

SHORT COMMUNICATION

Estimate of the Effect of Scale on Radiative Heat Loss Fraction and Combustion Efficiency

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Abstract—The effect of fire size on radiative heat loss fraction (χ_r) and combustion efficiency (χ_a) was examined by an analysis of scale for pool flames with varying diameter (D). Correlations between D and χ_r or χ_a were obtained. For $0.1\text{m} < D < 1\text{m}$, χ_r and χ_a are relatively constant and independent of D . For larger pool diameters, χ_r decreases with increasing D .

Key words: Burning rate, combustion efficiency, flame height, radiative heat loss fraction.

1 INTRODUCTION

The fractional amount of energy emitted as radiation from a flame and the combustion efficiency are two important parameters in engineering models of fire growth and fire hazard. Unfortunately, few studies can be found in the combustion literature relating the magnitude of the radiative heat loss fraction or the combustion efficiency with scale.

The radiative heat loss fraction (χ_r) and combustion efficiency (χ_a) are defined as:

$$\chi_r = \frac{Q_r}{M H_c} \quad (1)$$

$$\chi_a = \frac{Q_a}{M H_c} \quad (2)$$

where Q_r (kW) is the radiative heat loss to the surroundings, M (kg/s) is the fuel burning rate, H_c (kJ/kg) is the ideal heat of combustion, and Q_a is the actual heat release rate (kW).

Sibulkin (1973) gave an order of magnitude analysis of the variation of χ_r with scale (diameter, D) for gaseous diffusion flames burning in a pool fire configuration. For moderate sized burners ($0.1\text{m} < D < 1\text{m}$), it was inferred that $\chi_r \propto D^{1/2}$. For large burners ($D > 1\text{m}$), the analysis showed that $\chi_r \approx \text{constant}$. His results were based on the assumptions that the flames were not obscured by smoke, that the flame height (H) was directly proportional to the burner diameter (i.e., $H/D \approx \text{constant}$), that the flame temperature was independent of burner diameter and that the gas velocity at the burner exit was kept constant for all burners. The results, however, were not compared to experimental measurements.

Applying a simple energy balance on a pool fire for an assumed cylindrical flame, Moorhouse and Pritchard (1982) derived an equation for χ_r as follows:

$$\chi_r = \frac{E}{M'' H_c} \left(1 + \frac{4H}{D}\right) \quad (3)$$

where E is the emissive power of the flame (kW/m^2) and \dot{M}'' is the mass burning flux ($\text{kg/m}^2 \text{ s}$) of fuel. For large fires, they expected both \dot{M}'' and E to be independent of D . Thus, for χ_r to be constant in Eq. 3, H/D would have to be constant. The assumption of constant E , however, is questionable for large scale hydrocarbon fires because smoke obscuration leads to a decrease in the measured flame emissive power (Mudan, 1984). Moorhouse and Pritchard (1982) also argued that the ratio H/D was not always independent of D and concluded that χ_r should decrease with D for large fires.

A relationship between χ_r and D was reported by Sarofim (1986) with the assumptions that the heat feedback to the pool was *solely* due to radiation from the flame and that the flame temperature was constant.

$$\chi_r \propto \left(\frac{1 - e^{-KD}}{\sqrt{D}} \right)^{0.61} \quad (4)$$

where K is an extinction coefficient. Eq. 4 suggests that χ_r increases with D for $D < 1\text{m}$ and decreases with D for $D > 1\text{m}$. The use of Eq. 4 for small D may not be appropriate because conduction and/or convection, rather than radiation, would play a dominant role in the heat feedback process (Hottel, 1959).

Recent experimental observations showed a scale dependence for both χ_r (Souil et al., 1986; Koseki & Yumoto, 1988; Koseki, 1989) and smoke yield (Koseki & Mulholland, 1991), which is an indicator of combustion efficiency.

Since recent modeling efforts have focused on intermediate and large scale liquid pool fires, the objective of this work was to estimate the dependence of χ_r and χ_a on scale. In particular, our attention was focussed on diffusion flames in a pool fire configuration with diameters ranging from intermediate to large values. The resulting functional forms were then compared to recent experimental measurements.

2 ANALYSIS

2.1 Variation of χ_r with Scale

Following Sibulkin (1973), the time averaged radiation emitted by a pool fire to its surroundings is:

$$Q_r = \epsilon_T \sigma T_f^4 A_f \quad (5)$$

where ϵ_T is the global total flame emissivity, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-11} \text{kW/m}^2 \text{K}^4$), T_f (K) is a characteristic average flame radiation temperature, and A_f (m^2) is the flame surface area. A difficulty with this equation is that σ is the only quantity that is accurately known, and T_f probably is the least characterized parameter. To simplify the analysis, the time averaged flame shape was assumed to be cylindrical, with the flame diameter D (m) equal to the burner diameter and a flame height H (m). In this case, Q_r can be written as:

$$Q_r \approx \epsilon_T \sigma T_f^4 (\pi DH) \quad (6)$$

The total flame emissivity is related to the gaseous and particulate emissivities. Felske and Tien (1973) calculated the emissivity of luminous flames by assuming a uniform flame temperature and composition whose dominant emitting species were water vapor, carbon dioxide, and soot particles. Using the method outlined by Felske and Tien (1973) and assuming a cylindrical flame shape, Sibulkin (1973) showed that

$$\epsilon_T \propto D \quad \text{for } D < 0.01\text{m} \quad (7)$$

$$\epsilon_T \propto D^{1/2} \quad \text{for } 0.1\text{m} < D < 1\text{m} \quad (8)$$

$$\epsilon_T \approx 1 \quad \text{for } D > 1\text{m} \quad (9)$$

It is reasonable to assume T_f to be independent of D for $D < 1\text{m}$ because flame temperature measurements for pool flames with $D < 1\text{m}$ for a number of fuels give values on the order of 1300 K (Markstein, 1979; Koseki & Hayasaka, 1989).

The mass burning flux for a particular fuel is a known function of pool diameter (Hottel, 1959). For moderate sized pools ($0.1\text{m} < D < 1\text{m}$), it was found from measurements on crude oil fires (Koseki & Mulholland, 1991) that \dot{M}'' could be approximately scaled with D as:

$$\dot{M}'' \propto D^{1/2} \quad \text{for } 0.1\text{m} < D < 1\text{m} \quad (10)$$

Since $\dot{M} = \dot{M}'' \frac{\pi D^2}{4}$

then Eq. 10 yields:

$$\dot{M} \propto D^{5/2} \quad (11)$$

A similar dependence between \dot{M}'' and D can be obtained for other fuels (Hottel, 1959).

For intermediate sized pool diameters ($0.1\text{m} < D < 1\text{m}$), the correlation given by Heskestad (1983) can be used to estimate the flame height, H :

$$H \propto \dot{M}^{2/5} \quad (12)$$

with

$$\dot{M} \propto D^{5/2}$$

then

$$H \propto D \quad (13)$$

From Eq. 1 with H_c constant for a given fuel and Eqs. 6, 8, 11, and 13, χ_r is approximately independent of D or

$$\chi_r \approx \text{constant} \quad \text{for } 0.1\text{m} < D < 1\text{m} \quad (14)$$

The same conclusion can be obtained if the flame shape is assumed to be a cone instead of a cylinder for intermediate sized fires ($0.1\text{m} < D < 1\text{m}$). Based on experimental observations, however, it is more realistic to assume a cylindrical flame shape for large fires ($D > 1\text{m}$). Thus, for consistency the assumption of a cylindrical flame shape was used throughout the analysis.

Sibulkin (1973), however, inferred that $\chi_r \propto D^{1/2}$ in this pool size domain. In his case, \dot{M} was taken as proportional to D^2 or $\dot{M}'' \propto \text{constant}$. The assumption of a constant mass burning flux independent of pool diameter is not generally valid for liquid pool fires.

For large pools ($D < 1\text{m}$), Hottel (1959) showed that $\dot{M}'' \approx \text{constant}$ (or $\dot{M} \propto D^2$) for many fuels. Unfortunately, large uncertainties are associated with predicting flame heights with existing correlations (Moorhouse & Pritchard, 1982) for large pools. Thus, an approximate relationship between H and D , obtained by fitting the measured time averaged flame height measurements in heptane pool fires reported by Koseki (1989)

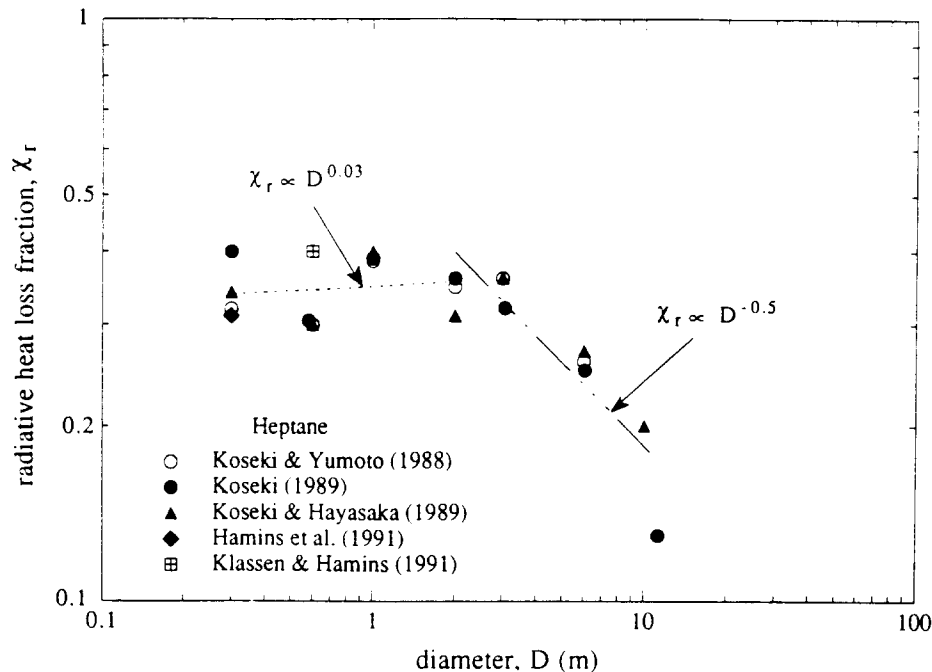


FIGURE 1 Radiative heat loss fraction of heptane as a function of burner diameter (from Koseki & Yumoto, 1988; Koseki, 1989; Koseki & Hayasaka 1989; Hamins et al., 1991; and Klassen & Hamins, 1991).

and Koseki & Hayasaka (1989), was used here. The measurements show that H was approximately proportional to $D^{1/2}$ for $D > 1\text{m}$.

For large and nonsmoking flames, the assumption that T_f is independent of D may still be reasonable (Sibulkin, 1973). However, for flames with large amounts of smoke generation, the flames become optically thick and the flame emissivities approach that of a black body, i.e., $\epsilon_T \approx 1$ (Gordon & McMillan, 1965; Moorhouse & Pritchard, 1982; Williams, 1982). The effective radiation temperature is difficult to estimate in such a case because of radiation trapping by an optically thick smoke layer, and an *effective* smoke temperature can be taken as the radiation temperature (Williams, 1982). From experimental observations (with some data scatter), the *effective* emissive power of the flame decreases with increasing pool diameter (Shokri & Beyler, 1989). This implies that the *effective* smoke temperature is scale dependent. However, for large fires it is expected that the *effective* emissive power remains relatively constant (Moorhouse & Pritchard, 1982). In order to provide an analysis that may be useful as a simple guide to data correlation, it is reasonable as a first approximation to assume a constant effective smoke temperature. Using Eqs. 1, 6, and 9 and with $M \propto D^2$ and $H \propto D^{1/2}$, the radiative heat loss fraction is:

$$\chi_r \propto \frac{1}{\sqrt{D}} \quad \text{for } D > 1\text{m} \quad (15)$$

Figures 1 and 2 respectively show measurements of χ_r as a function of D for heptane and kerosene fires as reported by Souil et al. (1986), Koseki and Yumoto (1988), Koseki (1989), Koseki & Hayasaka (1989); Hamins et al. (1991), and Klassen & Hamins (1991).

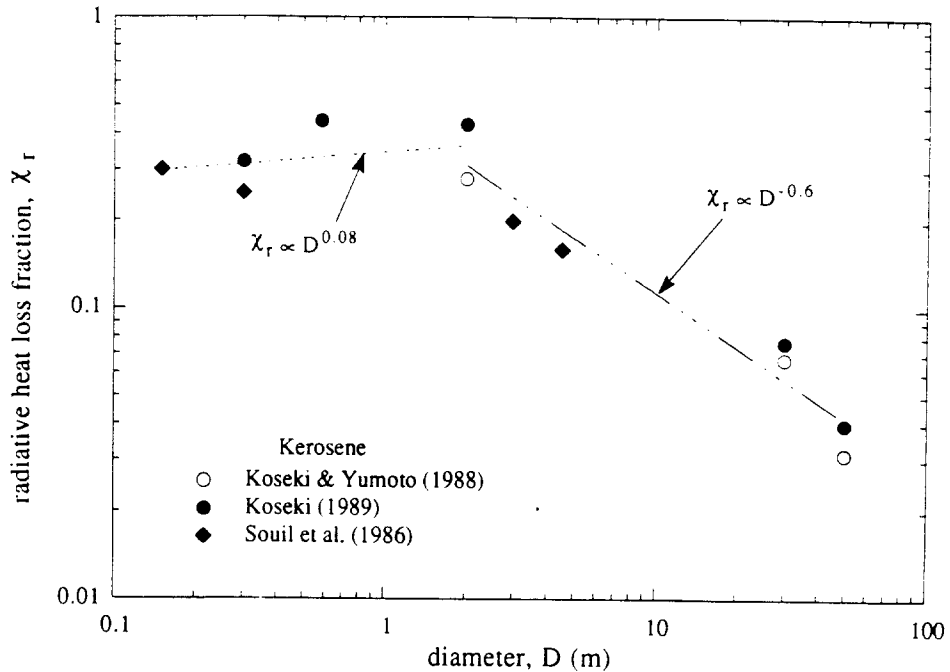


FIGURE 2 Radiative heat loss fraction of kerosene as a function of burner diameter (from Souil et al., 1986; Koseki & Yumoto, 1988; and Koseki, 1989).

The data plotted in the figures were generally determined from single location radiance measurements using the assumption of radiative isotropy. Two distinct regimes are delineated in the figures. For $0.15\text{m} < D < 2\text{m}$, χ_r is relatively constant. For $D > 2\text{m}$, χ_r is approximately proportional to $D^{-0.5}$ for heptane fires and proportional to $D^{-0.6}$ for kerosene fires. Given the scatter and the uncertainty in the experimental data, Eqs. 14 and 15 show qualitative agreement with experimental measurements. In addition, the radiative heat loss fraction was also found to be independent of D ($0.15\text{m} < D < 1.22\text{m}$) in polymethyl methacrylate (PMMA) pool fires (Modak & Croce, 1975).

2.2 Variation of χ_a with Scale

From experimental measurements of the actual heat release rate (Q_a) for heptane and crude oil pool fires (Mulholland et al., 1988), Q_a scales with D as:

$$Q_a \propto D^{5/2} \quad \text{For } D < 1\text{m} \quad (16)$$

For intermediate sized burners, substituting Eqs. 11 and 13, into Eq. 2, χ_a is independent of D . This result is in qualitative agreement with the measurements reported by Mulholland et al. (1988) which show that, within experimental uncertainty, χ_a for heptane is relatively constant for $D < 1\text{m}$. It is uncertain how to scale Q_a properly with D for large fires, and since no experimental data are available, no attempt is made to do that. However, for large D , the smoke yield (which is a measure of χ_a) was measured

to increase with D (Koseki & Mulholland, 1991), i.e., χ_a decreases with increasing D . Given the experimental results of Koseki and Mulholland (1991), Q_a should scale with D to a power of less than 2 in Eq. 16 for $D > 2m$. If this were the case (with $M \propto D^2$), χ_a would decrease with increasing D for large D . Future work calls for measurement of the actual heat release rate with scale.

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