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The influence of low atmospheric pressure on carbon monoxide of *n*-heptane pool fires

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Abstract

Qualitative theoretical analysis about air pressure influence upon the gas concentration of a fire plume was given, different scale *n*-heptane pool fires were conducted in a small and a standard compartment room in Lhasa and Hefei, respectively. The experimental results show that, in Lhasa, the average mass burning rates in the small room and the standard room both decrease, burning time increases at about 53% in small room and 45% in standard room more than in Hefei. Whereas for maximum changes of CO concentration, in the small room, in Lhasa, CO concentrations reach about twice bigger peak values at larger increase rates than in Hefei. While in the standard room, in Lhasa and Hefei, there are no significant changes for CO concentration, which agrees well with the theoretical analysis results.

Keywords: Tibet; Low pressure; Carbon monoxide; *n*-Heptane fire

1. Introduction

The Qinghai–Tibet Plateau in China was the latest to emerge on earth, but it is the largest in size and the highest in elevation, hence it is named as “Roof of the World” or the “Third Pole”. The average altitude of Tibet is about 4000 m, with the rise in elevation, the air pressure and oxygen content per cubic meter of air decline. In Lhasa, capital of Tibet, the atmospheric pressure and oxygen content are about only two-thirds of those in the plain areas.

There are more than 1000 historic buildings, including the world-famous Potala Palace in Tibet, also there are many tourists and pilgrims everyday, fire safety becomes very important to safeguard both the invaluable cultural heritages and the people.

The main toxic gaseous product of fire is carbon monoxide, its concentration and duration are the two key factors for its harm to the people. Compared with the fire behaviors in low-altitude areas, fire dynamics and its products are different in Tibet for its low atmospheric pressure and oxygen density.

Fire behaviors in different pressures have been under investigation by Kanury [1] and Alpert [2], Lockwood and Corlett and coworkers [3], Shinotake et al. [4], De Ris et al. [5,6], but they mainly focused on the large fire modeling methods by increasing air pressure and reducing the size of the combustible, little work was done under low air pressures.

In 1996, Most et al. [7] studied the influence of gravity and pressure on pool fire-type diffusion flames. They put emphasis on the individual influence mechanisms of gravity and pressure upon the flame size, shape, radiation heat flux, and temperature, but little work was done about the fire gaseous products under the influence of air pressure.

In 1997, Wieser et al. [8] investigated the fire tests

held at different altitudes in Austria, test fires were carried out in a 6 m × 4 m × 3.35 m well insulated container room. This container was transported by lorry from its first location at 420 m above sea level to location two at 1000 m above sea level, and then by helicopter to the third and fourth locations at 1800 m and 3030 m above sea level, respectively. Standard parameters, in particular optical extinction *m*, the *y*-value of the standard ionization chamber and increase in temperature, CO, CO_2, O_2, and burning rate were recorded. The results show a dependence of burning rates on pressure as $\propto p^{1.3}$, whereas the gas temperature increase, changes of CO and CO_2 concentration show no significant dependence on pressure.

In Wieser’s work, confined by the helicopter, the fire test room is not a standard combustion room, for *n*-heptane fire, it

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is 123 g *n*-heptane in a 15.5 cm × 15.5 cm × 2 cm bowl, no standard test fire was carried out. The standard combustion room is a rectangular room with a flat horizontal ceiling, and the dimensions are length: 9–11 m, width: 6–8 m and height: 3.8–4.2 m, which is a common fire research facility, standard *n*-heptane fire is 650 g *n*-heptane in a 33 cm × 33 cm ×5 cm bowl [9]. Furthermore, the highest altitude for the experiments is only 3030 m, and no theoretical explanations about the experimental results were given.

Different from Wieser's and other previous studies, in this work, first, a qualitative theoretical analysis about air pressure influence upon the gas concentration and temperature increase of a fire plume was given, then in Lhasa (altitude: 3650 m) and Hefei (altitude: 24 m), different scale *n*-heptane pool fires were carried out in a small room (typical workroom) and a standard combustion room, respectively, finally, the experimental results are discussed and compared with the theoretical analysis results.

2. Theoretical analysis

Practically all fires go through an important, initial stage in which a coherent, buoyant gas stream rises above a localized volume undergoing combustion into surrounding space. The buoyant flow, including any flames, is generally turbulent, and referred to as a fire plume [10]. Fire gas is produced in the combustion process, and diffuses into the air with the plume movements. Air pressure, correlated with oxygen content, not only influences the combustion process, but also has an effect on the plume movements.

As indicated by De Ris et al. [6], for lack of basic scientific understanding of chemical kinetic mechanisms in fires under different pressures, it is very difficult to know the pressure influence mechanisms upon toxic and corrosive product chemical release. So here, we employ the previous experimental study results, the ideal law, plume theory suggested by Heskestad [10], and some assumptions suggested by De Ris, to qualitatively obtain the air pressure influence upon the temperature increase and gas concentration of a fire plume.

In the deduction process, some assumptions and previous study results employed are:

(1) As Heskestad noted [10], a steady turbulent fire plume in an open space can be represented by a point source and assumed to be axisymmetric.

For a fire whose size is large compared with the dimension of a combustion room, the fire cannot be assumed to be a point source plume, the air entrainment is too strong, the combustion is not steady, this assumption is not suitable for this case. But when the combustion room is large, as for some standard fire tests, the fire size is comparatively small, the assumption is suitable.

(2) The fire gas is ideal gas.

(3) Radiative loss fraction χ_r is independent upon air pressure as noted by De Ris et al. [6].

(4) Mass loss rate $\dot{m}$ is proportional to air pressure p as noted by De Ris et al. [6].

(5) Fire gas yield rate Y_g, which is the fraction of fuel mass that is converted to fire gas, is assumed to be independent upon air pressure.

From Heskestad's dimensionless analysis results [10], the qualitative relationship between gas mass concentration and other fire parameters is as follows:

$$C_{(m)} \propto \left(\frac{g}{C_p T_0 \rho_0}\right)^{-1/3} \dot{m} Q_c^{-1/3} Z^{-5/3} Y_g \quad (1)$$

Here, $C_{(m)}$ is the fire gas mass concentration in the plume centerline at Z height, g is the gravitational acceleration, C_p is the specific heat at constant pressure, T_0 and ρ_0 are, respectively, the air temperature and density at the point source, Q_c is the convective part of the heat release rate, here subscript 'c' represents convection.

According to the ideal gas law, the relationship between mass concentration $C_{(m)}$ and volume fraction concentration $C_{(\upsilon)}$ is

$$C_{(\upsilon)} \propto \frac{T}{p} C_{(m)} \quad (2)$$

Here T is the smoke temperature, so substitute Eq. (1) into Eq. (2),

$$C_{(\upsilon)} \propto \frac{T}{p}\left(\frac{g}{C_p T_0 \rho_0}\right)^{-1/3} \dot{m} Q_c^{-1/3} Z^{-5/3} Y_g \quad (3)$$

where $Q_c = (1 - \chi_r)\dot{m}\Delta H_c$, ΔH_c is the heat of combustion, here subscript 'c' represents combustion, ΔH_c mainly depends upon the molecular composition of the combustible fuel and combustion products, it is independent upon pressure, thus $Q_c \propto \dot{m}$, and Eq. (3) becomes

$$C_{(\upsilon)} \propto \frac{T}{p}\left(\frac{g}{C_p T_0 \rho_0}\right)^{-1/3} \dot{m}^{2/3} Z^{-5/3} Y_g \quad (4)$$

For ideal gas, its enthalpy is defined as $h = u + p\upsilon$, ideal gas law is $p\upsilon = RT$ or $p = \rho RT$, here u is the internal energy, υ is the specific volume, $\upsilon = 1/\rho$, and R is the specific gas constant.

So $h = u(T) + RT$, while the specific heat at constant pressure is defined as $C_p = (\partial h/\partial t)_p$, then $C_p = \mathrm{d}h/\mathrm{d}t$, it is independent on the atmospheric pressure. Combine with the ideal law $p = \rho RT$, substitute $\rho T = p/R$ into Eq. (4), can obtain

$$C_{(\upsilon)} \propto \frac{T}{p}\left(g\frac{R}{p}\right)^{-1/3} \dot{m}^{2/3} Z^{-5/3} Y_g \quad (5)$$

R and Y_g are independent upon air pressure (5), can be further changed into

$$C_{(\upsilon)} \propto T p^{-2/3} \dot{m}^{2/3} Z^{-5/3} \quad (6)$$

As $\dot{m} \propto p$, then in the Z height:

$$C_{(\upsilon)} \propto T = T_0 + \Delta T \quad (7)$$

Here ΔT is the difference between the smoke and air temperature.

Combine Eqs. (2) and (7), the fire gas mass concentration in the Z height is

$$C_{(\mathrm{m})} \propto p \quad (8)$$

Heskestad's dimensionless analysis about ΔT is as below [10]

$$\Delta T \propto \left(\frac{g}{C_{\mathrm{p}} T_0 \rho_0}\right)^{2/3} \frac{T_0}{g} Q_{\mathrm{c}}^{2/3} Z^{-5/3} \quad (9)$$

By using the similar deductions as above, in the Z height of the fire plume centerline:

$$\Delta T \propto T_0 \quad (10)$$

So, combine Eqs. (7) and (10), can get

$$C_{(\upsilon)} \propto T_0 \quad (11)$$

Eqs. (8), (10) and (11) are the final analysis results for the gas temperature increase and concentration in the centerline of a fire plume, it can be seen that, temperature increase and gas volumetric concentration are independent upon air pressure, while gas mass concentration is proportional to the air pressure.

As the theoretical analysis is based on the assumption that the fire source is relatively small, so, in the below discussion, only the experimental results in the standard combustion room are compared with the theoretical results.

3. Experiments

The test n-heptane pool fire is selected for its good repeatability, it is burnt in square steel trays, whose areas are 133 cm^2, 200 cm^2, 325.5 cm^2, 576 cm^2 and 1100 cm^2, respectively, and the tray height is the same as 5 cm. The small room is 2 m long, 4 m wide and 3.35 m high, whose area and volume is characteristic of a typical workroom. The standard combustion room is 10 m long, 7 m wide and 4 m high as shown in Fig. 1.

In the experiments, electrical balance is used to record the mass loss rate, MRU gas analyzer is used to record the gas temperature increase, CO, CO_2 and O_2 concentration. For this kind of gas analyzer, the gases are sampled and analyzed through a stainless probe, gas temperature is measured by the NiCrNi thermocouple (type K) at the probe.

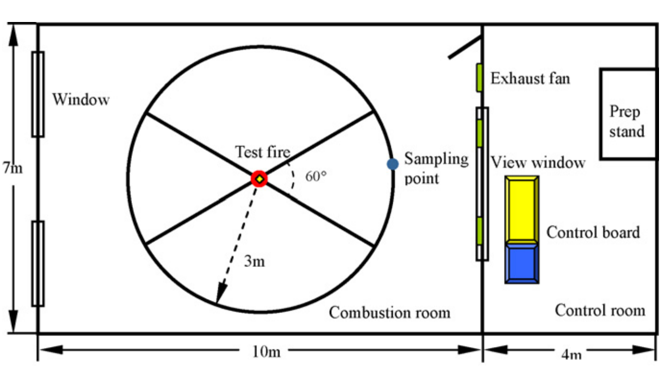

Fig. 1. Plan view of the standard combustion room.

Table 1
Small test room in Lhasa and Hefei

Case no.	Pool area (cm^2)	Initial mass (g)	Ambient temperature (K)		Relative humidity (%)	
			Lhasa	Hefei	Lhasa	Hefei
a	576	375	295	295	17	65
b	325.5	192	298	293	18	64
c	200	118	298	295	19	65
d	133	79	298	295	18	63

Table 2
Standard test room in Lhasa and Hefei

Case no.	Pool area (cm^2)	Initial mass (g)	Ambient temperature (K)		Relative humidity (%)	
			Lhasa	Hefei	Lhasa	Hefei
A	1100(std.)	650(std.)	290	290	25	61
B	576	375	295	294	24	62
C	325.5	192	294	293	25	65

In the small room, the probe is 2.75 m above the pool in the centreline of the fire plume, while in the standard room, according to the layout demands of standard combustion room [9], the probe is in the round ring about 4 cm below the ceiling as sampling point shown in Fig. 1. Also by using pressure gauge, humidity meter and thermometer, the initial ambient pressure, relative humidity and air temperature are recorded at the same time.

For the small and standard room, the test fire is put in the middle of the floor, the initial fire and ambient parameters are shown in Tables 1 and 2, where 1100 cm^2 pool area, 650 g n-heptane fire is a standard test fire. The atmospheric pressure of Lhasa and Hefei is 650 mbar and 1008 mbar, respectively.

4. Experimental results and discussion

4.1. Small combustion room

4.1.1. Burning time

The burning time of n-heptane fire is determined by the mass burning rate, which is the mass loss rate divided by the pool area. Figs. 2 and 3 are the comparisons of the mass burning rate for each case in the small test room in Lhasa and Hefei, respectively.

Figs. 2 and 3 show that, in Lhasa, for all n-heptane pool fires, they burn with more time than in Hefei. Fig. 4(a) further indicated, in low air pressure conditions of Lhasa, the burning time increases almost at an average value of 53%.

The average mass burning rates, which are the values of masses divided by the burning time and pool areas, and the ratios of the average burning rates in Lhasa to those in Hefei, are shown in Fig. 4(b). For all cases, in Lhasa, the n-heptane fire burns at lower average burning rates, the average mass burning rates in Lhasa and Hefei nearly keep constant to be 0.0013 g/(s cm^2) and 0.002 g/(s cm^2), respectively. The ratio of the average burning rates in Lhasa to those in Hefei approaches 0.65, this nearly equals the ratio of the air pressure in Lhasa to that in Hefei,

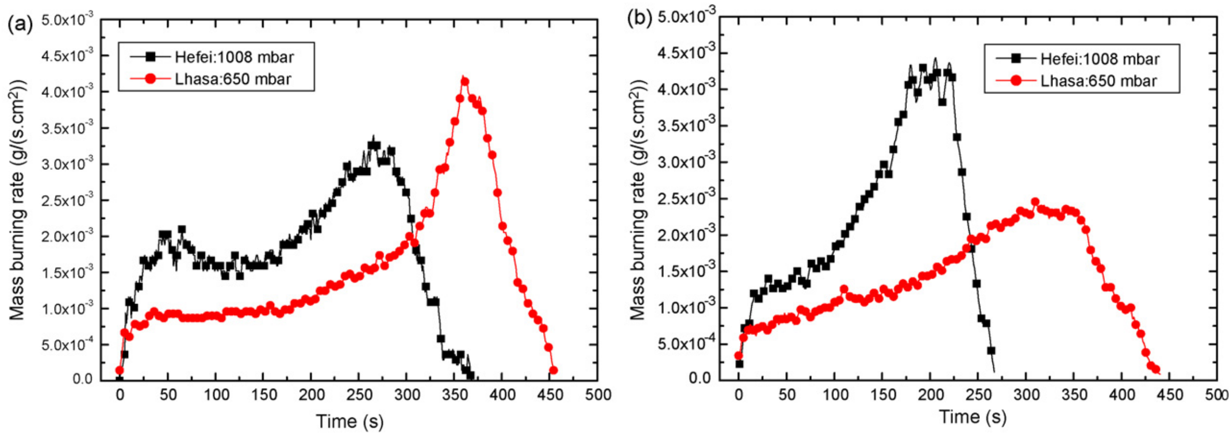

Fig. 2. Mass burning rate of Case a (a) and Case b (b).

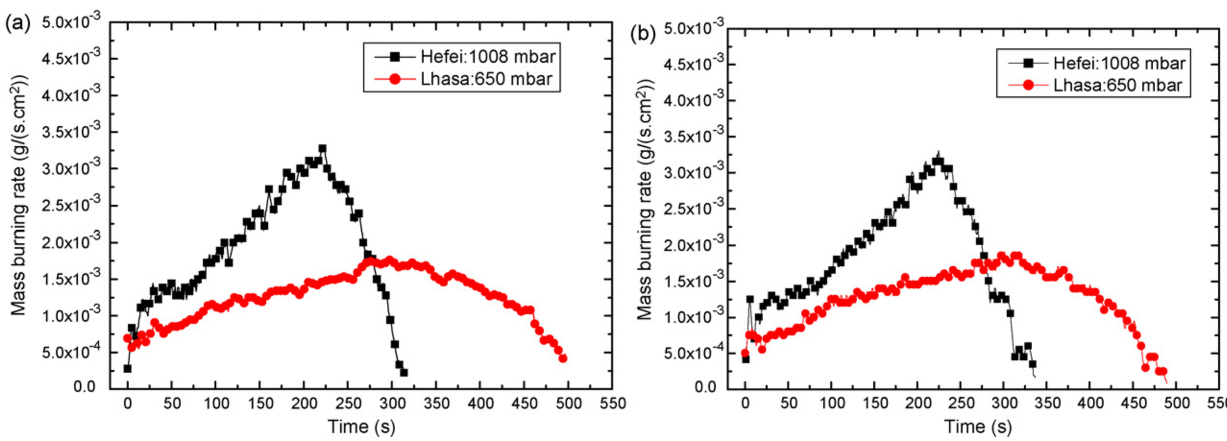

Fig. 3. Mass burning rate of Case c (a) and Case d (b).

about 0.64, that is to say

$$\frac{\dot{m}_{(\mathrm{Lhasa})}/A}{\dot{m}_{(\mathrm{Hefei})}/A} = \frac{p_{(\mathrm{Lhasa})}}{p_{(\mathrm{Hefei})}} \tag{12}$$

Here, $\dot{m}/A$ is the mass burning rate, $\dot{m}$ is the mass loss rate, A is the pool area and p is the air pressure.

So the average mass burning rate of *n*-heptane fire is approximately proportional to the atmospheric pressure, as $\dot{m}/A \propto p$. As the burning time $t = m_0/\dot{m}$, so the burning time is approximately inversely proportional to the atmospheric pressure, as $t \propto 1/p$.

A dependence of the burning rate on atmospheric pressure proportional to $p^{2/3}$ was obtained by De Ris et al. on the basis of dimensional consideration for the burning rate of natural diffusion flames with little radiation feedback [5]. But as Wieser et al. noted that [8], for radiation feedback dominant fire, the expo-

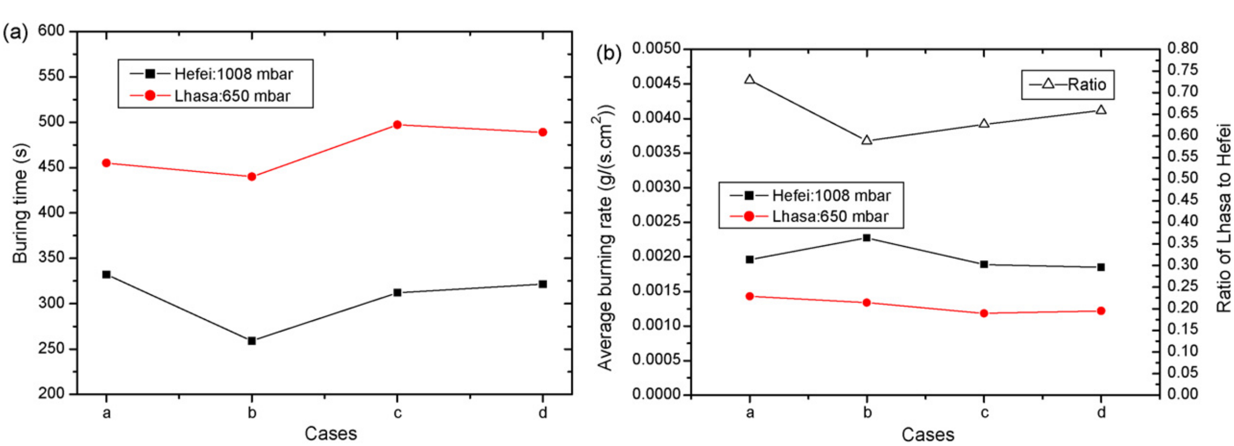

Fig. 4. Burning time (a), average burning rates and ratios (b) for small test room.

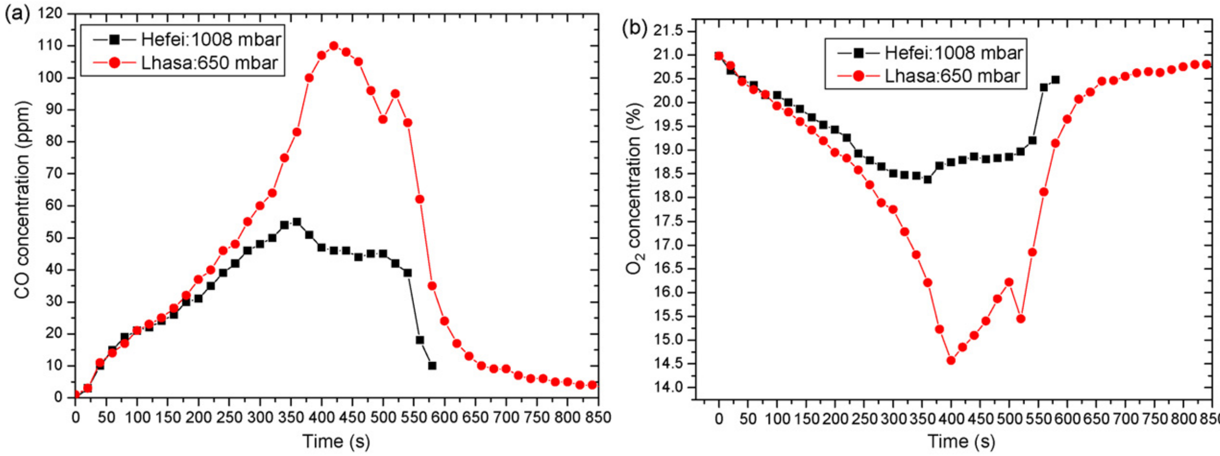

Fig. 5. CO (a) and O_2 (b) concentration of Case a.

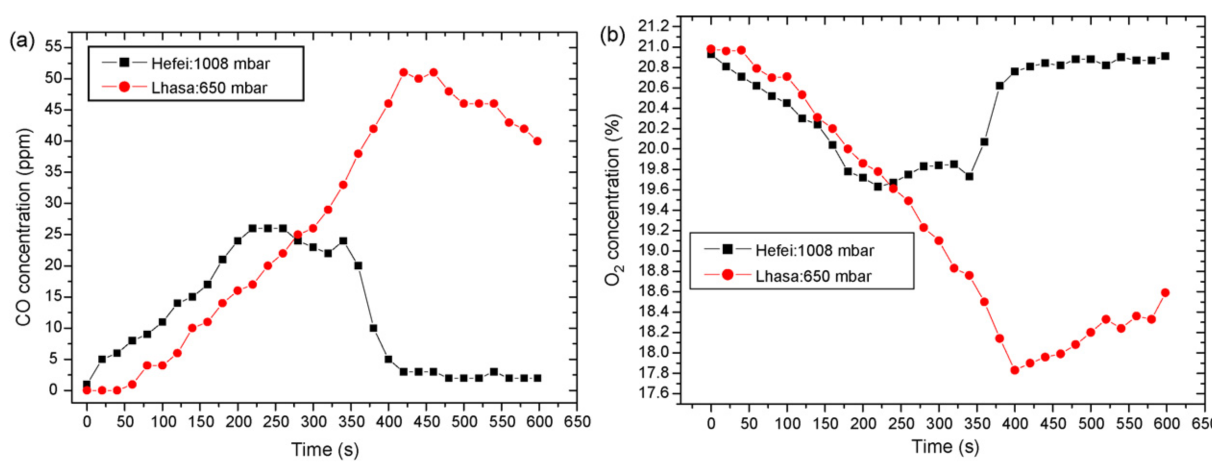

Fig. 6. CO (a) and O_2 (b) concentration of Case b.

nents of burning rates depending on the pressure would become bigger as confirmed by the experiments of Shinotake et al., exponent of 0.92 was registered for kerosene fire. For *n*-heptane pool fire, a lot of hot soot particles are produced, so radiation is the dominant feedback mechanism, in Wieser's work, the dependence of burning rates of *n*-heptane fire on pressure is as $\propto p^{1.3}$, but the mole fraction O_2 of the ambient air during the burning time was assumed to be constant, while in our small room, O_2 concentration changed a lot as below mentioned, so there is no meaning to compare the results with ours.

4.1.2. CO and O_2 concentration

Figs. 5–8 show the changes of CO and O_2 volume concentration in the small test room.

From Figs. 5–8, we can see, first, for all cases in Lhasa and Hefei, as *n*-heptane mass increases, CO concentration approximately increases linearly, correspondingly O_2 concentration decreases more for bigger combustion consumption. Secondly, for each case, the maximum CO concentration in Lhasa is almost twice bigger than that in Hefei.

Table 3 further shows the increase rate of CO product, which is the ratio of the maximum CO concentration to the needed time. It can be seen that, in low-pressure conditions, for all cases, CO concentrations increase at bigger rates.

In Wieser's 6 m × 4 m × 3.35 m test room [8], low air pressure has no significant effects on CO concentration, while the experiments in our small test room reaches the opposite conclusion. The reason is that, *n*-heptane flaming combustion consumes a large amount of O_2, in a small room, as O_2 supply is comparatively not very ample, O_2 consumption rate becomes

Table 3
Increase rate of CO concentration in Lhasa and Hefei

Case no.	Increase rate of CO (ppm/s)	
	Lhasa	Hefei
a	0.273	0.187
b	0.134	0.124
c	0.081	0.058
d	0.072	0.049

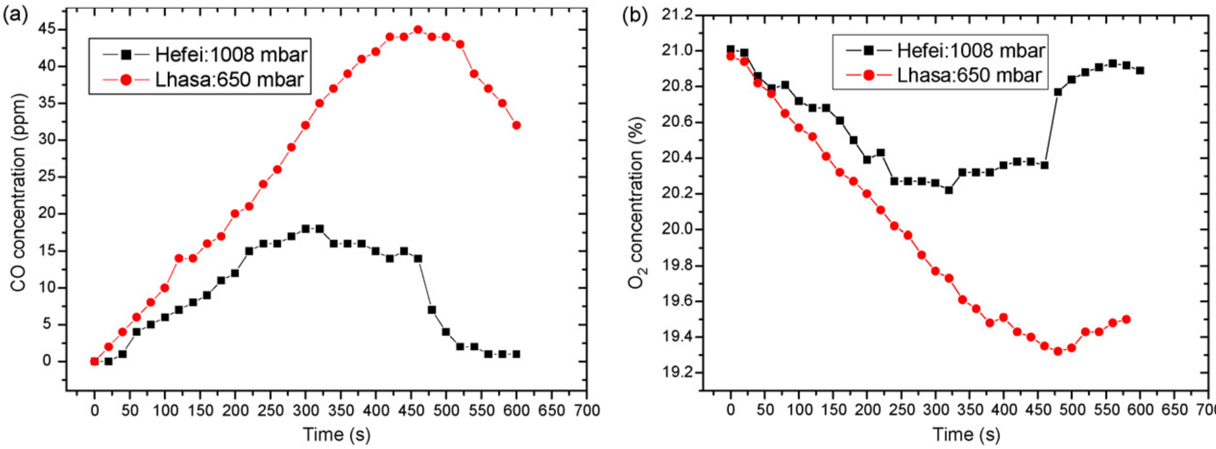

Fig. 7. CO (a) and O_2 (b) concentration of Case c.

bigger in Lhasa for lower oxygen content, so, the incomplete combustion product, carbon monoxide, increases more quickly and reaches bigger maximum values.

4.2. Standard combustion room

4.2.1. Burning time

The mass burning rates of Cases A and B are shown in Fig. 9, Case C is similar. The burning time, the average mass burning rates and their ratios are as Fig. 10 shows. Similar to the small test room results, for all cases, in Lhasa, the *n*-heptane fire burns slower, the burning time increases almost at an average value of 45%. But as below mentioned, here O_2 consumption rates are not big due to the comparatively more O_2 contents in the standard test room.

The average mass burning rates in Lhasa and Hefei also nearly keep constant, to be 0.00157 g/(s cm^2) and 0.00233 g/(s cm^2), respectively. The average ratio of the burning rate in Lhasa to Hefei is close to 0.67, also approaches to the air pressure ratio of Lhasa to Hefei, so the dependence of burning rates on pressure is also $\propto p$, while the burning time is $\propto 1/p$, still different from the results of Wieser's work [8] that the burning rates is $\propto p^{1.3}$. It is still unknown for the differences between our work and his work.

4.2.2. CO products

Fig. 11 shows CO and O_2 concentration of Case A, here, different from the small room tests, there are slight differences for the changes of CO and O_2 concentration in Lhasa and Hefei, it is similar for Cases B and C. The similar results are also found in Wieser's work [8].

The smoke temperature in our experiments is as Fig. 12 shows, it shows that the smoke temperature in Lhasa is very close to that in Hefei, air pressure has no significant influence on ΔT, it is also confirmed by Wieser's work [8].

The smoke temperature increase and concentration in the ceiling jet are proportional to those in the plume centerline, thus at the sampling point of the standard test room, as Eqs. (10) and (11) indicate, the plume temperature increase and gas volumetric concentration are theoretically independent upon air pressure and proportional to the air temperature, T_0.

In our experiments, since the ambient air temperature T_0 in Lhasa is very close to that in Hefei, thus the smoke temperature increase and CO volume concentration in the two places

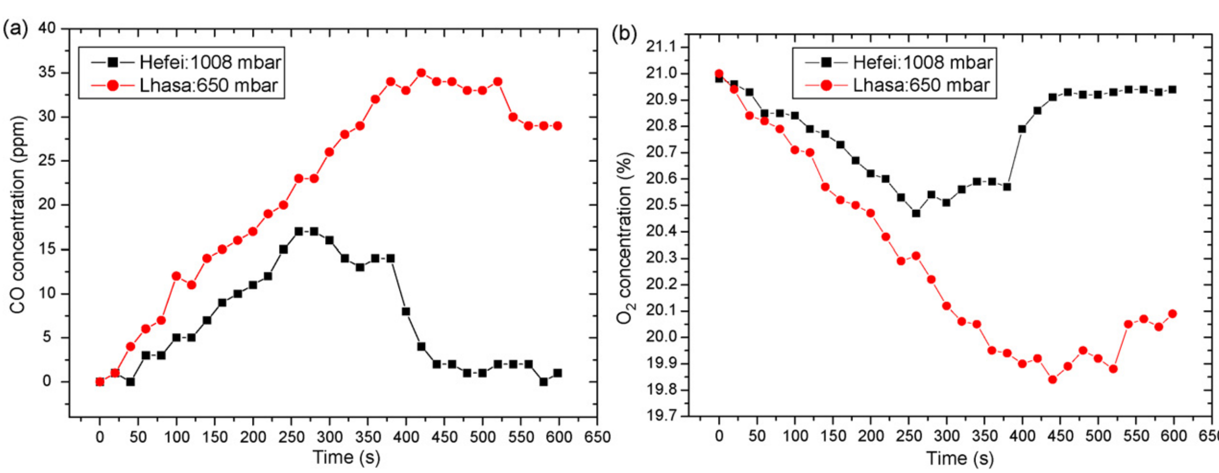

Fig. 8. CO (a) and O_2 (b) concentration of Case d.

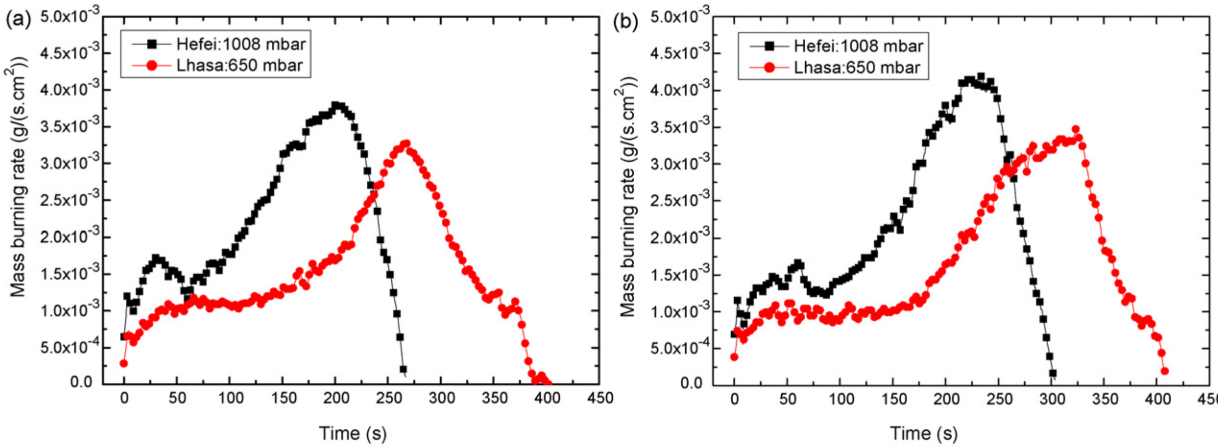

Fig. 9. Mass burning rate of Case A (a) and Case B (b).

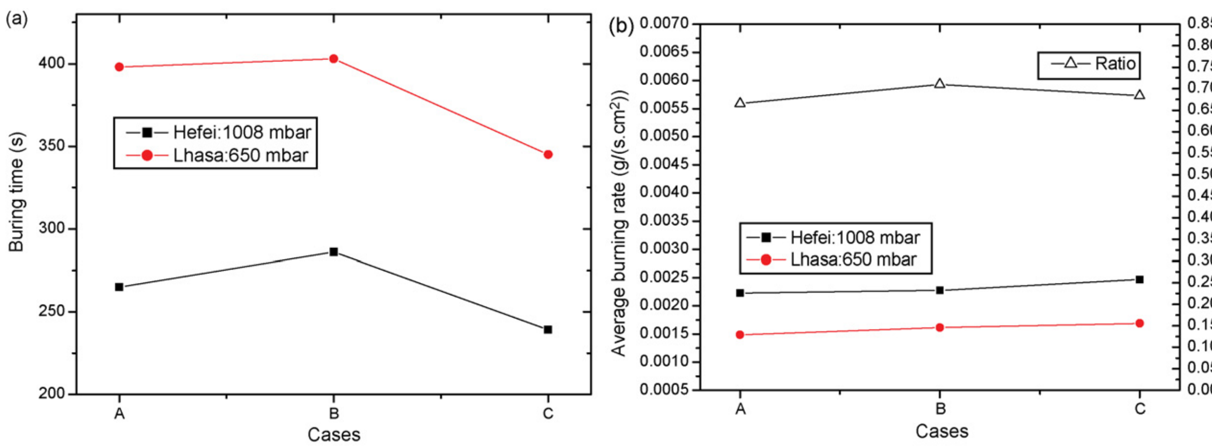

Fig. 10. Burning time (a), average burning rates and ratios (b) for standard test room.

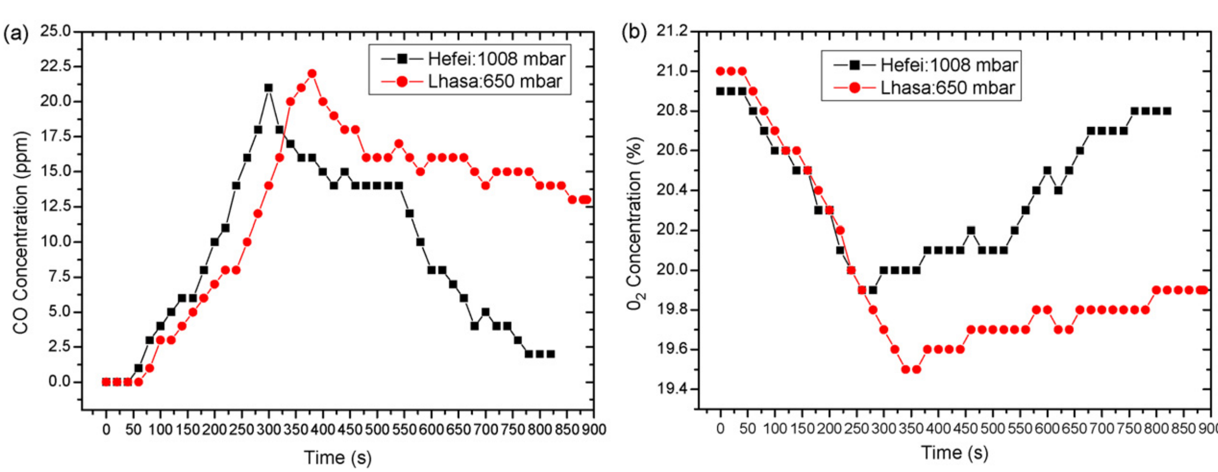

Fig. 11. CO (a) and O_2 (b) concentration of Case A.

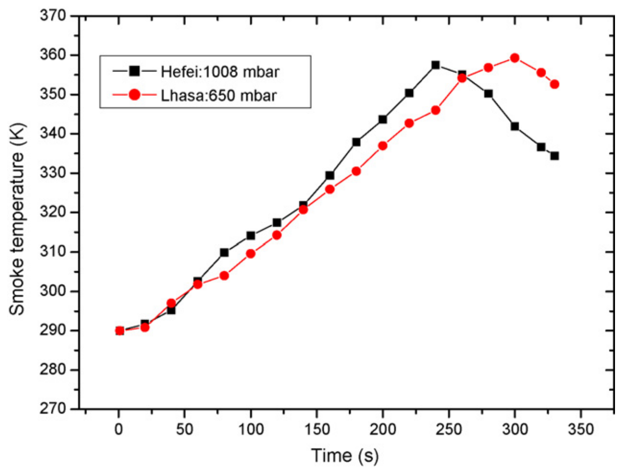

Fig. 12. Smoke temperature of Case A.

are theoretically the same and have no dependence upon the air pressure, so, the qualitative theoretical analysis is confirmed by our experiments, also validated by Wieser's experimental results.

5. Conclusions

(1) By employing the plume theory, ideal gas and other assumptions, air pressure is theoretically shown to have no significant influence upon gas volume concentration and temperature increase of a steady turbulent plume.
(2) Different scale *n*-heptane fire tests conducted in small and standard test rooms in Lhasa and Hefei show that, the mass burning rates of *n*-heptane fire in small and standard room are both approximately proportional to air pressure, while the burning time is inversely proportional to the air pressure.
(3) For CO products, in the small room, in Lhasa, CO concentration reaches about twice bigger peak values at larger increase rates than in Hefei, indicating the significant influence of pressure. While in the standard room, in Lhasa and Hefei, there are slight changes for CO concentration, which agree with the theoretical analysis results in a good way.

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References

[1] A.M. Kanury, Modeling of pool fires with a variety of polymers, in: Proceedings of the 15th Symposium on Combustion, The Combustion Institute, Pittsburg, PA, 1975, pp. 193–202.
[2] R.L. Alpert, Pressure modeling of fires controlled by radiation, in: Proceedings of the 16th International Symposium on Combustion, MIT, Cambridge, MA, August 15–20, The Combustion Institute, Pittsburg, PA, 1976, pp. 1489–1500.
[3] R.W. Lockwood, R.C. Corlett, Radiative and convective feedback heat flux in small turbulent pool fires with variable pressure and ambient oxygen[C], in: Proceedings of the 1987 ASME–JSME Thermal Engineering Joint Conference, American Society of Mechanical Engineers, New York, 1987.
[4] A. Shinotake, S. Koda, K. Akita, An experimental study of radiative properties of pool fires of an intermediate scale[J], Combust. Sci. Technol. 43 (1985) 85–97.
[5] J. De Ris, A.M. Kanury, M.C. Yuen, Pressure modelling of fires, in: Proceedings of the 14th Symposium on Combustion, 1973, p. 1033.
[6] J. De Ris, P. Wu, G. Heskestad, Radiation fire modeling, in: Proceedings of the 28th Symposium on Combustion, The Combustion Institute, 2000, pp. 2751–2759.
[7] J.-M. Most, P. Mandin, J. Chen, P. Joulain, Influence of gravity and pressure on pool fire-type diffusion flames, in: Proceedings of the 26th Symposium (International) on Combustion, The Combustion Institute, pp. 1311–1317.
[8] D. Wieser, P. Jauch, U. Willi, The influence of high altitude on fire detector test fires, Fire Saf. J. 29 (1997) 195–204.
[9] International Organization for Standardization, DRAFT INTERNATIONAL STANDARD ISO/DIS 7240-15, Fire detection and alarm systems. Part 15. Point-type multisensor (light and heat) fire detectors, 2002.
[10] G. Heskestad, Fire plumes, in: P.J. DiNenno (Ed.), SFPE Handbook on Fire Protection Engineering, Society of Fire Protection Engineers, Boston, 1988, pp. 1-107–1-115.