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Flame size and volumetric heat release rate of turbulent buoyant jet diffusion flames in normal- and a sub-atmospheric pressure

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HIGHLIGHTS

- Relationship between flame size and heat release rate obtained for jet diffusion flame.
- Unique data revealed for a sub-atmospheric pressure and compared with normal pressure.
- Non-dimensional global correlation proposed including HRR and pressure effect.

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ABSTRACT

This paper investigates the flame size (i.e. envelop surface area and flame volume) and the volumetric heat release rate of turbulent jet diffusion flames, in both normal and in a sub-atmospheric pressure. Experiments on turbulent jet diffusion flames, produced with nozzles of 4, 5, 6 and 8 mm in diameter and using propane as fuel, have been carried out at two different altitudes: Hefei, 50 m and 100 kPa and Lhasa, 3650 m and 64 kPa. Results have shown both the flame envelope surface area, A_f, and the flame volume, V_f, to be much larger in the sub-atmospheric pressure than in the normal pressure (i.e. $A_f \sim p^{-4/5}$; $V_f \sim p^{-7/5}$). The flame envelope surface area has been found to scale with the heat release rate, $\dot{Q}$, by the power of 4/5, $A_f \sim \dot{Q}^{4/5}$. The flame volume, V_f, has also been found to scale with the heat release rate by the power of 9/10, $V_f \sim \dot{Q}^{9/10}$. The volumetric heat release rate, $\dot{Q}'''$, has been found to be a function of both the heat release rate, $\dot{Q}$, and the ambient pressure, p ($\dot{Q}''' \sim \dot{Q}^{0.1}$; $\dot{Q}''' \sim p^{7/5}$). General non-dimensional correlations for all the present data, obtained for the different nozzle diameters and the two ambient pressures, have also been proposed for the flame envelope surface area and the flame volume, respectively.

1. Introduction

Flame size parameters, including flame envelope surface area and flame volume, are important basic features to describe diffusion flame heat release characteristics (for example, heat release rate per unit surface or unite volume).

Since the visible flame is actually only a thin shell of reacting material surrounding a volume of hot gases, it stands to reason that the heat release rate may depend linearly on the surface area [1].

Linteris and Rafferty [2,3], based on studies of laminar flame surface area of four gaseous flames and five burning solid polymers, have found that the flame area to be well correlated with heat release rate (80 kW/m^2).

More studies have been reported for the flame volume in the literatures for pool fires indicating generally that the flame volume is proportional to the heat release rate (or volumetric heat release rate is constant); however suggesting different relation slopes (or constant) [4–7]. The study of Rasbash and colleagues [4] has led initially to the conclusion that the volumetric heat release rate is independent of flame power over the range studied (20–160 kW), and is approximately 1900 kW/m^3. After that, Orloff and de Ris [5] have suggested that the volumetric heat release rate is constant, $\dot{Q}''' = \dot{Q}/V_f$ = 1200 kW/m^3. Recently de Ris [6] has shown that the volumetric heat release rate can be expressed through Eqs. (1) and (2), being dependent on local properties and independent on the overall size of the fire.

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Nomenclature

A_b	area defined in Eq. (12) (m^2)
A_f	flame envelope surface area (m^2)
a	flame area of each horizontal segment (m^2)
c_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
D	source diameter (m)
D_{eq}	equivalent flame diameter defined in Eq. (10) (m)
Fr_f	flame Froude number
g	gravitational acceleration (ms^{-2})
h	specific enthalpy (kJ kg^{-1})
ΔH_c	heat of combustion per unit fuel mass (kJ kg^{-1})
j	the number of horizontal segments
m	the number of flamelet disks in each horizontal segment
p	ambient pressure (Pa)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}'''$	volumetric heat release rate (kW m^{-3})
$\dot{Q}^*$	dimensionless heat release rate
q	volumetric fuel flow rate (m^3 h^{-1})
r	the equivalence flame radius (m)
R_e	Reynolds number
S	stoichiometric oxidant to fuel mass ratio
T_0	ambient temperature (K)
$\overline{\Delta T_f}$	mean peak flame temperature rise (K)
u	velocity (ms^{-1})
V_f	flame volume (m^3)
V_b	volume defined in Eq. (25) (m^3)
x	column coordinate value of the pixel
z	flame height above the fire source (m)

Greek symbols

α	thermal diffusivity (m^2s^{-1})
$[\alpha_T]_{lhasa}$	entrainment coefficient correction factor in Lhasa City
$[\alpha_T]_{hefei}$	entrainment coefficient correction factor in Hefei City
α_T	entrainment coefficient correction factor
ℓ_f	flame height (m)
ρ	density (kgm^{-3})
ρ_0	ambient air density (kgm^{-3})
ρ_s	fuel density at the nozzle (kgm^{-3})
χ	fraction
τ	time constant (s)
υ	kinematic viscosity (m^2s^{-1})
δ	image scale factor (m)
ε	dissipation rate

Subscripts

a	standard conditions
ch	chemical
f	flame
s	source conditions
0	ambient conditions

$$\dot{Q}''' \sim \rho h/\tau_f \sim \rho h\left[(\Delta\rho_f g/\rho)^2/\sqrt{\upsilon_f\alpha_f}\right]^{1/3} \quad (1)$$

$$h = \chi_{ch}\Delta H_c/(1+S) \quad (2)$$

Cox [7] has also proposed a value of 500 kW/m^3; however, it has been referred to be not acceptable for turbulent diffusion flames [8]. In [1], Stratton has made some studies about the flame volume of furniture fires and pool fires. In his study, a value of 800 kW/m^3 for the volumetric heat release rate of furniture fires has been obtained.

Meanwhile, from another point of view based on Froude modeling, the normalized flame height has been found to be a function of the dimensionless heat release rate of the fire to the power of 2/5 [9,10]:

$$\frac{\ell_f}{D} \sim \dot{Q}^{*2/5} \quad (3)$$

where ℓ_f is the flame height, D is the fire source diameter and $\dot{Q}^*$ is the dimensionless heat release rate [9,10], expressed by:

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_0 c_p T_0 g^{1/2} D^{5/2}} = \frac{\rho_s u_s \pi D^2 \Delta H_c/4}{\rho_0 c_p T_0 g^{1/2} D^{5/2}} \quad (4)$$

So, the volumetric heat release rate, $\dot{Q}'''$, is a function of heat release rate, $\dot{Q}$, to the power of $-1/5$:

$$\dot{Q}''' \sim [\dot{Q}/V_f] \sim [\ell_f^{5/2}/V_f] \sim \ell_f^{-1/2} \sim \dot{Q}^{-1/5} \quad (5a)$$

or we can have:

$$V_f \sim \dot{Q}^{6/5} \quad (5b)$$

which is similar to that reported by Rasbash et al. [11], correlating data in the range between 20 kW and 2800 kW,

$$V_f = 1.21\dot{Q}^{1.18} \quad (6)$$

The flame size characteristics (envelope surface area and volume) and hence the heat release per unit area or unit volume of turbulent jet diffusion flames are different from pool fires or burning solid combustible, due to the momentum effect on the turbulent mixing between fuel and air. The initial fuel discharge momentum for a turbulent jet diffusion flame is not zero, conversely from a pool-type fire. This momentum effect has not been quantified yet.

Another important issue is the pressure effect. For an elevated pressure condition over 100 kPa, the pressure effect on flame shape, soot emission and radiation for both premixed and diffusion flames have been explored [12–14]. Some experimental works have also been recently reported for diffusive pool fires in Lhasa (64 kPa) [15,16], showing the flame height and buoyancy strength (induced entrainment and mixing) be quite different from the normal pressure (100 kPa). From these studies, changes in the flame size and the heat release per unit size (area or volume) could also be inferred; however, these have not been quantified in the literature yet.

So, in this work, experiments have been carried out for turbulent buoyant jet diffusion flames to investigate the evolution of their envelope surface areas and volumes along with heat release rates. These characteristics have been revealed and compared in both normal pressure (Hefei city: 100 kPa) and in a sub-atmospheric pressure (Lhasa city in Tibet: 64 kPa).

2. Experimental

Fig. 1 depicts the experimental setup. Four circular gaseous nozzles made of stainless steel with diameters between 4 mm and 8 mm and propane as a fuel have been used. The real mass flow rate has been calibrated according to ambient pressure, based on which the heat release rates have been calculated according to the heat of combustion per unit mass of fuel [17].