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Technical Notes

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Effects of Pressure on Performance of Mesoscale Burner Arrays for Gas-Turbine Applications

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Introduction

A PROMISING development in the quest to improve gas-turbine efficiency is the use of mesoscale burner arrays. A burner array of millimeter-scale dimensions provides the possibility of distributed combustion with a very compact combustion region. With these compact flames, the mesoscale burners can be arranged in reheat stages, thereby increasing thermal efficiency without adding substantial length and weight to the engine [1,2]. Mesoscale arrays also may be used in the turbine main burner in a lean direct injection mode with no secondary air, and array elements can be operated in an on/off mode to provide improved efficiency and emissions at partial load. Moreover, to reduce NO_x emissions, the arrays can be run in a lean premixed mode or using highly vitiated combustion. Recently Lee et al. [3,4] reported on the design, fabrication, and performance of a 4×4-element mesoscale burner array cast from a single mold in silicon nitride. Performance results included pressure drop, flame stability, temperature distribution in the burned gas, and NO_x emissions for methane–air for two modes of operation, a fully premixed (mixing before entry) mode and a partially premixed (mixing in the array) mode, at ambient pressure and no air preheat.

Because the burner arrays are being developed for gas-turbine applications, array performance at elevated pressures and air preheat temperatures needs investigation. In the present work we report on the effects of pressure on the performance of the 4×4 mesoscale burner array developed by Lee et al. The role of air preheat will be addressed in a future study. Flame stability, NO_x emissions, and burned gas temperature were determined at pressures of 1, 2, and 4 bar using methane–air for fuel–air equivalence ratios in the range from 0.4 to 0.9 for both premixed and partially premixed operation.

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Experimental Setup

The mesoscale burner array used in the present study is a 4×4 square array of 4.5 mm-diam burner elements on 5 mm centers identical to the array used by Lee et al. [3]. A complete description of the array design and fabrication is provided in Lee et al. [3,4].

Experiments were conducted in a high-pressure flow facility that comprises a stainless steel cylindrical chamber 10 cm internal diameter $\times$ 75 cm length that encloses the burner and can be operated at pressures up to 15 bar. A quartz window installed in the chamber wall provides optical access for flame visualization. All data, including the atmospheric pressure data, were obtained with the pressure vessel in place to ensure consistent boundary conditions and using a 50 mm-long quartz chimney to prevent entrainment of air into the postcombustion gases above the array surface. Figure 1 shows a schematic of the flow configuration.

Results

Stability

The stability of the flames was measured by holding a fixed firing rate (fuel flow rate) and increasing the airflow rate until the last flame lifted off of the array and the fuel–air equivalence ratio at which this occurred was recorded. This stability criterion was employed by Lee et al. [3] and is adopted here to allow comparison between present and previously reported results at ambient pressure.

Stable flames are attached directly to the burner. As the airflow increases, one by one the flames lift off until one last flame remains attached to the burner. Last liftoff occurs when this last flame starts continuously lifting off of the burner. The condition of first liftoff, that is, when the first flame starts lifting off with all the other flames still completely attached, was also recorded at atmospheric pressure by Lee [5] but is not considered here.

Figure 2 shows the firing rate (W/element) for the last flame liftoff as a function of fuel–air equivalence ratio and pressure for both the premixed and partially premixed modes. The present atmospheric pressure data are in good agreement with Lee et al. [3]. In both modes, the flames show an increasing resistance to liftoff as pressure is increased and the flame stability scales nearly linearly with pressure, as expected [6]. There also is an increased resistance to liftoff for the partially premixed case compared with the premixed case, especially at low equivalence ratios. This increase in stability can be explained by the locally richer-burning flames in the partially premixed mode. The increased stability of the partially premixed flames enables stable operation at overall fuel–air equivalence ratios outside of the conventional lean flammability limit (LFL).

When operating in the premixed mode, flashback was observed at higher equivalence ratios for a pressure of 4 bar at low firing rates. Flashback was never observed with the burner operating in the partially premixed mode.

NO_x Emissions

NO_x mole fractions were measured in the burned gas using an uncooled quartz sampling probe and a chemiluminescent analyzer. The sampling probe was inserted through the top plate of the pressure chamber, with the probe tip located on the array centerline at a height of 40 mm above the array surface. This location is 10 mm below the top of the quartz chimney so as to avoid effects of entrainment of gases from outside the burner. The atmospheric-pressure

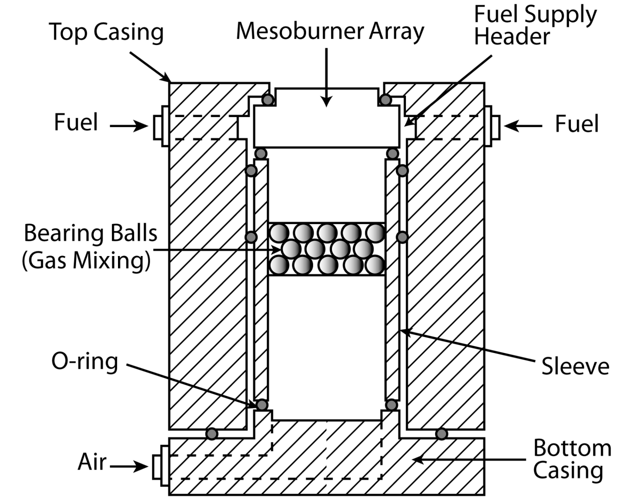

Fig. 1 Cross-sectional configuration of the array-housing assembly.

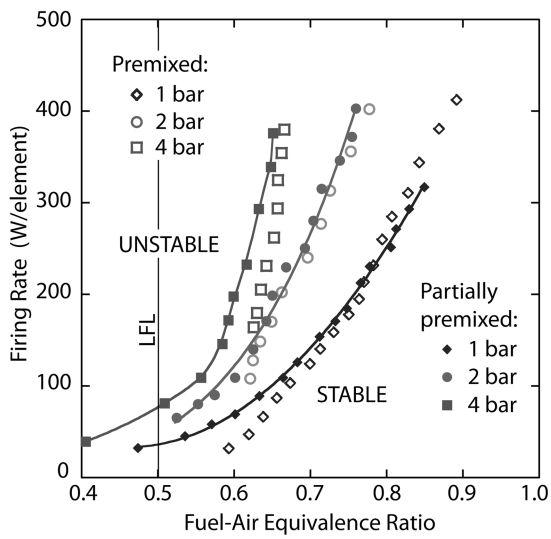

Fig. 2 Stability limits as a function of equivalence ratio and pressure. Open symbols: premixed; closed symbols: partially premixed; solid lines: fits to partially premixed data.

measurements of Lee et al. [3] show that at this location the NO_x concentration is uniform in the radial direction in both the premixed and partially premixed modes. All NO_x data are reported on a "dry, as-measured basis." For all experiments, the contribution of NO_2 to the measured NO_x values was less than 1–2 ppm(vol).

Figure 3 compares premixed and partially premixed values of measured NO as a function of fuel–air equivalence ratio and pressure. To allow comparisons of the data as pressure was varied, the burned gas residence time was held fixed at a given equivalence ratio by increasing the total mass flow rate proportionally to pressure, resulting in an increased firing rate at increased pressure. In both the premixed and partially premixed modes at low equivalence ratios, the measured NO is relatively insensitive to pressure. The pressure effect becomes more pronounced at higher equivalence ratios, where the measured NO increases with pressure. Because the burned gas residence time is nearly identical for all three pressures, the increase in NO with pressure must be attributed primarily to an increase in the NO formation rate. For a given equivalence ratio and pressure, NO emissions are higher in the partially premixed mode, as expected, and the measured NO shows stronger pressure dependence compared with the premixed mode. Because the array can be operated on leaner mixtures in the partially premixed mode, the minimum NO levels achievable are less than 9 ppm(vol) for both premixed and partially premixed operation.

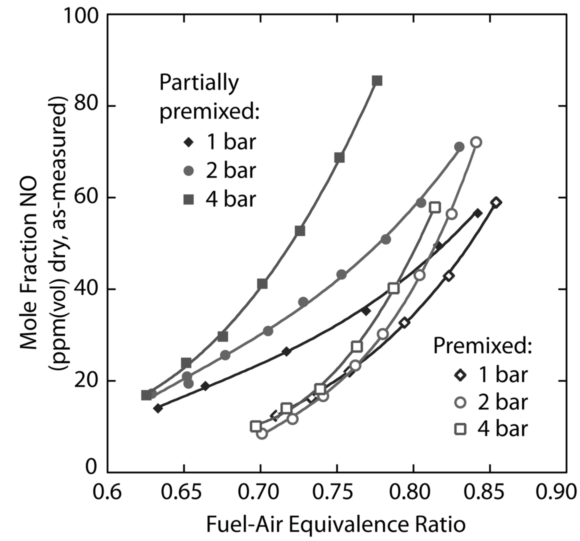

Fig. 3 NO as a function of equivalence ratio and pressure for firing rates of 50, 100, and 200 W/element at 1, 2, and 4 bar, respectively. Open symbols: premixed; closed symbols: partially premixed.

Temperature

To assist in the interpretation of the NO measurements, the burned gas temperature was measured using an uncoated 50 μm-diam type R thermocouple inserted through the top plate of the pressure vessel. Thermocouple readings were corrected for radiative losses. The temperature was measured on the centerline of the burner array at the same height above the burner surface as the NO_x measurements. The centerline temperatures for both premixed and partially premixed modes at this location were approximately the same and independent of pressure for a given fuel–air equivalence ratio. The measured burned gas temperature is a strong function of equivalence ratio, as expected, and at the measurement location it is only about 30–50 K lower than the adiabatic combustion temperature due to the low heat transfer rates to the ceramic burner matrix. A detailed discussion of the temperature measurements can be found in Lee et al. [3].

Summary and Conclusions

Flame stability and NO_x emissions for a mesoscale burner array were determined as a function of pressure for lean premixed and partially premixed methane–air mixtures. The flames show an increasing resistance to liftoff with increasing pressure, and the last liftoff (and blowoff) limits scale nearly linearly with pressure. At higher pressures, flashback was observed at low firing rates for premixed operation; however flashback never occurred for partially premixed operation. Partially premixed operation exhibits an increased resistance to liftoff compared with premixed operation, especially at low fuel–air equivalence ratios and low firing rates, thus enabling the array to be operated much leaner in the partially premixed mode at overall fuel–air equivalence ratios outside of the LFL. The pressure dependence of NO_x was found to be small at low equivalence ratios. At higher equivalence ratios, the measured NO_x increases with pressure. Kinetic modeling [7] indicates that the thermal (Zeldovich) NO mechanism is only a minor contributor to NO formation for lean mixtures, with relatively low burned gas temperatures, but becomes the dominant mechanism as equivalence ratio, and burned gas temperature, increases. The partially premixed mode exhibits higher NO_x emissions and stronger pressure dependence than the premixed mode. In both the premixed and partially premixed modes, NO_x was found to consist mainly of NO, with negligible contribution of NO_2.

Future development of the mesoscale array design to improve mixing for partially premixed operation can reduce partially premixed NO_x emissions to nearly fully premixed emissions [5,8] while still providing good flame stability.

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