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GLOBAL PROPERTIES OF GASEOUS POOL FIRES

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Global flame properties were measured as a function of fuel mass flux in a series of experiments conducted on gaseous pool fires burning in a quiescent environment. The measurements included radiative heat loss, heat transfer to the burner, and sensible enthalpy transfer to the surroundings by convection. A large number of fires was studied encompassing a wide range of pool fire parameters. Measurements were conducted using methane, propane, natural gas, and acetylene in burners varying from 0.1 to 1 m in diameter, producing flames from 0.1 to 2 m in height with total heat release rates from 0.4 to 200 kW. From these measurements, the combustion efficiency was calculated for smoky fires.

The measurements were used to test flame height correlations available in the literature for smoky fires. The correlations work well for nonsmoky fires but have not been proven for smoky fires. The measured flame heights conformed to the literature correlations for the nonsmoky flames burning methane, propane, and natural gas. When applied to high mass flux acetylene flames, however, the flame height measurements deviated from the literature flame height correlations. The correlations performed only slightly better when they were based on $\dot{Q}_c$, the sensible enthalpy heat loss. Caution is suggested when applying the standard literature flame-height correlations to smoky fires that may occur in realistic fire scenarios.

Introduction

A key objective of this study was to test the flame-height correlations available in the literature on smoky fires. These correlations work well for nonsmoky flames but have not been proven for smoky fires. To accomplish this objective, a series of measurements were conducted on gaseous pool fires to determine the values of key parameters necessary for use of the flame height correlations. The measurements included radiative heat loss, heat transfer to the burner, and sensible enthalpy convected to the surroundings.

These global fire properties are of interest by themselves because they have important implications in terms of fire safety. In an enclosure, heat convected to a ceiling may have dramatic consequences in terms of time to flashover. The magnitude of the radiative transfer to targets external to the flame controls fire spread rates, which greatly affects the hazard posed by a particular fire. Radiative transfer from the flame to the fuel surface is the dominant heat feedback mechanism in large pool fires, governing the fuel evaporation rate.

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Enthalpy Balance

An overall enthalpy balance for a diffusion flame shows that the actual heat release from chemical reactions ($\dot{Q}_a$) is equal to the sum of the enthalpy convected from the buoyant plume to the surroundings ($\dot{Q}_c$), energy feedback to the burner surface ($\dot{Q}_1$), and energy radiated by high temperature soot particles and gas species ($\dot{Q}_r$):

$$\dot{Q}_a = \chi_a \cdot \dot{Q} = \dot{Q}_r + \dot{Q}_c + \dot{Q}_1 \quad (1)$$

where the actual heat release ($\dot{Q}_a$) is equal to the idealized or total heat release ($\dot{Q}$) modified by the combustion efficiency (χ_a). The total heat release ($\dot{Q}$) is defined as

$$\dot{Q} = \dot{m} \cdot H_c \quad (2)$$

where $\dot{m}$ is the mass vaporization rate (kg/s) and H_c is the heat of combustion (MJ/kg). Dividing by $\dot{Q}$, Eq. (1) can be rewritten as

$$\chi_a = \chi_r + \chi_c + \chi_1 \quad (3)$$

where the fractional enthalpy losses take on values less than unity, depending on a number of factors. The heat feedback to the burner, χ_1, is defined as

$$\chi_1 = \dot{Q}_1/\dot{Q} \quad (4)$$

which represents the feedback via radiation, convection, and conduction. The fractional amount of enthalpy emitted as radiation from a flame is defined as the radiative heat loss fraction (χ_r):

$$\chi_r = \dot{Q}_r/\dot{Q} \quad (5)$$

The fractional amount of sensible enthalpy loss is defined as the convective heat loss fraction (χ_c):

$$\chi_c = \dot{Q}_c/\dot{Q} \quad (6)$$

For hydrocarbon pool fires, χ_r, χ_a, and χ_c take on particular values, assigned typically in terms of fuel type [1] and pool diameter [2]. This may be valid for liquid fuels, where the steady state $\dot{m}$ and the fire size are governed by the pool diameter and the fuel type, but is not generally valid. This study considered an enthalpy balance for pool fires burning gaseous fuels, which allowed variation of $\dot{m}$ for each particular pool diameter.

Flame Height

The shape and height of a fire have important implications in terms of fire hazard. Flame height is a key parameter in terms of the spatial distribution of radiative heat flux to targets external to the fire and therefore impacts the possible ignition of a secondary object. In global burning rate models, the flame height impacts the calculated radiative feedback rate to the fuel surface and thereby influences predictions of fire growth and spread. In zone fire models, the calculation of flame height impacts estimates of radiative flame emission, the occurrence of reignition in upper-layer gases in an enclosure, and estimates of the thermal insult on structural members [3]. Thus, uncertainties in flame height estimates can propagate through a model and lead to errors in calculated results.

Many studies have investigated flame heights for a variety of burner configurations, burner diameters, and fuels. McCaffrey [4] reviewed a large number of these studies. A common definition for flame height (or boundary) is that of the visible edge of flame luminescence. For turbulent diffusion flames, early research often relied on visual observation to estimate an average flame height. Zukoski et al. [5] used the 50% visible intermittency height to define a characteristic flame height (Z_f), defined as the location where the luminous flame extends above this threshold 50% of the time.

The flame height correlations of Zukoski et al. [5] and Heskestad [6] are commonly used in the fire literature. The original development of the Froude number based flame height model [7] proposed that the nondimensional flame height should be written in terms of N, a nondimensional heat release rate, and χ_c, the sensible enthalpy lost from the flame:

$$Z_f/D = f(N/\chi_c) \quad (7)$$

where D is the pool diameter and $N = N(\chi_c)$ is a function of the sensible heat loss fraction. In a compilation of previous flame height data from several researchers, Heskestad [6] suggested that χ_c in Eq. (7) can be ignored and still maintain sufficient accuracy. This was convenient because for most common fire scenarios, measurement of χ_c is impractical. Thus, consideration of a large amount of literature data for relatively clean fuels led to a power law correlation [6] of the normalized flame height in terms of $N(\dot{Q})$:

$$Z_f/D = -1.02 + 15.6 \cdot N(\dot{Q})^{0.2} \quad (8)$$

where the parameter $N(\dot{Q})$ was related to the total heat release of the fire ($\dot{Q}$),

$$N(\dot{Q}) = [c_p \cdot T_o/(H_c/r)]^3 \cdot (\dot{Q}_D^*)^2 \quad (9)$$

and r is the stoichiometric (mass-based) ratio of air to fuel, c_p is the heat capacity of air at the ambient temperature (T_o), and H_c is the heat of combustion for a particular fuel. $\dot{Q}_D^*$ was defined as

$$\dot{Q}_D^* = \dot{Q}/(\rho_o \cdot c_p \cdot T_o \cdot (g \cdot D^5)^{0.5}) \quad (10)$$

where ρ_o is the ambient air density and g is the gravitational acceleration. The value of the ratio of H_c/r can vary by a factor of almost 2 for different common fuels.

Zukoski et al. [5] correlated flame height to a power law in terms of $\dot{Q}_D^*$:

$$Z_f/D = 3.3 \cdot (\dot{Q}_D^*)^{(2/3)} \text{ for } \dot{Q}_D^* < 1 \quad (11a)$$

$$Z_f/D = 3.3 \cdot (\dot{Q}_D^*)^{(2/5)} \text{ for } \dot{Q}_D^* \geq 1 \quad (11b)$$

It is possible to relate Eq. (11) to Eq. (8) through $\dot{Q}_D^*$.

The flame height correlations were shown to be good predictors of flame height over a wide range of $\dot{Q}_D^*$ and N for data available in the literature [5,6]. Unfortunately, the fuels used to develop the flame height algorithms were almost exclusively nonsmoky, where χ_c is typically greater than 0.7 [5,6]. Common fuels, however, are often smoky, and, thus, it is necessary to test Eq. (8) and other flame height correlations with a fuel such as acetylene, which has a high sooting tendency and is represented by small values of χ_c [1]. Low combustion efficiency is also a characteristic of a fire in a vitiated environment such as an enclosure. There have been no tests of the flame height correlations for smoky flames where χ_a may be much less than unity. Furthermore, it is not clear that the correlations would then hold because the physics controlling the length scales in very smoky fires may be different than in nonsmoky fires [8].

In this study, a series of fires was investigated. Of particular interest were smoky fires, characterized by $\chi_a < 1$ and $\chi_c < 0.7$. A range of burner diameters (0.10–1.00 m) and $N(\dot{Q})$ values (10^{-6} to 10^{-1}) were investigated.

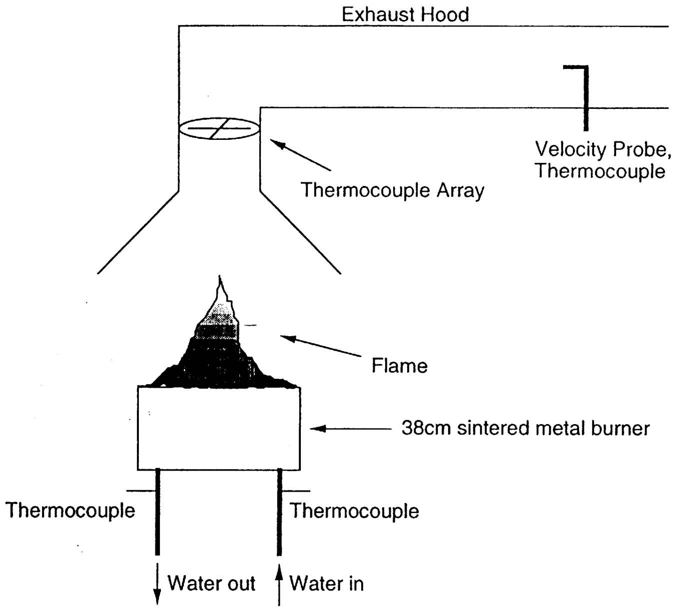

FIG. 1. A schematic diagram of the arrangement designed to measure $\dot{Q}_c$.

Experimental Method

Methane, natural gas, propane, and acetylene were burned in a quiescent environment in which radiative energy emission, sensible heat loss, flame height, and mass delivery rate were measured. The burners were stationed 2 m below the bottom of an exhaust hood, and air currents were damped by a double-layer 2 mm screen mesh. Heat release rates from 0.4 to 200 kW were accomplished using three burners. A water-cooled, porous, sintered-bronze, 0.38 m burner and 0.10 m and 1.0 m water-cooled sand-bed burners were used. The 0.10 m and 1.0 m burners had a 0.03 m layer of fine sand at the burner rim and 3 mm o.d. copper water-cooling tubing around the outside of the burner and in the form of a loosely wound spiral ≈1 cm below the top layer of sand. Mass flow for the gaseous fuels was obtained using a dry test meter and stopwatch to measure the volume per unit time of fuel delivered to the burner. Uncertainty (σ) in $\dot{m}$ was estimated as 2%.

Radiative emission was determined by measuring the radiative flux at multiple locations along a cylindrical control surface surrounding the fire using calibrated radiometers. Details of the experimental method are described in Ref. 2. The vertical and radial flux distributions were integrated numerically to obtain the radiant power emitted.

Heat loss to the burner, $\dot{Q}_1$, was determined by measuring the cooling water flow and its temperature change through the base of the burner. From 5 to 10 min of burning were required before the temperature difference between the cooling water inlet and the cooling water outlet stabilized. Once this temperature difference remained constant, the fire was considered to be in steady state and data acquisition was started. The uncertainty in $\dot{Q}_1$ was estimated as 2%.

If χ_a can be approximated as equal to unity, such as for lightly sooting flames like methane, natural gas, or propane [1], then χ_c (and $\dot{Q}_c$) can be determined from Eq. (1) in conjunction with the measurement of $\dot{m}$, $\dot{Q}_r$, and $\dot{Q}_1$. For a fuel with a high propensity to smoke such as acetylene, $\chi_a < 1$, the sensible heat loss ($\dot{Q}_c$) was determined by measuring the mass flow rate and temperature increase of the air being drawn into the exhaust hood. Figure 1 is a schematic of the experimental setup for determination of $\dot{Q}_c$ for the 0.38 m diameter burner. A thermocouple array was situated approximately 1 m downstream of the entrance to the exhaust duct, and a bi-directional velocity probe and thermocouple were placed approximately 20 m downstream. The sensible enthalpy loss was determined from the heat carried by the combustion products through the exhaust duct:

$$\dot{Q}_c = \rho \cdot V \cdot A \cdot c_p \cdot \Delta T \qquad (12)$$

where ρ is the gas density of the exhaust, V is the average exhaust velocity, A is the duct area, c_p is the gas heat capacity, and ΔT is the difference between ambient temperature and the average measured temperature at the thermocouple array. The heat capacity of the exhaust was based on the heat capacity of air at the measured temperature because the exhaust gases were composed almost entirely of entrained air. For the flow through the stack and the

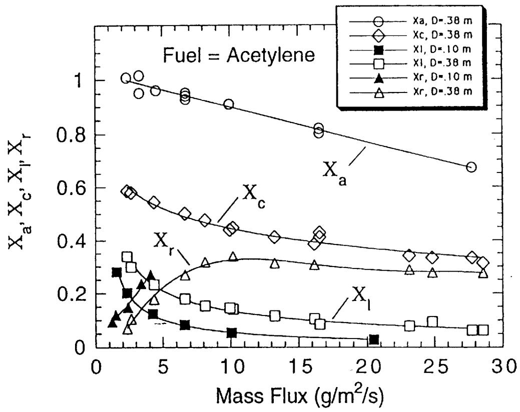

FIG. 2. Measured values of χ_c, χ_r and χ_l and calculated values of χ_a as a function of mass flux of acetylene in the 0.10 m and 0.38 m burners.

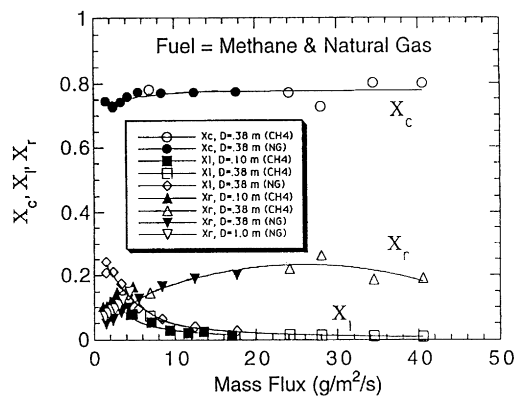

FIG. 3. Measured values of χ_r and χ_l and calculated values of χ_c as a function of mass flux of methane and natural gas (NG) in the 0.10 m, 0.38 m, and 1.0 m burners.

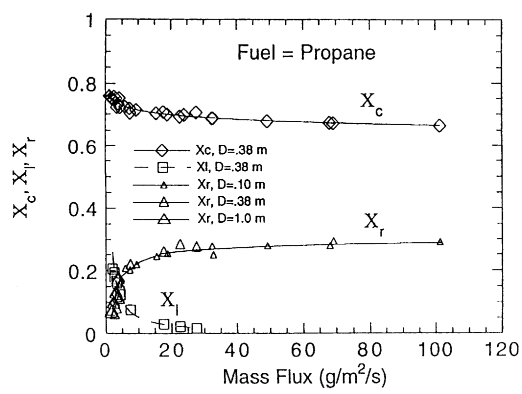

FIG. 4. Measured values of χ_r and χ_l and calculated values of χ_c as a function of mass flux of propane in the 0.10 m, 0.38 m, and 1.0 m burners.

size of fire studied here, only small amounts of combustion products (CO, CO_2, and H_2O) are typically measured in the exhaust stack. The mass flux (ρVA) was determined from measurements of the velocity and temperature far downstream. The temperature and velocity measurements were averaged for approximately 2 min after constant values were observed. The average velocity was determined assuming fully developed pipe flow. Data were acquired at a rate of 0.2 Hz. Uncertainty in $\dot{Q}_c$ based on a propagation of error analysis and repeat measurements was 5%.

The flame height (Z_f) was determined by averaging the measured 50% visible intermittency height for 150 frames using a Hi-8, 8-mm video format taken at 30 frames/s. Post processing used a VCR in conjunction with a DT-IRIS frame grabber and associated software that allowed numeric image processing and evaluation. Although some flames were very smoky, the smoke did not obscure visual observation of the flame. Uncertainty in the average flame height based on a propagation of error analysis and repeat measurements was 10%.

Results

Figure 2 shows the measured values of χ_r, χ_l, and χ_c and the calculated values of χ_a as a function of the mass burning flux ($\dot{m}''$) of acetylene in the 0.38-m, water-cooled, sintered-metal burner, where $\dot{m}''$ is defined as $\dot{m}$ divided by the pool area ($\pi D^2/4$). Figure 2 shows that the enthalpy feedback to the burner (χ_l) is a relatively small term except for small fuel fluxes. The χ_l decreased with increasing fuel flux, consistent with thin film models of convective transfer [9,10]. As the acetylene mass flux increased, χ_r increased and χ_c decreased, obtaining values less than 0.4. For very small acetylene mass fluxes, the flames were nonsmoky and χ_a was determined to be close to unity. This is because fuels such as acetylene, with a high tendency to soot, typically yield smoke only for moderate and high fuel mass fluxes. As the acetylene mass flux increased, the fires were observed to produce copious quantities of soot and χ_a decreased, obtaining values as low as 0.6.

Measurements similar to those for acetylene are shown for methane (and natural gas, composed of ≈96% methane) and propane in Figs. 3 and 4, respectively. Because sampling measurements above even the largest of the methane, natural gas, and propane fires showed no evidence of emitted visible smoke, it was assumed that χ_a was approximately equal to unity. A comparison of Figs. 2, 3, and 4 shows that for the same mass flux, the χ_r values for natural gas and methane were smaller and the χ_c values were generally larger than for the acetylene flames. When plotted in terms of mass flux, the χ_r and χ_l measurements for the 0.1 m and 1.0 m di-

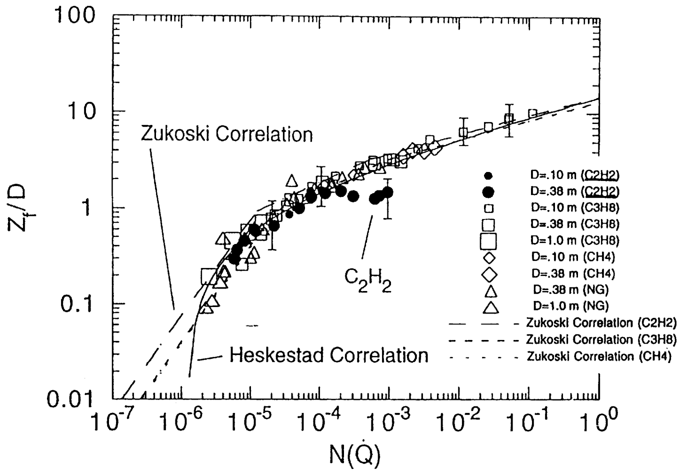

FIG. 5. The measured normalized flame height (Z_f/D) as a function of $N(\dot{Q})$ for a number of gaseous fuels and burner diameters. Vertical bars indicate the maximum and minimum observations. The fits represented by Eq. (11) from Zukoski (for CH_4 and C_2H_2) and by Eq. (8) from Heskestad are also shown.

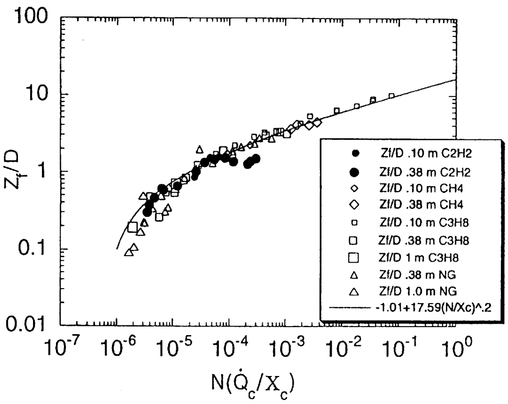

FIG. 6. The measured normalized flame height (Z_f/D) as a function of $N(\dot{Q}_c/\chi_c)$ as suggested by Eq. (7).

ameter burners were very similar to the 0.38 m results, throughout the range of mass fluxes studied. Also, the propane results were very similar to the methane/natural gas results except that the χ_r values were somewhat ($\approx$10%) higher.

It has been shown that χ_a, χ_r, and χ_c for small (0.1 m diameter) pool fires can be correlated in terms of the smoke point height measurement l_s [1]. The l_s characterizes the tendency of a fuel to emit smoke and the smoke point is a fuel property, not a function of burner diameter. Unfortunately, this sort of correlation invites use without consideration of fuel mass flux or fire size. Although the smoke point is helpful in ranking key parameters of various fuels, Fig. 2 illustrates that χ_a, χ_r, and χ_c are also a function of the fuel mass flux.

Figure 5 shows a log-log plot of the normalized flame height measurements as a function of $N(\dot{Q})$ in gaseous pool fires burning acetylene, propane, and methane in the 0.10 m, 0.38 m, and 1.0 m burners. The bars on the data points represent minimum and maximum observed nondimensional flame heights, which varied from approximately 0.7 to 3 times the average flame height. Measurement uncertainty is on the order of the symbol size representing the data. Measurements such as those shown in Figs. 2 and 3 were used as input to determine the flame height correlations of Zukoski (for CH_4, C_3H_8, and C_2H_2) and Heskestad (Eqs. [11] and [8], respectively). Their correlations behave very similarly for $N(\dot{Q}) > 4 \cdot 10^{-5}$. For $N(\dot{Q}) < 4 \cdot 10^{-5}$, however, the fits are significantly different. The fit using Zukoski's correlation for propane is not shown because it falls nearly on top of the methane fit. The fit using Zukoski's correlation for acetylene is approximately 20% higher than the fits for methane and propane. Heskestad's correlation [6] appears to represent the data adequately, except for the high C_2H_2 mass flows (or $N(\dot{Q}) > 2 \cdot 10^{-4}$) when the flames are smoky and the combustion efficiency is small. Some data scatter is evident for values of $Z_f/D < 0.5$ for the nonsmoky fires when the flames are very small and have been observed to be different in character (i.e., shape, fluctuation frequency) [11]. The differences between the large acetylene data and Heskestad's correlation [Eq. (8)] were as large as a factor of 2.0. In those cases, even the maximum measured flame height falls below the correlations. Use of the literature fits for the height of a fire could lead to significant error in the estimate of local radiative heat flux to targets external to the fire.

Figure 6 is a log-log plot of the measured nondimensional flame height as a function of $N(\dot{Q}_c/\chi_c)$ as suggested by Eq. (7). This functional form fails to collapse the high mass flow acetylene results, by as large as a factor of 1.9, but adequately correlates the propane, natural gas, methane results and the low-flow acetylene results. This suggests that the physics controlling the length scales in very smoky fires may be different than in nonsmoky fires [8].

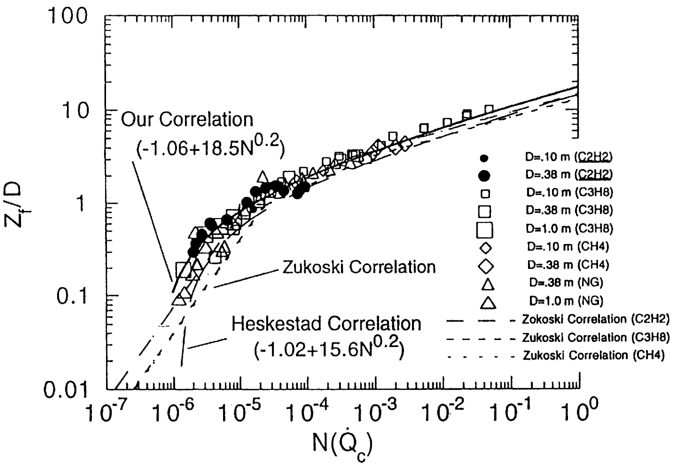

FIG. 7. The measured normalized flame height (Z_f/D) as a function of $N(\dot{Q}_c)$. The fits represented by Eq. (11) from Zukoski (for CH_4, C_3H_8, and C_2H_2) and by Eq. (8) from Heskestad are also shown. A best fit to the data is also presented.

Considering the form of Eq. (11), Zukoski et al. [5] pointed out that nothing precludes the use of $\dot{Q}_c$, rather than $\dot{Q}$, as a correlating parameter for the flame height through use of Eqs. (10) and (11). Figure 7 shows the normalized flame height as a function of $N(\dot{Q}_c)$. The $N(\dot{Q}_c)$ was calculated using $\dot{Q}_c$ instead of $\dot{Q}$ in Eq. (8). Compared to Fig. 5, the data are shifted to smaller values of N because $N(\dot{Q}_c) < N(\dot{Q})$. The correlations given by Eq. (11) for methane, propane, and acetylene and Eq. (8) in terms of $N(\dot{Q}_c)$ are also shown. The fit using Eq. (8) does not adequately represent the high-mass-flux acetylene data because it was derived for $N(\dot{Q})$, not $N(\dot{Q}_c)$, with χ_c taken as unity. The fits using Eq. (11) for methane and propane fall nearly on top of each other. Figure 7 shows that the methane and propane fits are somewhat lower than the corresponding data, whereas the fit (using Eq. [11]) for acetylene falls lower than a portion of the data corresponding to it. A best fit to the data in terms of a power law in $N(\dot{Q}_c)$ was determined (see Fig. 6), yielding

$$Z_f/D = -1.06 + 18.5 \cdot N(\dot{Q}_c)^{0.2} \qquad (13)$$

Figure 6 shows that this best-fit curve does not follow the trends in the acetylene data.

The fit, however, does a marginally better job in predicting the high mass flux acetylene data as compared to Eq. (8). For example, the high mass flow acetylene data deviate from Eq. (13) by less than a factor of 1.4, as compared to a factor of 2.0 when Eq. (8) was used. For the remainder of the data (propane, methane, natural gas, and the low mass flux acetylene flames), a fit on the basis of a power law in terms of $N(\dot{Q})$ (Eq. [13]) appeared to be as appropriate as the fit in terms of $N(\dot{Q}_c)$ (Eq. [8]). This implies that a relationship exists between the two correlations, such that $N(\dot{Q})$ is related to $N(\dot{Q}_c)$ through a factor that is approximately constant over a range of fuel types and fire sizes typical of the laboratory-scale fires on which the fits were based. Equating Eqs. (8) and (13) demonstrates the relationship between $N(\dot{Q}_c)$ and $N(\dot{Q})$:

$$N(\dot{Q}_c) \approx 0.43\, N(\dot{Q}) \qquad (14)$$

Using Eq. (9), this is equivalent to the statement

$$\dot{Q}_c \approx 0.65\, \dot{Q} \qquad (15)$$

Summary and Conclusions

In summary, measurements of a number of global properties as a function of fuel mass flux are reported for pool fires burning gaseous fuels. The measurements included radiative heat loss, heat transfer to the burner, and sensible enthalpy transfer to the surroundings by convection. For all fuels and burner sizes, the radiative fraction increased, the enthalpy loss fraction to the burner decreased, and these parameters asymptotically obtained nearly constant values as a function of fuel mass flux. Except for very small mass fluxes, the sensible enthalpy loss fraction was nearly a constant for the methane and propane fires ($\chi_c \approx 0.7$) but decreased as a function of mass flux for the acetylene fires to rather small values ($\chi_c \approx 0.35$).

Measurements of the average flame height were also reported and compared to correlations reported in the literature. The measured flame heights generally conformed to the literature flame-height correlations (e.g., Eq. [8]) when $\chi_c \approx 0.7$. For smoky flames, however, when both χ_a and $\chi_c \ll 1$, the measured flame heights deviated from the literature correlations. This was true when the correlations were based either on $N(\dot{Q})$, $N(\dot{Q}_c)$, or $N(\dot{Q}_c/\chi_c)$.

Realistic fire scenarios often lead to smoky fires including virtually all fires burning solid materials. Smoky fires can also be expected under vitiated conditions, which typically occur in enclosures, although a depleted oxygen concentration will also impact the flame height. A fire model that uses the current flame height correlation on the basis of $\dot{Q}$ will overestimate the flame height and thereby overestimate the potential hazard. A correlation on the basis of $\dot{Q}_c$ rather than $\dot{Q}$ is somewhat more accurate, but further data from larger and smokier fires is required to better assess fire growth and to better understand the physics controlling the length scales in very smoky fires and how they differ fundamentally from nonsmoky fires. Caution is suggested when applying the standard literature flame height correlations to smoky fires.

Acknowledgments

The authors are grateful to Dr. J. deRis for loaning us the 0.38 m diameter sintered-metal burner; to R. Mclane, E. Braun, L. Delauter, and G. Roadarmel for assisting us with data collection; and to Professor E. Zukoski, Dr. M. Delichatsios, Professor B. Cetegen, and Dr. S. Ritchie for helpful suggestions.

REFERENCES

1. Tewarson, A., "Prediction of Fire Properties of Materials," U.S. Dept. of Commerce Report # NIST-GCR-86-521, U.S. Government Printing Office, Washington, D.C., 1986.
2. Hamins, A., Klassen, M., Gore, J., and Kashiwagi, T., *Combust. Flame* 86:223–229 (1991).
3. Deal, S., "Technical Reference Guide to FPEtool Version 3.2.," U.S. Dept. Commerce Report # NISTIR 5486, U.S. Government Printing Office, Washington, D.C., 1994.
4. McCaffrey, B., in *SFPE Handbook of Fire Protection Engineering* 2d ed., (DiNenno, P. J., Beyler, C. L., Custer, R. L. P., Walton, W. D., and Watts, J. M., Eds.), 1989, pp. 1-298–1-305.
5. Zukoski, E. E., Cetegen, B. M., and Kubota, T., *Twentieth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1984, p. 361.
6. Heskestad, G., *Fire Safety J.* 5:103–108 (1983).
7. Heskestad, G., *Eighteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1981, pp. 951–960.
8. Delichatsios, M. A., Oroloff, L., and Delichatsios, M. M., *Combust. Sci. Technol.* 84:199–215 (1992).
9. Orloff, L. and deRis, J., "Froude Modeling of Pool Fires," Factory Mutual Technical Report No. OHON 3.BU RC81-BT-9, Factory Mutual Research, Norwood, MA, 1983.
10. Orloff, L. and deRis, J., *Nineteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1982, p. 885.
11. Hasemi, Y. and Nishihata, M., *Fire Sci. Technol.* 7:27–37 (1987).

COMMENTS

I. Glassman, Princeton University, USA. The use of a visible flame height must lead to spurious correlations since the visible flame height is the soot burn limit. Thus fuels which characteristically give more soot should not correlate as well as those that do not, just as your acetylene results show.

Author's Reply. The visible flame height is dependent on the radiation emitted by hot soot particles, and thereby related to the convolution of the temperature and soot concentration fields. Lacking local measurements, the visible flame height has been used in engineering approximations of radiative transfer. We believe that the literature flame height correlations for acetylene and other highly sooting fuels (such as 1,3 butadiene and propylene) may not correlate as well as non-smoking fuels because the correlations are based on total heat release, rather than on sensible enthalpy convected by the plume.

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M. A. Delichatsios, FMRC, USA. Your maximum radiant fraction measured for acetylene was about .28, if I am right (ie. same as propane). Other measurements on pool fires show maximum values of about greater than .50 (Markstein, McCaffrey and others).

Author's Reply. This is an interesting point. As you suggest, McCaffrey reports large values of radiative fraction for buoyancy dominated acetylene fires [1]. We were not able to track down results by Markstein on this topic.

For very small acetylene mass fluxes, the flames produced in our water cooled burners were essentially blue in color, and the measured radiative fraction was less than 0.1, as seen in Fig. 2 of the paper. As the fuel flux increased, the flames became luminous (i.e., yellow), and the radiative fraction attained a maximum measured value of 0.35 in the 0.38 m diameter burner. Under those conditions, the fractional enthalpy lost to the burner was measured to be 0.15 and the enthalpy convected by the plume was measured to be 0.45 (see Fig. 2). For high mass fluxes, the radiative fraction decreased to approximately 0.28 in this burner, possibly due to blockage by smoke. The same trends in the radiative fraction of acetylene flames were reported by McCaffrey [1], who used a single location measurement to estimate the value of the radiative fraction. His results showed a peak radiative fraction of ≈0.52 for acetylene flames burning in a 0.25 m diameter burner. As the fuel flux increased, the radiative fraction decreased to ≈0.38, without having yet reached an asymptote. Differences in the values of the peak radiative fraction between our study and that of McCaffrey may be related to radiation trapping. For optically thick flames, burning in a larger diameter burner could lead to decreased radiative fraction.

REFERENCE

1. McCaffrey, B., "Some Measurements of the Radiative Output of Diffusion Flames," Presented at the Western States Section of the Combustion Institute, Paper No. WSS/CI 81-15, 1981.