INFLUENCE OF HIGH ALTITUDE ON COMBUSTION EFFICIENCY AND RADIATION FRACTION OF HYDROCARBON FIRES

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Fire behaviors of three gaseous hydrocarbon fuels were experimentally measured and compared at two different altitudes (Lhasa city, 64 kPa at an altitude of 3650 m; Hefei city, 100 kPa at an altitude of 50 m). The heat release rates were calculated through a simplified thermochemistry based on the measured concentrations of O_2 and CO_2 in the exhaust duct, then the combustion efficiencies and the radiation fractions were compared at the two altitudes. The heat release rates and combustion efficiencies were higher at lower pressure, and the overall temperatures of methane fires rose at a lower pressure. The radiative heat fluxes and radiation fractions at a low pressure were smaller than those at a normal pressure, while the smoke transmittances of acetylene fires at a low pressure were higher.

KEY WORDS: *hydrocarbon fire, heat release rate, combustion efficiency, radiation fraction, transmittance*

1. INTRODUCTION

Fire behavior research at a low pressure has been a hotspot recently to meet the fire protection requirements in plateau districts and cruising airplanes. Previous studies showed that ambient pressure has a significant influence on combustion behaviors such as burning rate (Yao, 2013; Yin et al., 2013), flame shape (Tao et al., 2013), flame radiation flux, and product concentrations (Jun et al., 2008). The plateau regions provide low atmospheric pressure conditions to investigate flame and smoke characteristics.

Wieser et al. (1997) carried out solid and liquid fire tests in a mobile room at altitudes from 400 m to 3000 m and showed that the burning rate varies as the 1.3 power of pressure. Based on both theoretical analysis and experimental measurements, Nikitin (1998) reported that the mass combustion rate is proportional to the gas pressure raised to the two-thirds power. Jun et al. 2008 concluded that the ratios of the average burning rates of *n*-heptane fires in Lhasa to Hefei approaches approximately the air pressure ratio of Lhasa to Hefei, i.e., 0.64. Li et al. (2009) investigated wood and *n*-heptane fires at two altitudes (50 m and 3650 m) and found that the ratio of burning rates at these two pressures coincides with the conclusion of Wieser et al. (1997). In order to compare the combustion behaviors at two altitudes for the same burning rate, Li et al. (2009) employed larger *n*-heptane pan tests and reported that the flame radiation flux is lower while the average flame

NOMENCLATURE

A	coefficient ratio of CO_2 to O_2 in global reaction equation	K	light extinction coefficient, m^{-1}
		L	optical path length, m
a, b, c	coefficients in global reaction equation		fuel mass loss rate, kg/s
C_xH_y	hydrocarbon consisting of x carbon atoms and y hydrogen atoms	$\dot{Q}$	heat release rate, HRR, kW
		$\dot{Q}_r$	overall radiative heat flux, kW
ΔH	enthalpy of reaction for per unit mass fuel in incomplete combustion, kJ/kg	q_r	radiative heat flux per unit area, kW/m^2
ΔH_c	heat of combustion, i.e., enthalpy of reaction for per unit mass fuel in complete combustion, kJ/kg	R	distance from flame center to the radiometer, m
		Greek symbols	
I	received light intensity	χ	combustion efficiency
I_0	incident light intensity	χ_r	radiation fraction

temperature is higher at a high altitude. The subsequent experimental investigation conducted at a higher altitude of 4250 m by Hu et al. (2011) confirmed the findings for the burning rate and combustion behaviors made in Li et al. (2009).

The burning rate or mass loss rate, as a primary parameter of solid and liquid fuel fires and a governing factor that influence the combustion behaviors, has been inevitably investigated in these previous works (Hu et al., 2011; Jun et al., 2008; Li et al., 2009; Nikitin, 1998; Wieser et al., 1997; Yao, 2013; Yin et al., 2013). So a gaseous fuel of acetylene was used by Yang et al. (2012) to obtain exactly the same burning rate at two altitudes (50 m and 3650 m) in a more recent work. But in fact, the effective heat release rate or combustion efficiency are likely to be different under various buoyancy conditions for the same burning rate at different pressures. The combustion efficiency generally depends on fuel type, flame size, soot production, and ventilation condition (Tewarson, 2004). The combustion efficiency usually ranges from unity to the lowest value 0.46 reported in Tewarson (2002). The products of incomplete combustion are usually CO, soot, and unburnt hydrocarbons (e.g., aromatics, aldehydes).

From this point of view, the product composition and concentration reflect the completeness of combustion. In the case of hydrocarbon fuels, a higher combustion efficiency means that carbon in the fuel ends up with more CO_2, and less CO, soot and other unburnt hydrocarbons (Bourguignon et al., 1999). Koseki and Mulholland (1991) employed the ratio of CO/CO_2 and smoke yield as measures of the combustion efficiency, and a high level of CO concentration as a sign of poor combustion efficiency (X1, x1). The different CO concentrations in Lhasa and Hefei tests (Jun et al., 2008) indicated that the ambient pressure exerts some influence on combustion efficiency. These parameters, the so-called carbon conversion expressions, mentioned above are compromized and qualitative measures of combustion efficiency. However, the quantitatively and traditionally measured combustion efficiency, defined as the chemical heat of combustion divided by the net heat of complete combustion (Tewarson, 2002), has not been revealed at different pressures in the past and is to be evaluated in this paper.

In the present work, fire tests of three gaseous hydrocarbon fuels were carried out at two different altitudes, 3650 m in Lhasa (64 kPa) and 50 m in Hefei (100 kPa).The heat release rates were calculated based on concentrations of O_2 and CO_2. The combustion efficiencies and radiation efficiencies at the two altitudes were compared to reveal the influence of pressure on the fire characteristics.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1 Test Platform

The fire tests were conducted on a scaled platform 0.4 times the size of ISO9705 fire test platform (ISO 9705, 1993) in Lhasa (64 kPa, 3650 m) and Hefei (100 kPa, 50 m), as shown in Fig. 1. The platforms were located in large enough spaces to ensure full development of fires in a windless environment. The dimensions of the cone body are 1.2-m long, 1.2-m wide, and 1.2-m high. Glazed windows were embedded in the upper part of the cone body to facilitate experimental observation, while the lower part was vacant to entrain fresh air. The exhaust hood and duct were designed to collect and pump out combustion products. Two baffles in the top of the hood and two guide vanes at both ends of the duct were designed to mix the products uniformly for more accurate sampling measurements. A fan volumetric flow rate of 0.18 m^3/s was found enough to exhaust the combustion products in both Lhasa and Hefei through the ducts with internal diameter of 0.16 m.

Fuels were supplied from compressed cylinders and regulated by a thermal mass flow controller, then through a stainless steel burner with 50 mm inner diameter located at the center of the cone base. The Sevenstar D07-19B flow controller has a measure range of 0–30 slm and a resolution of 0.1 slm. The measure accuracy of mass flow rate is within ±1% and the repeatability is ±0.2%. Heat-resistant glass beads in the
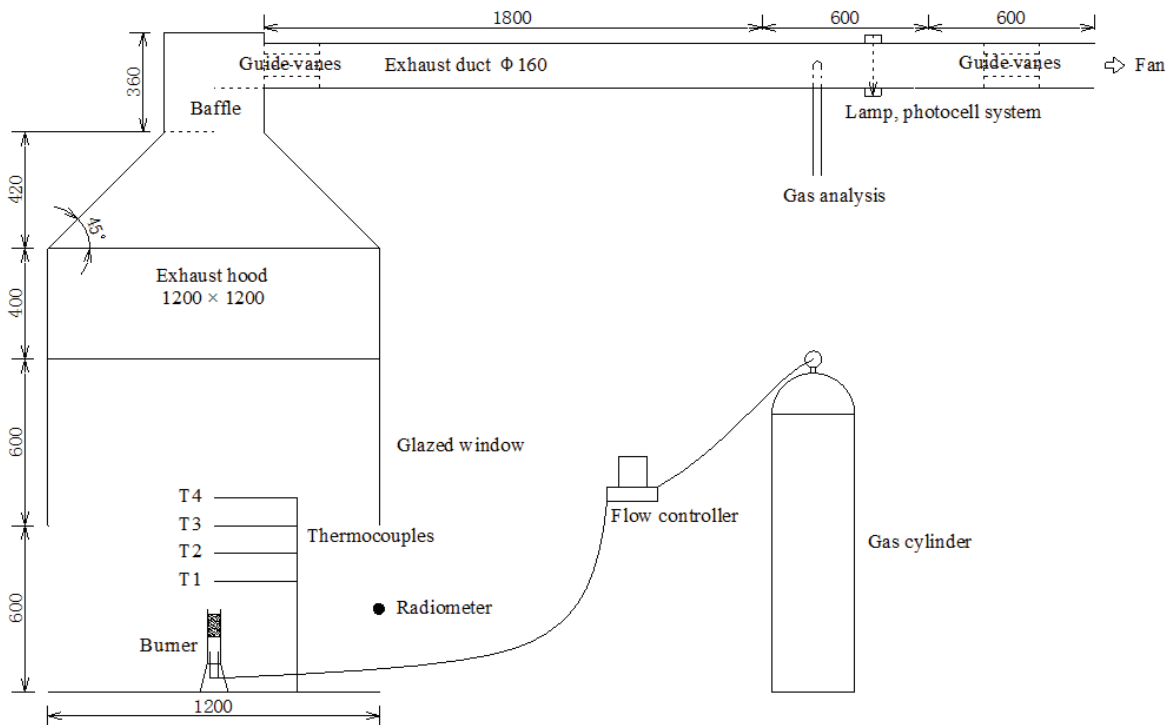

FIG. 1: The test platform and instrumentation layout

burner tube were used to stabilize the flame and make the velocity profile at the exit uniform. Three hydrocarbon fuels with increasing carbon ratio were selected to be methane, propane, and acetylene with industrial purities ≥99.9%.

2.2 Measuring Instruments

The concentrations of oxygen and carbon dioxide flowing through the exhaust duct were measured by a Servomex 4100 analyzer based on principles of paramagnetic and infrared ray, respectively. The ranges for measuring oxygen and carbon dioxide are 0–25% and 0–10%, respectively, both with ±0.001% resolution. An array of four K-type thermocouples with 0.5 mm bead diameter labeled as T1–T4 were vertically distributed along the burner axis, with a spacing of 10 cm and the lowest thermocouple T1 was 10 cm above the burner exit. A wide angle water-cooled radiometer was placed at the same elevation as the burner exit and 55 cm horizontal distance from the edge of the burner to measure the ensemble emitted radiation flux from the fires. The horizontal distance is 11 times the diameter of the burner so that the point source model would be suitable (Hamins et al., 1991; Markstein, 1985). A photoelectric kapnometer mainly consisting of a lamp and photocell was mounted on the exhaust duct to measure the smoke transmittance. The sampling rates of the thermocouples and radiometer are both 1 Hz, while the sampling rates of the gas analyzer and kapnometer are 3 Hz.

2.3 Test Cases

The fuel flow rates of methane, acetylene, and propane were designed to obtain specified heat release rates of 4, 8, and 12 kW assuming the fuel was fully burned to carbon dioxide, as listed in Table 1. The test for each different fuel and flow rate lasted more than 100 s and was repeated three times to ensure reproducibility. The environmental temperature and humidity of all the tests were approximately the same, i.e., room temperature of 18–23°C and relative humidity of 50–62%.

3. RESULTS AND DISCUSSION

3.1 Thermochemistry Technique

Assuming that the fuel is partially converted to carbon dioxide and carbon monoxide, the total heat release rate can be calculated by a thermochemistry technique (Enright, 1999) by only measuring two of the three concentrations of O_2, CO_2, and CO in the exhaust duct. The thermochemistry technique is only suitable for the known fuel composition. In this study, the volumetric concentrations of O_2 and CO_2 in the exhaust duct are measured, then the volumetric concentration of CO can be calculated from the global reaction:
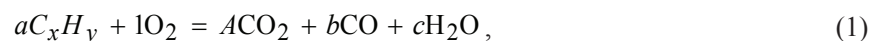
$$aC_xH_y + 1O_2 = ACO_2 + bCO + cH_2O, \tag{1}$$

TABLE 1: Summary of test conditions

Fuel	Specified HRR, kW	Fuel Flow Rate, g/s
Methane	4, 8, 12	0.080, 0.160, 0.240
Acetylene	4, 8, 12	0.083, 0.166, 0.249
Propane	4, 8, 12	0.086, 0.172, 0.259

where A is the mole of CO_2 produced per unit mole of O_2, A can be determined by the increment of CO_2 divided by the decrement of O_2 during the combustion process. The other coefficients a, b, and c can be calculated by the conservation of atoms for C, H, and O, as $a = \dfrac{4 - 2A}{2x + y}$, $b = \dfrac{4x - 4Ax - yA}{2x + y}$, and $c = \dfrac{2y - yA}{2x + y}$.

Finally, the total heat release rate is calculated from the enthalpy of reaction and the flow rate

$$\dot{Q} = \dot{m}\Delta H, \tag{2}$$

where $\dot{m}$ is the fuel mass loss rate and ΔH is the enthalpy of reaction representing the change of enthalpy between the products and reactants. The combustion efficiency χ is calculated as the ratio of the enthalpy of reaction to the heat of combustion:

$$\chi = \frac{\Delta H}{\Delta H_c}, \tag{3}$$

where the heat of combustion ΔH_c is the enthalpy of reaction when the hydrocarbon fuel is completely converted to carbon dioxide without any carbon monoxide formed.

3.2 Heat Release Rate and Combustion Efficiency

The flow rates corresponding to 4 kW, 8 kW, and 12 kW were adjusted continuously for the same fuel, as shown in Fig. 2. The steady stage for each flow rate lasted for at least 100 s for taking average; for instance, the average oxygen concentration of the 4 kW fire was averaged from 138 s to 240 s. In the sebsequent analysis, the measured quantities including concentrations, radiation flux, and transmittance were all averaged on each steady stage in both Hefei and Lhasa tests.

After determining the values of A in Eq. (1) as the variation ratios of the carbon dioxide concentration to the oxygen concentration for each test case, the heat release rates calculated from Eq. (2) were plotted in Figs. 3–5, where the heat release rates were all higher in Lhasa than in Hefei. The combustion efficiency was plotted along in Figs. 3–5 to characterize the completeness of sensible energy release under different combustion conditions. The combustion efficiencies were higher in Lhasa than in Hefei for all the test cases. The combustion efficiency increases from methane to propane to ethylene. The χ of methane is close to unity and
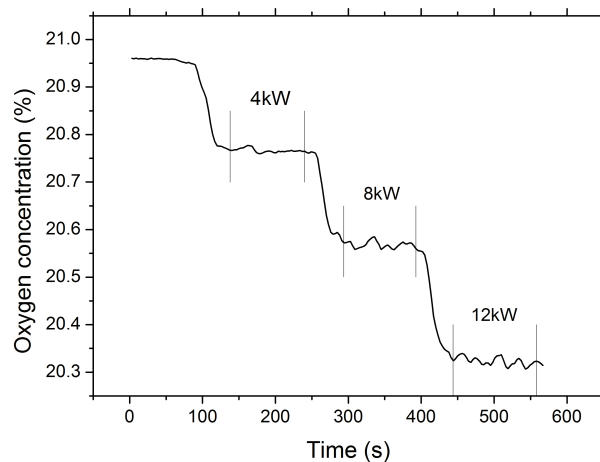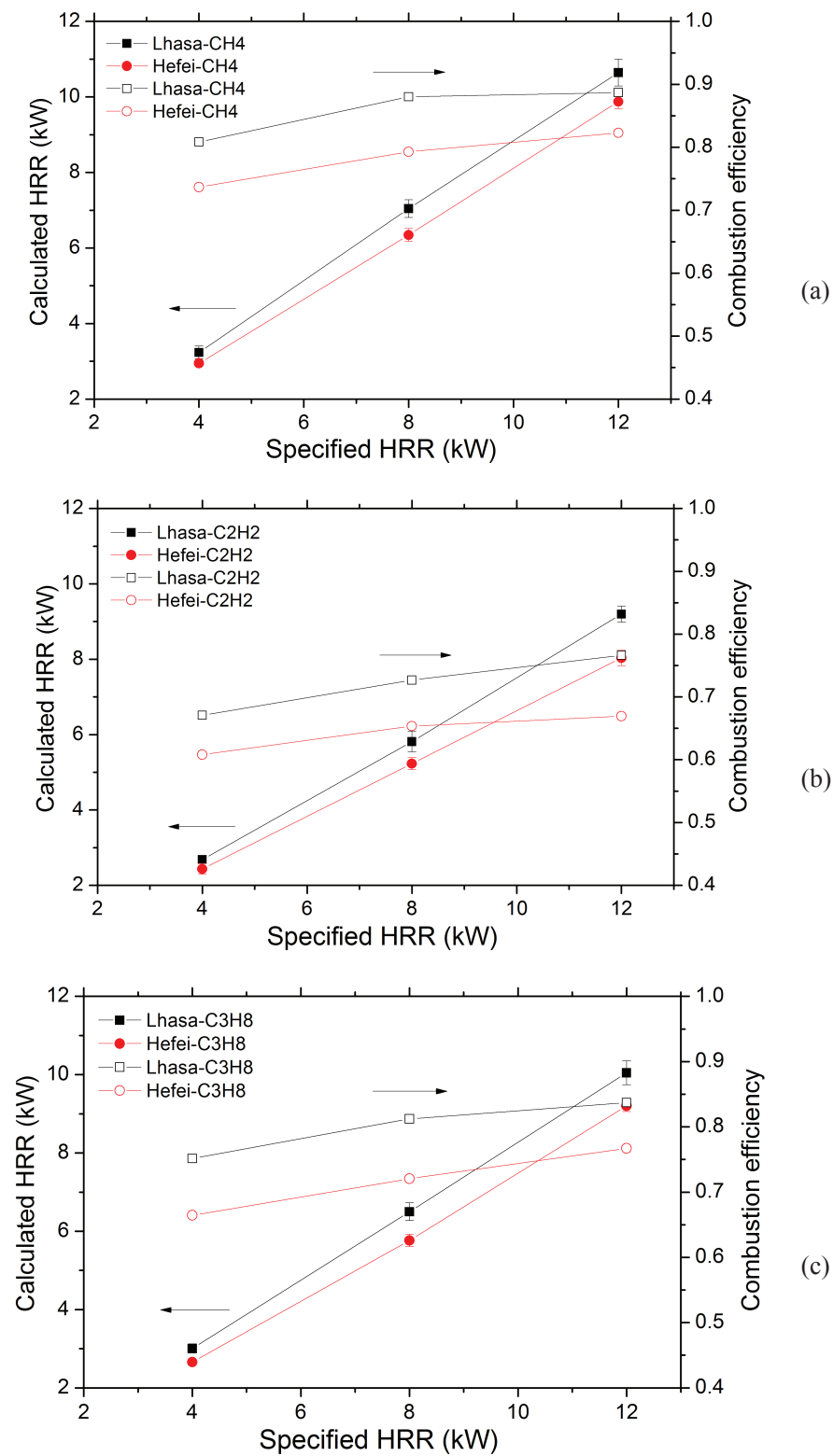

FIG. 2: An example for data reduction

FIG. 3: Calculated HRR and combustion efficiency of fires: (a) methane fires, (b) acetylene fires, (c) propane fires
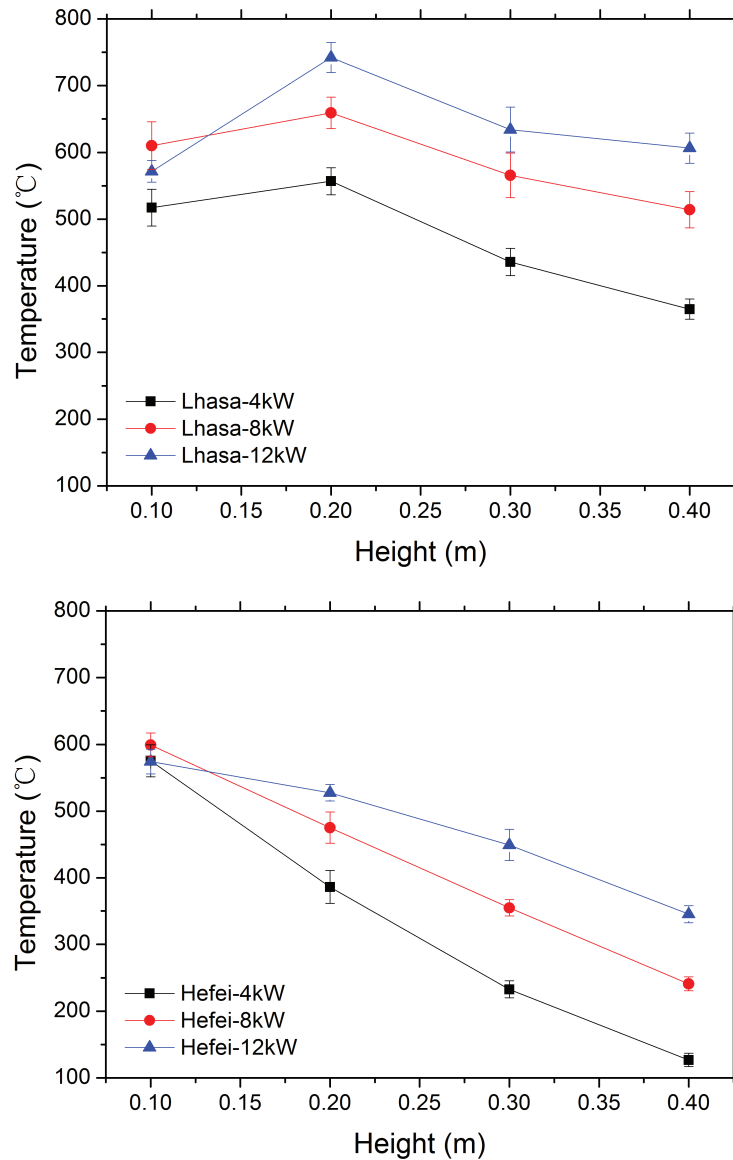
FIG. 4: Axial temperature distribution of methane fires at two altitudes: (a) temperatures at low pressure in Lhasa, (b) temperature at high pressure in Hefei

that of acetylene is approximately 0.75 as previously given in Janssens (2002). The combustion efficiencies in Hefei are lower since the carbon dioxide concentrations were observed to be lower and the flames were more sooty. Besides, flame expansion and higher temperature will result in higher combustion efficiency in Lhasa, which will be discussed below.

3.3 Axial Temperature

The time-averaged axial temperature of methane fires under the two pressures was plotted in Fig. 4, where the overall plume temperature is greater at a low pressure than at a normal pressure as validated in previous
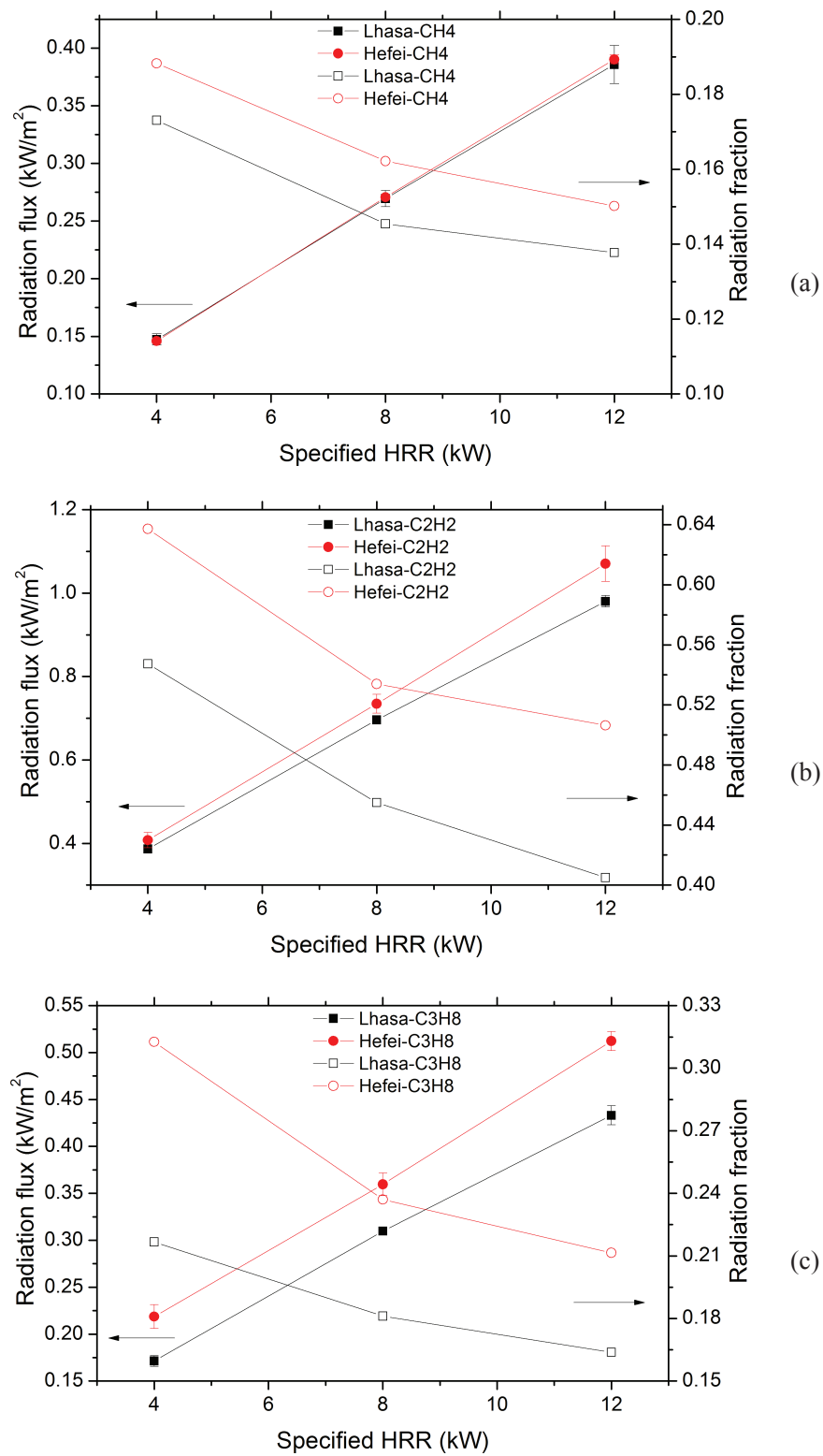
FIG. 5: Radiation flux and radiation fraction: (a) methane fires, (b) acetylene fires, (c) propane fires

gaseous jet fire and solid box fire tests at these two altitudes (Yang, 2012; Yao, 2013). Only methane fire measurements were presented as the soot deposited on the thermocouples made the measurements for ethylene and propane fires impossible. The higher combustion efficiency at a lower pressure implies that more heat was released and hence the axial temperature was raised in Lhasa. The lower air density at lower pressure means that the flame fronts will shift to a higher location to entrain more oxygen for the combustion (Hu et al., 2013), therefore the peak temperature of methane fires occurred at around 0.2 m in Lhasa tests, while the peak temperature occurred at around 0.1 m in Hefei tests and then the axial temperature decreased upward.

3.4 Radiation Flux

Figure 5 plots the measured radiation fluxes of all fires and their corresponding flame radiation fractions at both low and normal pressures. Flame radiation fraction can be calculated by using the measured overall radiation flux as follows:

$$\chi_r = \frac{\dot{Q}_r}{\dot{Q}} = \frac{q_r 4\pi R^2}{\dot{Q}}, \tag{4}$$

where $\dot{Q}_r$ is the total radiation flux emitted from the flame, q_r is the overall radiation flux per unit area measured by the radiometer, and R is the distance from the flame center to the radiometer. The radiative heat fluxes at a low pressure are lower than those at normal pressure, which is consistent with the previous finding in Fang et al. (2011). Since the heat release rates are higher at a low pressure, the radiation fractions become even lower in Lhasa, especially for the acetylene fires. Higher radiation flux and radiation fraction in Hefei are due to the increased soot formation at a higher pressure (Intasopa, 2011; Roditcheva and Bai, 2001).

3.5 Light Extinction Coefficient

The light extinction coefficient is the most widely measured quantity to characterize the smoke tendency of the flame, and it can be derived from transmittance through the exhaust duct (Mulholland, 2002). According to Bouguer's law, the light extinction coefficient K is related to the incident light intensity I_0, the received light intensity I, and the optical path length L:

$$K = -\ln\left(I/I_0\right)/L, \tag{5}$$

where the transmittance I/I_0 is measured directly by the photoelectric kapnometer. Methane and propane fires produced negligible smoke obscuration because of their low smoke emitting tendencies (Berry and Roberts, 2006; Kent, 1986). So only the transmittances of acetylene fires at the two pressures are presented in Fig. 6, where it can be seen that the transmittances in Lhasa were greater than those in Hefei. Correspondingly the light extinction coefficients of the exhausted smoke of acetylene fires in Lhasa were smaller than those in Hefei. The observation that smoke yield in Lhasa was weaker is consistent with the previous results of acetylene fires (Yang, 2012) and n-heptane pool fires (Hu et al., 2011). The lower smoke yield also increases the combustion efficiency in Lhasa.

4. CONCLUSIONS

In this study, the heat release rate and radiative heat flux for methane, acetylene, and propane fires at two altitudes were experimentally measured to reveal the influence of low pressure on combustion efficiency and
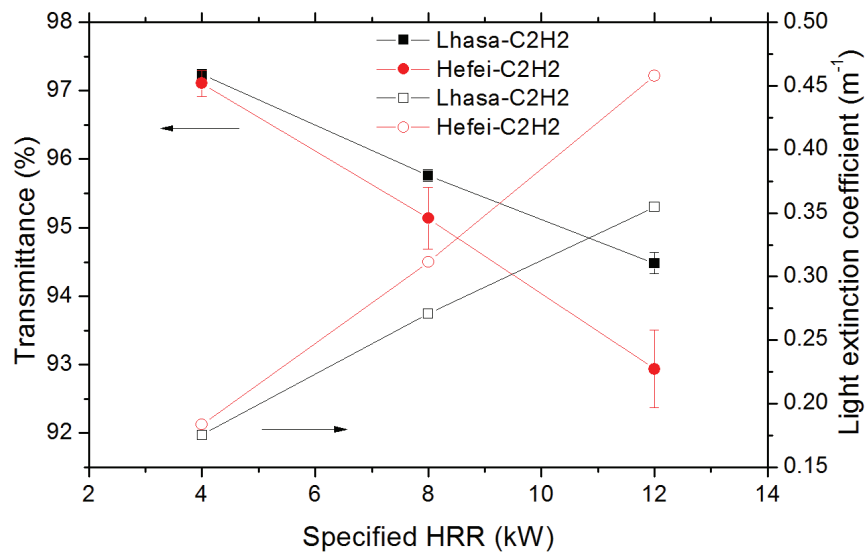
FIG. 6: Transmittance and light extinction coefficient of acetylene fires

radiation fraction. A simplified thermochemistry technique based on concentrations of O_2 and CO_2 for calculating heat release rate was proposed.

The heat release rate and combustion efficiency were found to be higher at a lower pressure for all the three fuels studied. The overall plume temperatures of methane fires were higher at a lower pressure. The radiative heat fluxes and radiation fractions were lower at a lower pressure. The transmittances of acetylene fires were greater at lower pressure implying that smoke yield at a low pressure was smaller. In summary, the findings in this paper contribute to a better understanding of the influence of pressure on fire behaviors, especially for actual heat release rates of the same burning rate, and provide data for fire protection in high altitude environment.

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