases along the centerline. Due to this acceleration, the results suggest that the optimum placement of a fin-and-tube heat exchanger would be at least 70 mm upstream of the restriction for the present configuration. Otherwise, the decrease in flow velocity at the edges of the enclosure would compromise heat transfer efficiency.

Figure 3 compares the effects of enclosure length, $L$, for open/channel/restricted cases (with constant $\phi$, $S$, and power). For both $L = 200$ and $L = 300$, the leading edge of the reaction zone moves 5 mm upstream when the downstream restriction is in place. As shown by this
FIGURE 3: Centerline velocities with different enclosure lengths, L

comparison, U at the leading edge of the reaction zone is higher for the restricted cases than for either the open or open-ended channel runs. This suggests downstream restriction may have caused increases in the turbulent burning speed. This notion, however, can only be confirmed with more thorough investigation that includes changes in radial velocities and mean flame stretch. The restricted-channel for L = 200 mm again shows the centerline flow acceleration occurring at approximately x = 80 mm. For the longer cylinder, L = 300 mm, the velocity profile downstream of the flame zone is almost identical to the two open-channel cases. This is reasonable because the last measurement point is 100 mm upstream of the restriction and as shown earlier, the convergence of the products has not yet begun to affect the flow.

The reacting and non-reacting flowfields for open and open-cylinder situations are compared in Figure 4. The condition of φ = 0.8, power at 18 kW, and S = 0.06, is the same as the optimum conditions found for the laboratory water heater. The two non-reacting flows show the cylinder flow results in a much greater divergence of the velocity vectors. An analysis of the strain rates, dV/dr, in the central core flow (0 ≤ r ≤ 18) for 5 ≤ x ≤ 25 shows an average strain
FIGURE 4: Open/Enclosed flowfields for non-reacting and reacting conditions
rate of 15.8/sec for the open condition versus $dV/dr = 31.8$/sec for the enclosed flow. The cylinder eliminates the influence of the ambient air and causes the premixture to fill the entire enclosure (to $r = 78$ mm) within a short distance downstream. The open condition imposes no such static boundary condition or defined volume to fill, and thus the premixture diverges at a slower rate. The slight asymmetry seen in the enclosed flowfield is likely due to an imbalance in the swirl jets.

The reacting flowfields show similar trends as the non-reacting cases. It should be noted that the LDA measurements for the enclosed reacting condition could not be extended as far radially due to thermophoresis depositing alumina particles on the quartz cylinder and greatly diminishing the data collection rate. As seen earlier, there is greater divergence for the enclosed condition. However it is not as dramatic as in the non-reacting situation. Average mean stretch were computed to be 29.4/sec and 36.7/sec for the reacting open and enclosed conditions respectively, versus 15.8/sec and 31.8/sec for non-reacting cases. The flowlines at $r = 10$ and 20 mm clearly illustrate the effects of higher strain rates. Not only is a greater divergence seen for the enclosed flowfield, but the divergence persists farther downstream as the products continue to fill the entire enclosure area. The open flowlines have an inflection point at $x \approx 50$ mm, causing the traces to straighten out. Thus, $U$ is higher further downstream for the open case than for the enclosed case (Fig. 2).

The flame crossing spectra were used to determine if enclosing the WSB had caused any regular flame bouncing motion that could lead to coupling between the flame and acoustics characteristics of the chamber. Figure 5 shows the normalized frequency spectra of the open/open-channel/restricted-channel runs for $L = 200$ and $L = 300$. In order to easily compare these spectra each trace was displaced by 1 db from the other. Discounting the inflection at the high frequency end of the open-channel, $L = 300$ case (likely caused by diminishing of the signal to noise ratio due to clouding of the quartz cylinder), there is no noticeable difference for any of the spectra traces in both sets. If acoustic coupling was to occur, definite spikes would appear at energetic frequencies corresponding to resonant conditions. These scalar and velocity measurements of the WSB in enclosures demonstrate that the flame zone is relatively insensitive to the downstream boundary conditions and therefore should be quite amenable for adaptation to a wide range of practical applications.
\( \phi = 0.80, \text{Power} = 18 \text{ kW, } S = 0.06 \)

\[
\begin{array}{c|c|c|c}
\text{One decade per division} & \text{Restricted channel} & L = 200 \text{ mm} & \text{Restricted channel} & L = 300 \text{ mm} \\
\hline
\text{Open} & \text{Channel} & \text{Open} & \text{Channel} \\
\end{array}
\]

**FIGURE 5:** Frequency spectra for open/cylinder/restricted cases for different L.

**CONCLUSION**

This study is prompted by recent progress in adapting the weak-swirl burner to a laboratory water heater system for the development of low NO\(_x\) natural gas appliances. To scale the burner for larger water heaters and to evaluate the feasibility for other industrial and commercial heating systems, there is a need to gain a better understanding of the fluid dynamics of an enclosed WSB and any destabilizing effects the enclosure might produce. Laser diagnostic techniques (LDA and MSOD) were used to investigate flame and flowfield behavior in configurations that simulate practical situations. The measurements include centerline velocities, mean stretch, flame crossing spectra, and 2D velocity vectors. Using a quartz cylinder to simulate a combustor or heat exchanger casing, the experiments involve an open flame, a flame enclosed in an open cylinder (open-channel), and a flame enclosed in a cylinder with a restricted exit (restricted-channel).

Within the flame zone, the centerline velocity profiles showed very little effect of enclosure and downstream restriction. Most importantly, there was no evidence of recirculation zones developing anywhere inside the enclosure. The divergence of the reacting flowfields were
fairly uniform under both the open and enclosed conditions. Mean stretch was found to increase in the enclosed flowfields as the products spread until filling the entire enclosure. This leads to lower centerline velocities when compared to the open cases. Placing a downstream restriction on the enclosure caused the divergence to increase even more and moved the flame closer to the burner exit. In the product region downstream of the flame brush, the profiles of the open-channel and restricted-channel cases are comparable. Flow acceleration is shown beginning about 70 mm upstream of the restricted exit where the constriction of combustion products begins.

There was no observable discrete flame crossing frequency on the spectra to suggest coupling between the flame motion and the acoustics of the system. In fact, the frequency spectra were remarkably similar under all observed conditions. These were found for different enclosure lengths and downstream restriction. As these tests and measurements have shown that enclosing the WSB does not result in any destabilizing effects, the WSB should be amenable for adaptation to a wide variety of low NOx applications.

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