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Influence of different low air pressure on combustion characteristics of ethanol pool fires

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Abstract
Small-scaled ethanol circular pool fire experiments were conducted in a self-designed low pressure experiment tank to investigate the influence of ambient pressure on the combustion characteristics of the pool fire. The difference of combustion characteristics under different pressure environment were investigated, combustion characteristics of ethanol pool fire, such as fuel's mass burning rate, flame shape, flame centre-line temperature and plume velocity in different ambient pressure conditions were measured. The experiment results show that the mass burning rate decrease when the ambient pressure decrease, and the variation could be well fitted by a power function. Plume centre-line velocity also decrease with the ambient pressure. Generally, flame height would increase with the decreasing of the ambient pressure, until reaching the turning point, and then decrease. Temperature rise of plume centre-line take a power function of height and heat release rate.

Keywords: Low air pressure; Pool fire; Burning rate; Flame height; Plume centerline temperature

Nomenclature

- \( P \) air pressure (kPa)
- \( \dot{m}^n \) mass burning rate (g/m\(^2\)s)
- \( n \) exponent for mass burning rate dependence upon air pressure (\( \dot{m}^n \propto P^n \))
- \( z \) vertical height (m)
- \( \Delta T \) plume centreline temperature rise above ambient (°C)
- \( D \) Burner inner diameter or equivalent diameter (m)
- \( M \) molecular weight (kg/mol)
- \( \kappa \) absorption coefficient (1/m)
- \( H_e \) ethanol enthalpy of combustion (29.64 kJ/g)
- \( \dot{Q} \) heat release rate (kW)
- \( R \) universal gas constant (8.314 J/mol K)
- \( T \) mean temperature of plume centre-line (K, °C)
- \( h \) convection heat transfer coefficient (W/m\(^2\)K)
- \( L_f \) mean flame height (m)
- \( \rho \) air specific heat (1.0 kJ/kg K)
- \( T_a \) air temperature (K, °C)
- \( g \) acceleration of gravity (9.81 m/s\(^2\))

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The ambient pressure and oxygen density will decrease with altitude increasing. This will affect burning rate, flame temperature, density of the smoke [1-3], etc. which are very important parameters to conduct the fire prevention and suppression effectively on the plateau.

Fang et al. [4] studied the influence of low atmospheric pressure on carbon monoxide of n-heptane pool fires and found: in the small room, CO concentration reaches about twice bigger peak values in Lhasa than that in Hefei; while no significant changes in the standard room. Xu et al. [5] found that for the same pan size, the flame in Lhasa is higher and larger in area and oscillates faster than that in Hefei. TU et al. [6] conducted ethanol pool fire experiment in Lhasa and Hefei to study the radiation characteristics difference. The result shows that: as the burning rate of pool fire in Lhasa is lower than that in Hefei, the radiation hazard is also relatively small in plateau. Li et al. [7] studied on combustion characteristics of n-heptane and wood crib fires at different altitudes. The results show that the burning rate, radiation heat flux and flame temperature at plateau are lower than those at plain for the same fuel size. Wieser et al. [8] conducted small scale European standard fire experiment at altitudes from 400 to 3000 m. Their results show that the fire burning rate is proportional to $\left(\frac{P}{P_0}\right)^{1.3}$. However the change of CO$_2$ concentration show no significant dependence on pressure. Most et al. [9] studied the effects of gravity and ambient oxygen concentration on a gas-phase ignition and found that: the flame height increase with the ambient pressure increasing and the high temperature area of the flame approach the burner. Hu et al. [10] also conducted n-heptane and gasoline fire experiment and got the similar conclusion. Cai et al. [11] carried out n-heptane and gasoline fire experiment under different ambient pressure with an airtight steel box. The results show that mass burning rate and flame height are proportional to ambient pressure and the high temperature area of flame moves upward with the pressure decreasing. Hua et al. [12] also carried out methanol pool fire experiment under different pressure and found: flame height would increase with the decreasing of the pressure, until reaching the turning point and then decrease.

Literatures [4-7] involve only two altitude height in Lhasa and Hefei. The ambient pressure difference of Literature [8, 10] is not so much large. The experiment of literature [9] was carried out at the constant mass burning rate of gas fuel. The preliminary research work on the influence of different low pressure upon combustion characteristics of pool fires has been undertaken in literature [11, 12], obviously there is more work to do. Based on the previous studies, small-scaled ethanol pool fire experiments have been conducted in a self-designed low pressure experiment tank to investigate the influence of ambient pressure on the combustion characteristics of the pool fire, the experiment results are discussed and compared with previous research work.

2. Experimental design

Although the ambient pressure decreases with the altitude increasing, the component proportions per cubic meter of air basically keep constant. So it is valid to simulate the low pressure environment of high altitude area by reducing ambient pressure in plain. In this article, an airtight steel experimental tank with a frame dimension of $1 \times 0.6 \times 1$ m$^3$ has been designed. The frontispiece of experimental tank is a door that could be switched either on or off, upon which lies an observing window made of transparent glass. On the side wall of the tank there is an exhausting hole connected with the vacuum pump and beneath the tank there is an air inlet with an electromagnetic valve to control its status of open and close. The whole experimental tank is located in a compartment under the normal pressure environment and the ambient temperature is 15 °C. Before the experiment, the vacuum pump will firstly extract air to reduce the ambient pressure to the
set value and then the electromagnetic valve will be working to control the amount of air incoming. So the whole air amount of this tank will be in a dynamic balance and its interior environmental pressure will be constant, which is different from the literature [11]. After the pressure is kept constant, the fire source will be ignited by an igniter of electronic spark controlled by manual operation. Six circular fuel pan of different size \( D = 3, 4, 5, 6, 7, 8 \) cm yet the same 2.7 cm depth have been utilized in this experiment. Ethanol (whose combustion heat is estimated as 29.64 kJ/g) was chosen to be fuel and all experiments were carried out under four different pressures \( P = 100, 80, 65, 50 \) kPa. The air specific heat \( c_p = 1 \) kJ/(kg K), and the air density can be calculated by the formula \( \rho = \frac{PM}{RT} \).

Fig. 1. Experimental setup for ethanol pool fire. (a) anatomy of experimental equipment; (b) experimental tank entity.

Figure 1 represents a concise configuration of the experimental equipment. During the experiment, the LA8200S series electronic balance was used to measure the mass loss rate of fuel with a resolution of 0.01 g. Under the protection of insulation board, the fuel pan has been laid on the center of the electronic balance, which was located at the bottom-center inside the tank and the bottom of the pool has been elevated 10 cm above the underside of the tank. Sixteen sheathed thermal-couples of K-type have been vertically placed alongside the centerline of the fuel pan to gauge the temperature distribution of the centerline of flame, and keep a distance of 4.1 cm, 6.6 cm, 9.9 cm, 13 cm, 16.1 cm, 18.3 cm, 21.5 cm, 25.5 cm, 30.7 cm, 35.7 cm, 40.8 cm, 45 cm, 50.4 cm, 55.1 cm, 58.4 cm, 63.8 cm from the upper-surface of the pool. The diameter of the former eight thermal-couple is 0.5 mm while the later eight is 1 mm. A velocity probe was located at 60 cm above the surface of fuel pan to measure the plume velocity. A camera has been located outside the observing window and takes real-time pictures of flame shape at a speed of 25 frames/sec.

3. Results and discussion

3.1. Mass burning rate

To pool fire, heat fed back from flame to the surface of fuel is the main cause of the change of mass burning rate, whereas feedback of heat, which is consisted of three aspects: heat transfer, convection and radiation, can be denoted by the following Eq. (1) [13]:

\[
\dot{m}^n = \left( \left( \frac{4}{D} + h(T_f - T_i) + \sigma(T_f^4 - T_i^4)(1 - \exp(-\kappa_i D_i)) \right) / H_v \right)
\]

where \( T_f \) is the flame temperature near the surface of fuel, \( T_i \) represents the surface temperature of fuel, and \( H_v \) means the latent heat of fuel.

Figure 2(a) shows the mass burning rate of each working condition under different pressure. From which it is apparent that when it comes to different ambient pressure, mass burning rates tend to decrease when the diameter of pools vary from 3 cm to 5 cm. When diameter \( D \) is greater than 5 cm, mass burning rate under each pressure can hardly change. Blinov[14] thinks that when \( D \) is smaller than 0.05 cm, heat transfer from flame to the wall of pool plays a determinant role of controlling the mass burning rate of pool fire. In this case, mass burning rate decreases against the growth of \( D \). Whereas when \( D \) is greater than 0.05 and smaller than 0.2 m, feedback of convection heat from turbulent flame is mainly responsible for the control of mass burning rate \( \dot{m}^n \), under which case \( \dot{m}^n \) reach the minimum value and stay static to the change of pool diameter. As a consequence, Fig. 2(a) tells us that under different ambient pressure, the changing of mass burning rate \( \dot{m}^n \) is coherent with the changing of pool diameter \( D \). This proves that Blinov’s conclusion suits the case of low-pressure
environment.

![Mass burning rate graph](image)

**Fig. 2.** Mass burning rate. (a) $m^*$ under different ambient pressures; (b) exponential relationship between $m^*$ and $P$.  

By launching the exponential fit to mass burning rate against pressure, we gain Fig. 2(b). Since mass burning rate for pools with diameter ranging from 5cm to 8cm generally don’t change with the variation of diameter $D$, we make fit of these four groups of data as a whole. And from Fig. 2(b) it is clear that with the increasing of the diameter of pool, pressure launches greater impact to mass burning rate. This phenomenon takes place because the larger the diameter of pool, the greater the quantity of oxygen consumed, and consequently the deeper impact ambient pressure gives mass burning rate.

### 3.2. Plume velocity

Via non-dimensional analysis, McCaffrey [15] brings forward that to buoyant plume zone, the centerline velocity of plume satisfies the following formula:

$$u_0 = \kappa z^{1/3} \dot{Q}^{1/3}$$  

(2)

where $u_0$ represents the centerline velocity of plume at height $z$, $\dot{Q}$ is heat release rate with the unit of kW, and $\kappa$ is a constant whose value is $1.1 \text{ m}^{4/3}/(\text{kW}^{1/3} \text{s})$ under standard condition.

The average plume velocities can be got through averaging the data obtained by anemometer. The heat release rate can be obtained by multiplying the mass burning rate with ethanol enthalpy of combustion. Subsequently we can calculate the value of $\kappa$ for each working condition according to Eq. (2), as is shown in Fig. 3. Because flame of pool with diameter of 3 cm under 50 kPa ambient pressure turns to laminar liquid, the velocity of plume of 60 cm height is basically zero.

![Kappa values graph](image)

**Fig. 3.** Values of $\kappa$ for each case.

It is shown from Fig. 3 that under different pressure, $\kappa$ for each working condition stabilizes inside a certain interval of average value. This means that the relationship $u_0 \propto \dot{Q}^{1/3}$ is still valid for different low ambient pressure. The average value
of $\kappa$ for four different pressures is 0.82, 0.61, 0.49 and 0.29, respectively. And $\kappa$ will drop with the decreasing of ambient pressure.

3.3. Flame shape characteristic

With the technology of digital image processing, we can yield the probability image of light spot emitted by flame at any possible position during steady section of combustion of one minute long. Fig. 4 has shown the grey image of ethanol pool fire under different pressure.

![Flame images](image)

Fig. 4. Probability image of pool fire at different pressures. (a) 3 cm, (b) 4 cm, (c) 5 cm, (d) 6 cm, (e) 7 cm, (f) 8 cm.

From Fig. 4 we can see that, when ambient pressure drops, flame shapes of different pools change in different manner. For pools of diameter 3 cm, because its heat release rate is small, so the height of flame is mainly controlled by buoyancy. When ambient pressure decreases, immediately heat release rate drops, resulting in the gradual shrinking of flame height. Once pressure approaches 65 kPa, flame keeps a steady state. For pools with diameter of 4 cm, 5 cm and 6 cm, respectively, when pressure lowers, flame height at the beginning increases and gains the peak value when pressure reaches 65 kPa. Then flame height will go down when pressure drops to 50 kPa. This says that when pressure drops, flame height is not likely to grow monotonely but will produce a maximum value. And to pools with diameter 7 cm and 8 cm, when pressure drops to 65 kPa, their flame heights basically not change and will both increase once pressure equals 50 kPa.

Based on numerous experiments, Heskestad puts forward the formula to estimate average flame height when no wind is involved [16]:

$$\begin{align*}
\frac{L_f}{D} &= 3.7\left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{gD^2}}\right)^{2/5} - 1.02
\end{align*}$$

(3)

where $L_f$ is the average flame height, $D$ is the equivalent diameter of flame source, both with unit m; $\rho_\infty$, $c_p$, $T_\infty$ and $g$ mean air density, constant-pressure specific heat, temperature and gravity acceleration, respectively.

Figure 5 shows the comparison between the average flame height as a result of experiment and the theoretical values. From Fig. 5 it is apparent that under ordinary pressure, formula submitted by Heskestad to estimate the average flame height fits elegantly with experimental values. Though little error exists, theoretical values cohere excellently with experimental values when pressure is either 80 kPa or 65 kPa. What should be noted is that when pressure drops to 65 kPa, flame of pool with diameter of 3 cm turns into laminar flow, making the maximum difference between theoretical values and experimental values. And when pressure is 50 kPa, theoretical value is slightly greater than that from experiment, as a result of the decreasing tend of pool flame height when pressure is below 50 kPa.
3.4. Flame center-line temperature

Figure 6 shows the mean value of the steady section of the centerline temperature for each group.
From Fig. 6 it is shown that with the dropping of pressure, the temperature of plume over each pool flame all elevate and their magnitude of the dropping of temperature slows down. To pools with diameters from 4 cm to 8 cm, centerline temperature distribution of height below 15 cm will present peak value. Furthermore, when pressure decreases, peak value of temperature grows, so is its related flame height. Temperature value on the left side of peak temperature value reaches the greatest when pressure is 50 kPa. And once pressure drops, temperature inside this zone reduces. This is since that when pressure drops, flame height will increase and subsequently results in the upper-shift of high temperature zone. To small pool of diameter of 3 cm, thanks to its smaller flame height, there exists no peak value for centerline's temperature distribution where flame height is less than 15 cm.

Through a great number of experiments, Heskestad raises the formula for virtual origin [15]:

$$z_0 = \frac{Q}{\rho c_p T_\infty g D^2} (2/5 - 1.02)$$

(4)

where $z_0$ represents the height of virtual origin source height, $D$ is the equivalent diameter of flame, both with unit m. We can calculate the height for virtual origin under each working condition via Eq. (4).

According to the relations between the temperature rising of plume's centerline, height and heat release rate, we find that these three aspects can satisfy related exponential restriction. Thus, assume that the temperature rising of plume satisfies Eq. (5):

$$\Delta T = k Q^{2/3} (z - z_0)^{5/3}$$

(5)

Figure 7 presents the relationship between the experimental values of plume temperature's rising over the flame, flame height and heat release rate of each pool under different pressure.

As is shown from Fig. 7, under different pressure, the temperature's rising of plume's centerline over the flame, the flame height and the heat release rate satisfy an exponential relationship. The smaller the pressure, the larger the coefficient $k$.

![Fig. 7. Plume temperature's rising at different pressures. (a) 50 kPa, (b) 65 kPa, (c) 80 kPa, (d) 100 kPa.](image-url)
4. Conclusions

This paper carries out experimental research into the burning rate of ethanol pool fire, the centerline temperature, flame height and plume velocity under different pressure. Different ambient pressure caused significant difference in combustion characteristics. This paper mainly shows that:

(1) When pressure drops, mass burning rate of pool fire reduces in the exponential way. The greater $D$, the larger exponent $n$. The mass burning rate with pool diameter from 5 cm to 8 cm under different pressure essentially keeps static.

(2) $u_0 \propto \dot{Q}^{1/3}$ relationship is adaptive for different situations of lower pressure. When ambient pressure drops, coefficient $\kappa$ decreases.

(3) When ambient pressure drops, the rule of the change for the flame height of each pool varies.

(4) Under different pressure environment, the temperature's rising of plume zone, height and heat release rate satisfy an exponential relationship. The smaller the pressure, the larger the coefficient $k$.

Mass burning rate is an important parameter in fire safety engineering design. Pool fire experiment of different diameter was carried out and the results show that Blinov's conclusion suits the case of different low-pressure environment. In different ambient pressure, the exponential relationship of plume velocity and temperature rise dependence upon heat release rate are still valid. With pressure decreasing, the coefficient $\kappa$ for $u_0$ decreases whereas $k$ for $\Delta T$ increases. As to the flame height, the pool diameter in this paper relatively small and the flame turbulent degree is also small. Compared with the experimental flame height, the theoretical flame height calculated from Heskestad formula deviate much especially in very low ambient pressure. Experimental studies are being planned to carry out more pool fire experiment of different size to deeply investigate the influence of low ambient pressure upon combustion characteristics of pool fire.

References