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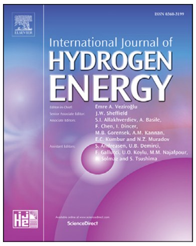

Generalization of the radiative fraction correlation for hydrogen and hydrocarbon jet fires in subsonic and chocked flow regimes

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ABSTRACT

The radiative fraction is one key parameter to characterize the jet flame combustion dynamics and to calculate the thermal radiant heat emitted from jet fire. A theoretical analysis is conducted to clarify the key parameters that dominate the radiative fraction of jet fires, with discussion of the limitation of previous radiative fraction correlations. A completely new dimensionless group, consisting of the mass fraction of fuel at stoichiometric conditions, the density ratio of fuel gas to ambient air and the flame Froude number, is proposed to correlate the radiative fraction of jet fires. The current up-to-date experimental data are used to build the radiative fraction correlation that covers orifice exit diameters from one to hundreds of millimeter, hydrogen, methane and propane fuels, vertical and horizontal jets, buoyance- and momentum-controlled releases, subsonic, sonic and supersonic jets. It is found that the source Froude number can fit the radiative fraction of a particular fuel jet fire. However, the new dimensionless group can correlate the radiative fractions of fuel-different jet fires. The predictive capability of the new correlation exceeds that of previously published work based on the source Froude number only or the global residence time with/without correction factors.

Introduction

The accidental releases of high-pressure fuel storage and transportation systems and oil and gas wells, are often reported to cause the large jet fires. In addition, the controlled flare has been the traditional method for safe disposal of unwanted flammable gases and vapors in the process industry. For example, a historical survey conducted on data from several accident databases has shown that 50% of jet fires will induce at least one additionally severe event such as explosion [1]. Thus the questions and issues of jet fires have occupied scientific and engineering research for many years

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and are still of major concern in the combustion and fire safety field.

Lots of attentions have been paid to the combustion dynamics of jet fire [2–6]. Becker and Liang [2] proposed a flame Richardson number to dominate the transition from buoyance- to momentum-controlled jet fires, by which the jet flame length correlation was built for type-different fuels. Instead of the flame Richardson number, a flame Froude number was developed to correlate the flame length of fuel-different jet fires by Delichatsios [3], which has been evaluated and validated by the later works [5]. Recently Bradley et al. [4] proposed a dimensionless flow number to correlate both the jet flame length and lift-off distance for extensive ranges of fuel types and flow rates. Later, they also developed generalized correlations of blow-off and flame quenching for subsonic and chocked jet fires in terms of the dimensionless flow number [6]. There is no doubt that during the past decades, great progress has been made towards deep insight into the jet flame combustion behavior, with generalized correlations proposed for flame length and lift-off distance and blow off.

In comparison, a generalized correlation for the radiative fraction is not available, even though it is of crucial importance for calculating the potential threaten or damage due to the radiant heat from jet fires. The radiative fraction is one basic input parameter of different engineering-type thermal radiation models [7,8]. Chamberlain [9] measured the radiative fraction of natural gas jet fires both in laboratory and from flare systems, and found that the radiative fraction can be exponentially correlated with the orifice exit velocity. Markstein and De Ris [10] experimentally studied the radiative fractions that were fitted against the total heat release rate by means of power function, for jet fires of four different hydrocarbon fuels, respectively. The global residence time, derived from the convective timescale, was also used to correlate the radiative fractions of methane, ethylene and propane jet fires, respectively [11]. The global residence time was also validated to be effective for fitting the radiative fraction data of large hydrogen jet fires [5]. Proust et al. [12] measured the radiant heat flux from high pressure hydrogen fires and fitted the radiative fractions against the flame length for orifices of 1–3 mm in diameter, respectively. Recently, Zhou et al. [8] proposed the source Froude number to correlate the radiative fraction of propane jet fires without physical interpretation in detail. However, these correlations are so empirical to strongly depend on the experimental conditions. That is to say, their application is limited to particular gases and/or flow regimes. Even though Molina et al. [13] developed a radiative fraction correlation that couples the global residence time and the correction factor based on the differences in thermal emittance of combustion gases of different fuels, and its validation was further verified by large methane/hydrogen mixture jet fires [14], their correlation has also limited to non-sooting fuel gases (e.g. hydrogen and methane) and the momentum-controlled flow regime.

Thus this paper presents a theoretical analysis on the radiative fraction, with the aim to propose the generalized correlation for the radiative fraction of jet fires. Firstly the theoretical analysis is conducted to determine the key parameters that dominate the radiative fraction, followed by a comprehensive survey of the available experimental data on the radiative fraction of jet fires. The data bank is then used in the radiative fraction correlation in terms of the source Froude number and finally in terms of a proposed new dimensionless group, with the physical interpretation on the variation of the radiative fraction.

Theoretical analysis on the radiative fraction

The radiative fraction (χ_r) is defined as the ratio of the total radiant energy escaping from the flame ($\dot{Q}_r$) to the total heat release rate ($\dot{Q}$) as follows

$$\chi_r = \dot{Q}_r \big/ \dot{Q} \tag{1}$$

And the total heat release rate can be expressed by

$$\dot{Q} = \dot{m}_0 \Delta H_c \tag{2}$$

in which $\varDelta H_c$ is the fuel combustion heat, generally given by

$$\Delta H_c = c_p \Delta T_a / f_s \tag{3}$$

where c_p and f_s are the specific heat of combustion products and the mass fraction of fuel at stoichiometric conditions, respectively, and $\varDelta T_a$ the adiabatic flame temperature rise. In Eq. (2), $\dot{m}_0$ is the fuel mass flow rate at the orifice exit and can be written as follows

$$\dot{m}_0 = \frac{1}{4}\pi d_0^2 u_0 \rho_0 \tag{4}$$

where d_0 and u_0 are the orifice exit diameter and velocity, respectively, and ρ_0 the gas fuel density at the orifice exit.

The jet flame is assumed to be an isothermal and homogeneous grey emitter with a constant absorption-emission coefficient (α_p). Then the total radiant output can be expressed by

$$\dot{Q}_r = \sigma A \left(1 - \exp\left(-\alpha_p l_m\right)\right) T_f^4 \tag{5}$$

where σ is Stefan-Boltzmann constant, A the entire area enclosing the flame, T_f the mean effective radiation temperature, and l_m the mean optical path length of the whole flame volume, conventionally given by

$$l_m = 3.6V/A \tag{6}$$

in which V is the entire flame volume. In general, the hydrogen combustion holds a little absorption-emission coefficient, and the small jet flame holds a little mean optical path length. In addition, the absorption-emission coefficient also could be little for hydrocarbon jet flames of large orifice exit velocity, which is indicated by the appearance of much bright blue flame [15]. Therefore, the $\alpha_p l_m$ can be considered to be little for most of jet fires, and then Eqs. (5) and (6) can lead to

$$\dot{Q}_r = 3.6\sigma\alpha_p V T_f^4 \tag{7}$$

The jet flame is often considered to be a cone with the height being the flame length (L_f), and then the flame volume can be expressed by