Fuel 116 (2014) 781–786

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

# Flame radiation fraction behaviors of sooty buoyant turbulent jet diffusion flames in reduced- and normal atmospheric pressures and a global correlation with Reynolds number

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## HIGHLIGHTS

- Data achieved in a reduced pressure through unique experiments at high altitude.
- A dimensional scaling theory for flame radiation fraction dependency on pressure.
- Flame radiation fraction well correlated by a negative power law function of Re.

## ARTICLE INFO

*Article history:*
Received 12 April 2013
Received in revised form 19 August 2013
Accepted 21 August 2013
Available online 5 September 2013

*Keywords:*
Turbulent buoyant jet diffusion flame
Reduced atmospheric pressure
Flame radiation fraction
Reynolds number

## ABSTRACT

This paper reports new experimental observations on flame radiation fraction of sooty turbulent buoyant jet diffusion flames in a reduced atmospheric pressure (at high altitude in Tibet) and corresponding scaling theoretical interpretations. A global correlation of the flame radiation fraction with Reynolds number is proposed for both the reduced- and normal pressures. Experiments are carried out in both Hefei (altitude: 50 m) with atmospheric pressure of 100 kPa and Lhasa (altitude: 3650 m) with atmospheric pressure of 64 kPa. The turbulent buoyant jet diffusion flames are produced by nozzles with diameters of 4, 5, 6, 8 and 10 mm using propane as fuel at different flow rates. The emitted thermal radiation fluxes by the flames, for both attached condition and lifted off condition, are measured by a water-cooled radiometer. The flame radiation fraction change due to pressure reduction is clarified. Results show that the flame radiation fraction changes little with atmospheric pressure. A dimensional scaling theory is proposed to interpret this pressure dependency behavior. The flame radiation fraction for attached flame is found to be higher than that for lifted-off flame, decreasing in both cases with increasing nozzle fuel velocity or turbulent mixing at the flame base. Such decreasing behavior is found to be well fitted globally by a negative power law function on source Reynolds number ($\chi_R \sim \mathrm{Re}^{-0.32}$) of the discharged fuel flow at the nozzle.



## 1. Introduction

Flame radiation fraction, as an important parameter of jet diffusion flames, has been investigated extensively as well as for its pressure dependency. The radiation fraction $\chi_R$ of a jet diffusion flame is affected mainly by the soot formation and volume of the flame, which both change with pressure.

The pressure levels considered in the literatures are mainly elevated pressure conditions over 100 kPa [1–4] or atmospheric pressure [5–7] for premixed or diffusion flames. For example, De ris et al. [2] has studied, by a series of model-scale pool-fire experiments (pan diameters of 0.15, 0.23, and 0.30 m), the diffusion flame radiation characteristics at elevated pressures. The proportionality of the ratio of burning rate to the pressure for radiation-controlled pool fires is derived.

As for conditions of lower pressures (less than 100 kPa), some experimental works have also been reported recently for diffusion pool fires and solid combustible combustion behaviors, based on data achieved specially in Lhasa city at high altitude of 3650 m (64 kPa) [8,9]. For example, Li et al. [8] has carried out experiments on combustion characteristics of *n*-heptane and wood crib fires at the two altitudes (Hefei city: 50 m, atmospheric pressure: 100 kPa; Lhasa city: 3650 m, atmospheric pressure: 64 kPa). It has been revealed that the burning rate and radiation heat flux at the higher altitude is lower. The behaviors of laminar jet flames in sub-atmospheric pressure have also been clarified [10]. Most [11] has studied the effects of gravity and pressure (30–300 kPa) on the

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0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.08.059

**Nomenclature**

| | |
|---|---|
| $D$ | nozzle diameter (m) |
| $g$ | gravitational acceleration (m/s$^2$) |
| $\Delta H_c$ | heat of combustion per unit fuel mass (kJ/kg) |
| $H_R$ | radiometer height (m) |
| $I_R$ | radiation flux (kW/m$^2$) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $p$ | ambient pressure (Pa) |
| $\dot{Q}$ | heat release rate (kW) |
| $\dot{Q}*$ | dimensionless heat release rate |
| $R$ | horizontal radiometer-nozzle distance |
| $R_f$ | distance from the vertical flame mid-point height to the radiometer position (m) |
| Re | Reynolds number |
| $T_0$ | ambient temperature (K) |
| $\Delta T_f$ | temperature rise at the flame tip (K) |
| $U_s$ | fuel velocity at nozzle orifice (m/s) |
| $V_f$ | flame volume (m$^3$) |
| $Y_s$ | average characteristic soot centration |

*Greek symbols*

| | |
|---|---|
| $\ell_f$ | flame height (m) |
| $\rho_0$ | ambient air density (kg/m$^3$) |
| $\rho_s$ | fuel density at nozzle (kg/m$^3$) |
| $\chi_R$ | flame radiation fraction |
| $\phi_s$ | soot volume fraction |
| $\tau_f$ | characteristic flow time |
| $\tau_s$ | characteristic soot formation time |
| $\tau_{Kolmogorov}$ | Kolmogorov time scale |
| $\nu$ | Kinematic viscosity (m$^2$/s) |
| $\varepsilon$ | dissipation rate |
| $\mu$ | dynamic viscosity (N s/m$^2$) |
| $\sigma$ | Stefan–Boltzmann constant (W m$^{-2}$ k$^{-4}$) |

*Subscripts*

| | |
|---|---|
| 0 | ambient |
| $f$ | flame |
| $s$ | soot |

characteristics of diffusion flames produced by a 62 mm gaseous pool fire with nearly zero initial momentum. The results have indicated that the flame radiation fraction shows weak dependency on pressure (in a power law of $p^{-0.1}$ empirically). There are also some works on laminar jet diffusion flames. For example, Kim [12] has investigated the soot surface growth and oxidation at pressures of 10–100 kPa in laminar diffusion flames. Yang et al. [13] has studied the influence of pressure on the laminar non-premixed acetylene jet flame at the two altitudes (Hefei city: 50 m, atmospheric pressure: 100 kPa; Lhasa city: 3650 m, atmospheric pressure: 64 kPa), in which it is found that the radiation heat flux displays a positive proportionality to pressure.

However, how the radiation fraction $\chi_R$ of a buoyant turbulent jet diffusion flame changes in a reduced pressure atmosphere still remains to be quantified. A special character of a jet flame, which differs from a pool-type fire, is that the initial fuel discharge momentum is not zero (which is the basic characteristic of a pool-type fire). As the discharge velocity of the diffusion jet fire increases, the source turbulence increases accordingly. The change of the turbulence will influence the turbulent mixing of the fuel with the surrounding ambient air at the base of the flame. So, how the initial turbulence of the discharged fuel jet flow at the nozzle, in both normal and reduced pressures, affects the flame radiation fraction $\chi_R$ also needs to be clarified. These behaviors have not been revealed in the past and are to be quantified in the present work.

In this paper, experiments are carried out at two different altitudes: 50 m (atmospheric pressure: 100 kPa) and 3650 m (atmospheric pressure: 64 kPa) as described next in Section 2. In Section 3, a dimensional scaling theory is proposed and compared with the experiments for the dependence of the flame radiation fraction on pressure; the flame radiation fraction change due to lift-off is also clarified; the flame radiation fraction is fitted with Reynolds number for both the reduced- and normal pressure to develop a global correlation model. The last section summarizes the major findings of this work.

## 2. Experiments

### 2.1. Experimental facility and setup

Fig. 1 shows the experimental facility and measurement setup. The jet diffusion flames are produced vertically by stainless pipe nozzles with diameters of 4 mm, 5 mm, 6 mm, 8 mm and 10 mm. The delivered flow rate is controlled by a throttle valve and measured by a flow rate meter. The real mass flow rate is calibrated according to local ambient pressure. For each nozzle diameter, 10–13 cases with different mass flow rates (correspondingly discharge velocities) are carried out. The experimental condition ranges are summarized in Table 1. Each case is repeated 3 times.

The flame geometry is visualized by a digital CCD (Charge-Coupled Device) camera of sensor size 8.5 mm with 3,000,000 pixels. The film speed of the camera is 25 frames per second. In previous experimental works investigating pressure effect on combustion behaviors, the change of the ambient pressure is usually achieved by using pressurized vessel or box. For the turbulent jet diffusion flames considered in this work, if using the pressurized method, both the boundary constraint effect and the fire-buoyancy induced inside-box (vessel) air flow will affect the flame behaviors considerably, only except the box is very big enough. A feature of

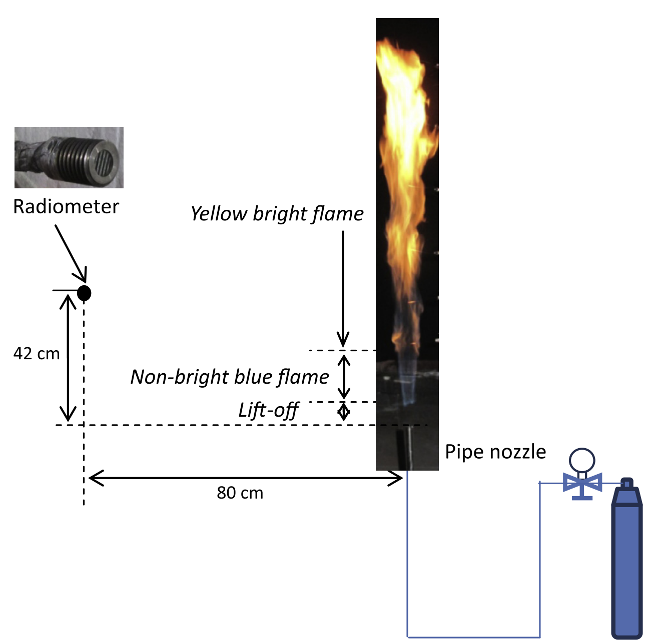


**Fig. 1.** Experimental setup.