Advances in Biochemistry
2017; 5(2): 22-30
http://www.sciencepublishinggroup.com/j/ab
doi: 10.11648/j.ab.20170502.12
ISSN: 2329-0870 (Print); ISSN: 2329-0862 (Online)

Burning Characteristics of N-Heptane Pool Fire in a Controlled Dynamic Pressure Environment

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To cite this article:

Quan-yi Liu, Yuan-hua He, Rui Yang, Hui Zhang. Burning Characteristics of N-heptane Pool Fire in a Controlled Dynamic Pressure Environment. *Advances in Biochemistry.* Vol. 5, No. 2, 2017, pp. 22-30. doi: 10.11648/j.ab.20170502.12

Received: March 7, 2017; **Accepted**: March 25, 2017; **Published**: April 19, 2017

Abstract: Cabin fires during in-flight and fires in high altitude airport have attracted a lot of attention. The previous fire tests at high altitudes were all conducted under very limited number of static pressure levels. It is important to design a controlled oxygen and pressure environment and conduct experiments to study the fire behaviors at different depressurization rates. A low-pressure chamber with oxygen and pressure control of $2 \times 3 \times 4.65 m^3$ in volume is developed and built to simulate high-altitude environment. Pool fire experiments using 20-cm and 30-cm-diameter pans are performed at three different depressurization rates, e.g. 5.46kPa/min, 10.92kPa/min, and 19.68kPa/min. The parameters measured include burning rate, flame temperature, radiative heat flux, and heat release rate, et al. The results from fire experiments under different depressurization rates demonstrate the difference and impacts of dynamic pressure environment on liquid fire behaviors and helpful for fire prevention during the flight of the aircraft.

Keywords: Burning Characteristics, Low-Pressure Chamber, Depressurization Rates, Dynamic Pressures, Pool Fire

1. Introduction

In recent years, the global aircraft accidents occur frequently, while most of aviation accidents are accompanied by combustion and explosion. Special low-pressure environment of high altitude during flight affects the combustion process of physical and chemical reactions. Fuel combustion characteristics are different from that under atmospheric environment. As a direct supply of aircraft fuel, liquid fuel fire safety is drawn sufficient attention from the international community.

There are some previous pan fire tests carried out at different static pressures in the literature which preliminarily showed the impact of low pressure on fire behavior. These low pressure fire studies are usually through field tests and chamber tests, where the former are conducted in high-altitude regions and the latter are done in an enclosed chamber with controllable pressure. The altitude tests conducted by Wieser et al [1] with a mobile test platform to test EN54 fires at 4 altitudes from 400m (97kPa) to 3000m (71kPa), the results of which showed that the burning rate at higher altitude is lower for about $\sim P^{1.3}$. With the high-altitude fire lab built in Lhasa, China, Li [2] and Fang [3] tested different sizes of n-Heptane pool fires, the results of which showed that the burning rate at higher altitude is lower, so is the flame radiation; but the flame temperature is slightly higher at higher altitude and the soot volume fraction decreases with pressure as $\sim P^{0.9}$.

Chamber tests by various pressure vessels have shown to be effective as indicated in the previous low-pressure fire studies. Hirst [4] and Hill [5] studied the combustion of Jet A fuel as well as propanol and acrylic in a small-scale altitude chamber under low pressures and found that the burning rates decrease approximately linearly with the equivalent altitude. Based on the $3 \times 2 \times 2 m^3$ altitude chamber built in Hefei and a low pressure laboratory in Tibet, several researches [6-14] have been done to explore the influence of low pressures on fire behaviors, the results of which showed that pressure changes more slowly, and burning time is longer for the same quality of the fuel. As well as the dimensionless fire plume temperature is correlated with the pressure to the power of -2/3. However, the previous studies have been conducted in a small size chamber and the fire could not develop fully.

In order to further observe fire behaviors and comprehensively reveal the dependence of fire behavior on pressure, a large size low-pressure chamber with ventilation control of $2\times3\times4.65m^3$ in volume is developed and built in Tsinghua University to simulate more realistic high-altitude environment, in which oxygen concentration can be maintained through adjusting the air flow and ventilation rate. Pool fire tests under different fixed low pressures have been conducted [15-17], the results of which agrees well with that of Hirst [4]. However, the mechanism of the effect of dynamic low pressures on fire behaviors is still unknown and needs to explore.

In this study, n-heptane pool fire tests under dynamic pressure were conducted in the $2\times3\times4.65m^3$ chamber to comprehensively reveal the dependence of fire behavior on depressurization rates. Pressure conditions are from 101kPa to 38 kPa with three depressurization rates: 5.46kPa/min, 10.92kPa/min, 19.68kPa/min. Using 20-cm and 30-cm-diameter pans are configured at three different dynamic pressures. Parameters such as mass burning rate, flame temperature, radiative heat flux, oxygen concentration and heat release rate et al are all measured to reveal the mechanism of dynamic pressure effect on pool fire behavior.

2. Experimental Configurations

The low-pressure chamber with oxygen and pressure control used in this study is shown in Figure 1. There are two major parts, that is, the chamber body and pressure controlling system (including the exhaust sub-system and the air-inletting sub-system).

The schematic diagram of experimental platform designed for N-heptane pool fire tests in the altitude chamber is shown in Figure 2. 20-cm and 30-cm-diameter pans, the height of which are all 15cm, are used for the pool fire experiments in the study. The fuel pan was positioned 0.3m from the ground in the center of the device. The fuel pan was placed on top of an electronic scale, which was placed on a platform combined by angle steels. A 20cm-diameter round stool with four feet and a 60 × 60cm insulation board was placed between the pan and scale to protect the scale. An array of 18K-Type Nickel Cadmium thermocouples labeled as T1-T18 from the bottom up to the top was laid on the centerline above the pan to measure the flame temperature. All the thermocouples are 1-mm-diameter, and the vertical distance between T1 to T18 is 5cm, where the first thermocouple T1 is 2.5cm above the surface of the liquid fuel.

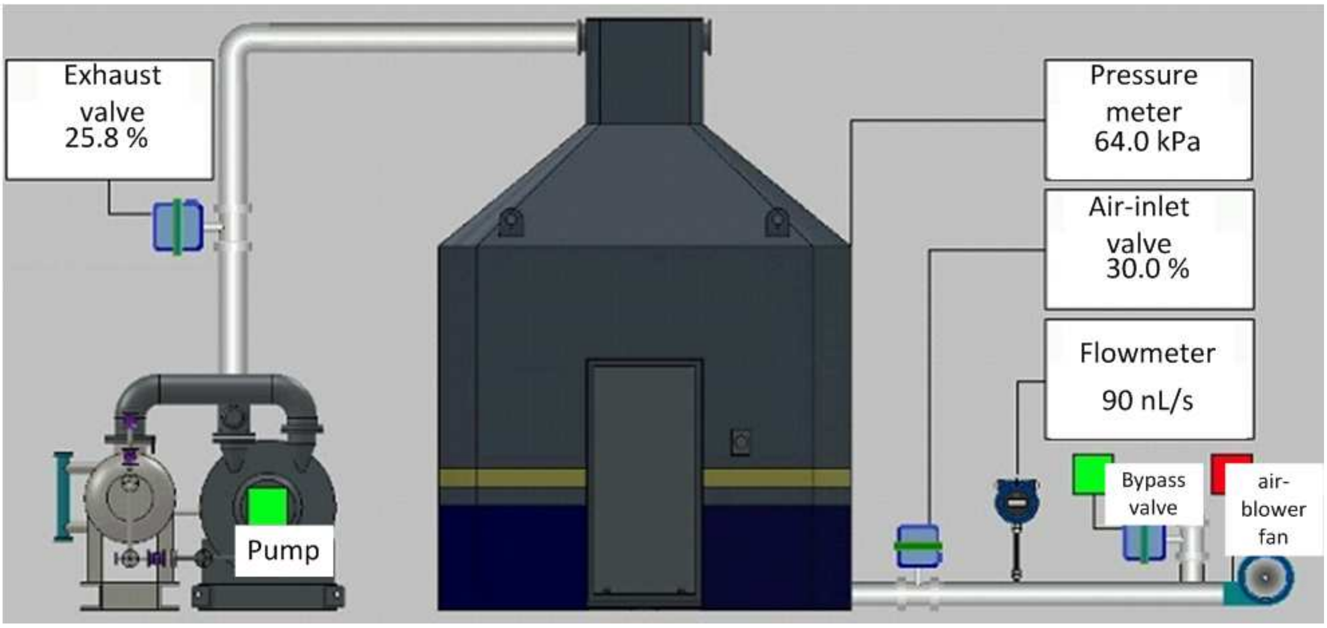
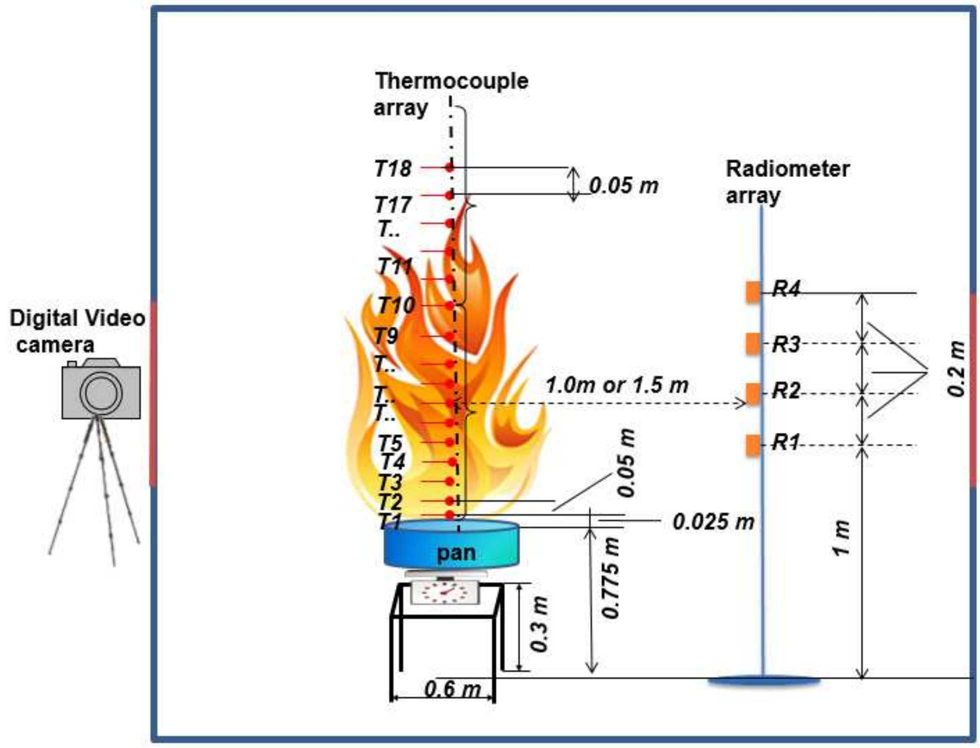
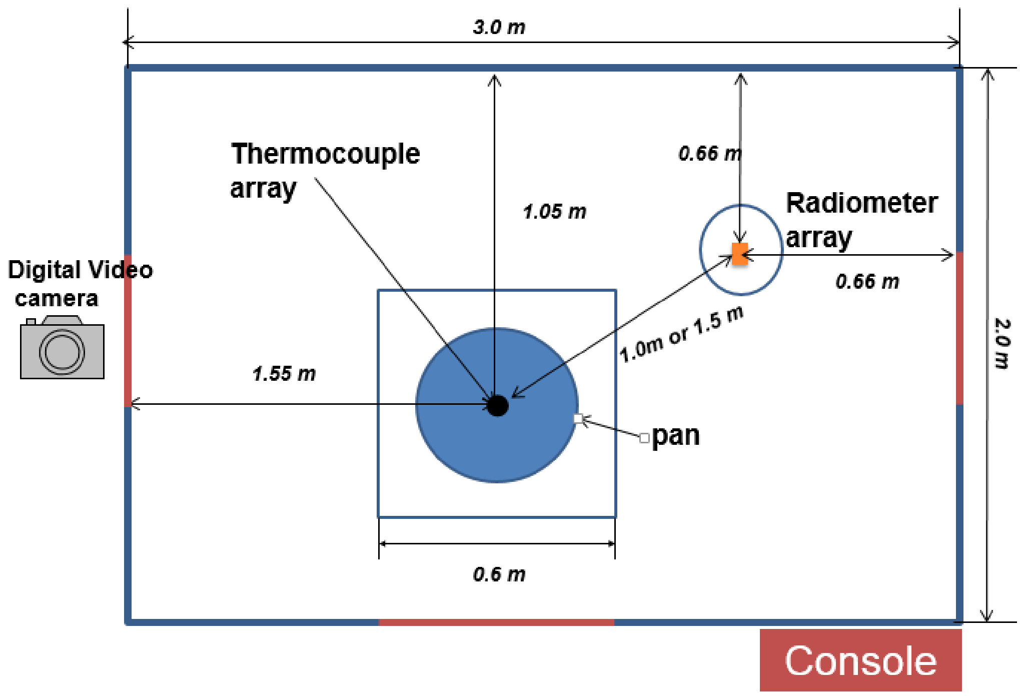


Figure 1. *Altitude chamber system.*



(a) front view



(b) top view

Figure 2. *The schematic diagram of the test setup for liquid pool fire tests; (a) front view, (b) top view.*

The radiative heat flux is measured by an array of radiometers, which are placed 1.0m horizontally from the center of the pan for 20-cm-diameter pan while 1.5m for 30-cm-diameter pan to characterize the axial radiation output from the flame. The vertical distance between any two axial radiometers is 20cm, where the first radiometer R1 is 1m above the floor. Burning rate is calculated based on the mass loss measured through high accurate electronic scale placed beneath the pan. Fire videos are recorded by a hi-speed camera for the whole burning process. The sampling rates of electronic scale, thermocouples and radiometers are 1Hz.

Cold water will be added beneath the fuel layer to cool the pan and minimize the temperature rise in the fuel. The measured parameters include burning rate, axial flame temperature, heat flux, oxygen concentration, and heat release rate. Tests are repeated at least three times to ensure repeatability.

3. Results and Discussion

3.1. Burning Rate

Figure 3 shows the comparison of average weight loss between the two sizes of pans under different depressurization rates. It can be observed that weight loss curve of the same size of the pan is kept substantially coincident under different depressurization rates. The average burning time is approximately same as 800s for 20cm pan tests while 500s for 30cm pan tests under different depressurization rates when the total fuel is burning out.

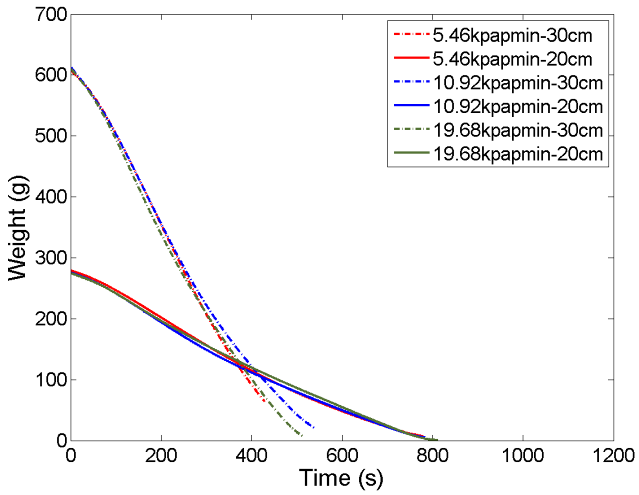


Figure 3. *The comparison of weight loss for all the pan fire tests.*

The burning rate is derived from weight loss recorded by the electronic scale. Figure 4 shows the comparison of average burning rates between the two sizes of pans under different depressurization rates. It is shown that the burning rates of 20cm and 30cm pan tests both reach the peak in about 200 seconds. Burning rates of 30cm pan tests increase sharply after ignition, and then an obvious peak of burning rate appears, and decreases sharply for all the cases. However, burning rates of 20cm pan tests gradually decrease to a stable stage after reaching the peak for all the cases.

It is shown in Figure 4 that there is not significant stable combustion stage for 30-cm-diameter pan tests other than 20-cm-diameter pan tests under different depressurization rates.

The average peak burning rates for 20cm pan tests are 0.46g/s, 0.48g/s and 0.46g/s for three depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively. The average peak burning rate for 30cm pan tests are 1.54g/s, 1.51g/s and 1.60g/s for three depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively.

The fitting function is utilized for the relation between burning rates and the depressurization rates. Figure 5 shows the curves fitting for the burning rates versus depressurization rates for 20-cm- and 30-cm-diameter pan pool tests.

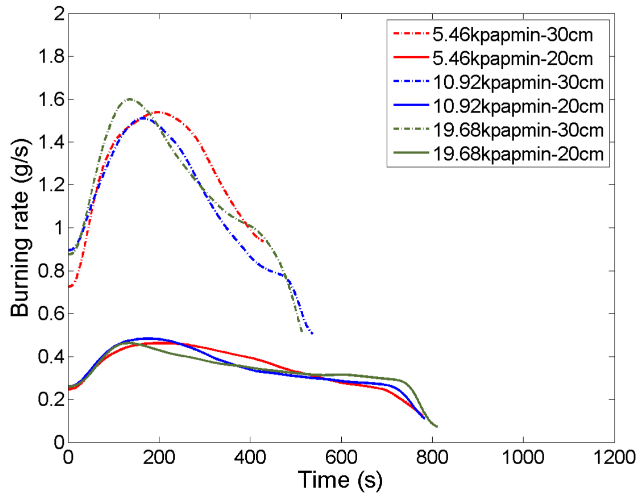


Figure 4. *The comparison of burning rate for all the pan fire tests.*

For 20cm pan pool fire tests, the dependence of burning rate on depressurization rate can be respectively expressed as,

$$\dot{m}'' = -0.00043v_p^2 + 0.011v_p + 0.42 \quad (1)$$

For 30cm pan pool fire tests, the dependence of burning rate on depressurization rate can be respectively expressed as,

$$\dot{m}'' = 0.0011v_p^2 - 0.022v_p + 1.63 \quad (2)$$

Where $\dot{m}''$ is the burning rate of n-heptane pool fire, v_p is the depressurization rate.

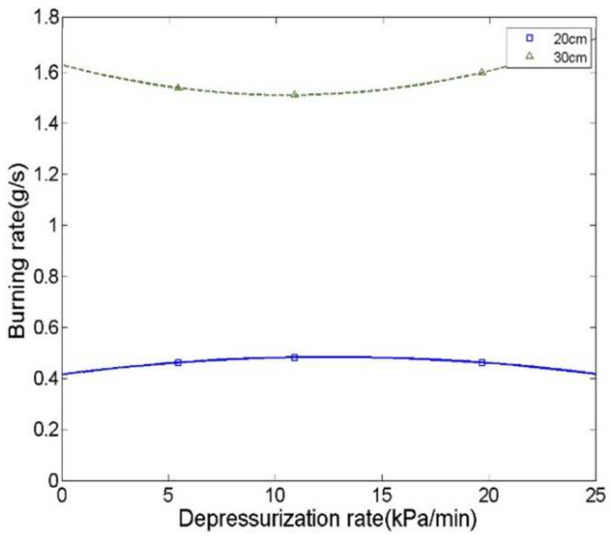


Figure 5. *Fitting for the relation between burning rates and the depressurization rates.*

It is shown in Figure 5 that there is little effect of different depressurization rates on the burning rate. Compared with large deposit of pan fire, when the fuel layer is thin, the combustion process involving boiling combustion process become relatively complex, especially for n-heptane with a low flash point of burning, because the fuel is easy to be boiling due to the influence from the surface and the bottom of the pan.

3.2. Axial Temperature

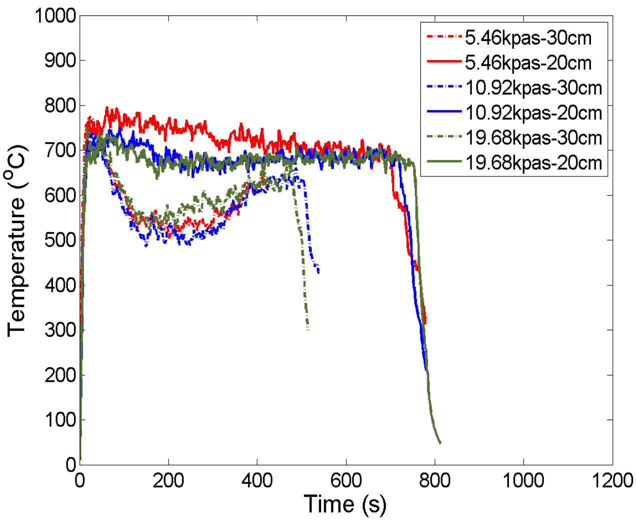
Figure 6 shows the comparison of average flame temperature of T1, T5, T10, and T15 between the two sizes of pans under different depressurization rates.

T1 temperature of 20cm pan is higher than 30cm pan. As the thermocouple's height increases, 30cm pan temperature rises faster than the 20cm pan. When the height of thermocouple reaches T5 position, two sizes of the pan temperature curves begin to overlap. When the Height of thermocouple above T5, temperature of 30cm pan is higher than that of 20cm pan, and the temperature decrease sooner at the same position after reaching the peak with the increase of the depressurization rate .

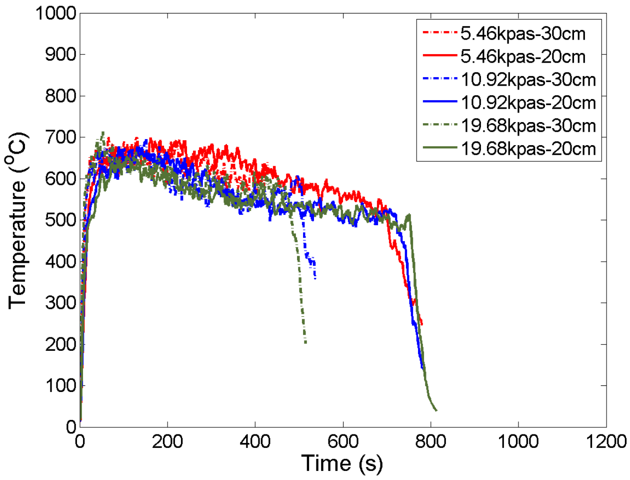
With the increase of the depressurization rate, the impact to flame transition zone is small at the bottom of the pan, Flame stable zone and plume zone at higher location of the pan are affected more evident.

The average peak temperature of 20cm pan is 837.82°C, 809.59°C and 797.30°C for depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively. The average peak temperature of 30cm pan is 807.65°C, 781.55°C and 755.36°C for depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively.

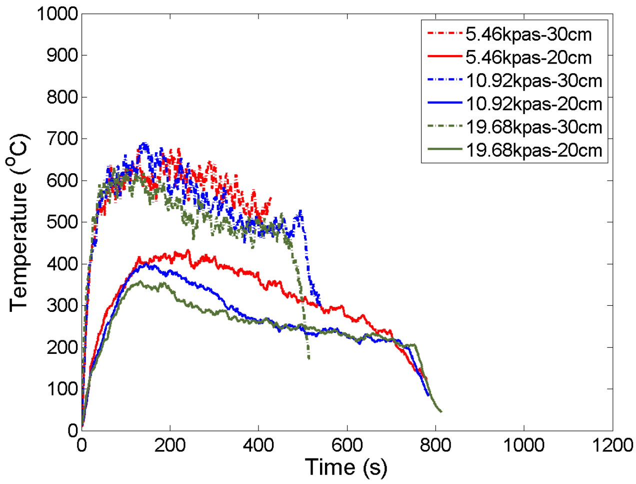
The fitting function is applied for the relation between peak temperature and the depressurization rate. Figure 7 shows the curves fitting for the peak temperature versus depressurization rates for 20cm and 30cm pan pool fire tests.



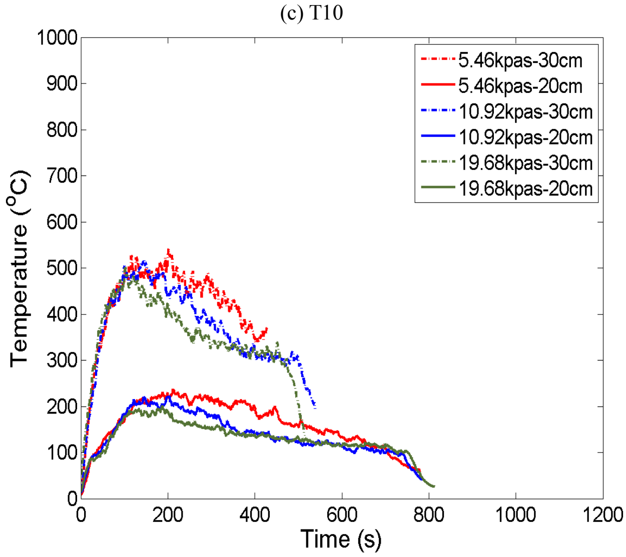
(a) T1



(b) T5



(c) T10



(d) T15

Figure 6. *The comparison of the average flame temperature of T1, T5, T10 and T15 for all the pool fire tests.*

For 20cm pan pool fire tests, the dependence relationship of peak temperature on depressurization rates can be expressed as,

$$T_{peak} = 0.26{v_p}^2 - 9.5v_p + 881.8 \quad (3)$$

For 30cm pan pool fire tests, the dependence relationship of peak temperature on depressurization rates can be expressed as,

$$T_{peak} = 0.13{v_p}^2 - 6.84v_p + 841.2 \quad (4)$$

Where T_{peak} is the peak temperature in the centerline of the flame, v_p is the depressurization rate. Generally, the peak temperature decreases with the depressurization rates increases for the same pan tests.

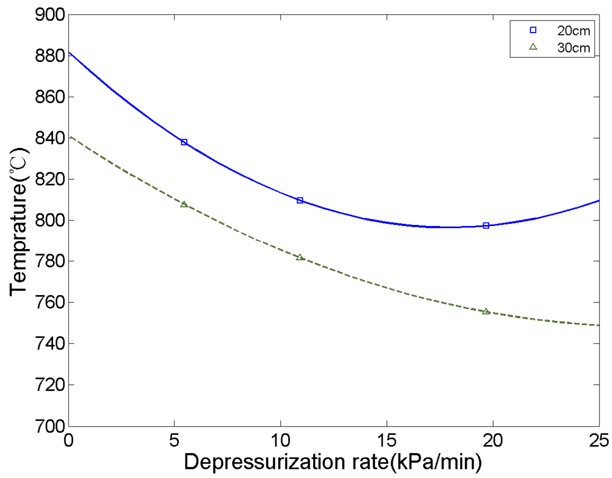


Figure 7. *Fitting for the relation between temperatures and the depressurization rates.*

3.3. Radiative Heat Flux

Figure 8 shows the comparison of average radiative heat flux of R1, R2, R3 and R4 between the two sizes of pans under different depressurization rates.

In the same experimental conditions, all heat flux measured of 30cm pan fire is higher than that of 20cm pan fire. The heat flux of 20cm and 30cm pan fire both reaches the peak in about 200 seconds. The heat flux decreases soon with the increase of the depressurization rate.

The average peak heat flux of 20cm pan is 0.48kW/m^2, 0.49kW/m^2 and 0.47kW/m^2 for the depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively. The average peak heat flux of 30cm pan is 0.66 kW/m^2, 0.68kW/m^2 and 0.67 kW/m^2 for three depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively.

The fitting function is applied for the relation between peak heat flux and the depressurization rate. Figure 9 show the curves fitting for the peak heat flux versus depressurization rates for 20cm and 30cm pan pool fire tests.

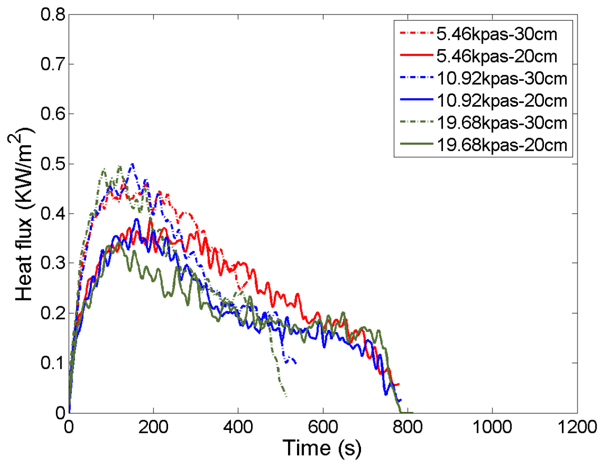
For 20cm pan pool fire tests, the dependence relationship of peak heat flux on depressurization rate can be expressed as,

$$R_{peak} = -0.00036{v_p}^2 + 0.0084v_p + 0.44 \quad (5)$$

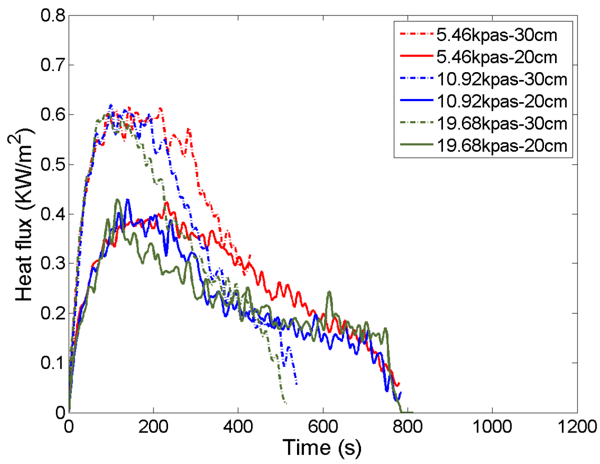
For 30cm pan pool fire tests, the dependence relationship of peak heat flux on depressurization rate can be expressed as,

$$R_{peak} = -0.00037{v_p}^2 + 0.0097v_p + 0.62 \quad (6)$$

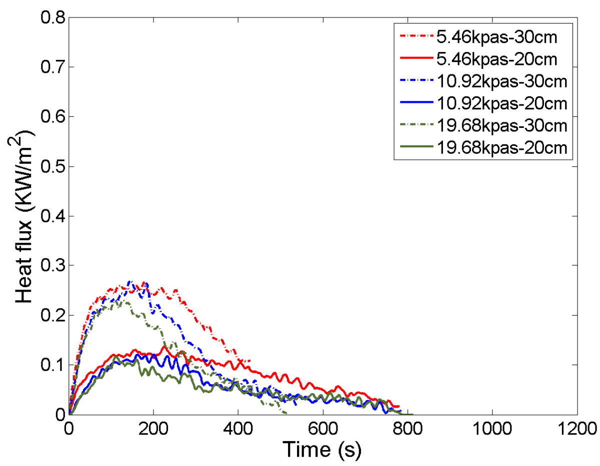
Where R_{peak} is the peak heat flux, v_p is the depressurization rate. It is clearly shown that there is little influence of different depressurization rates on the peak heat flux for the same pan tests.



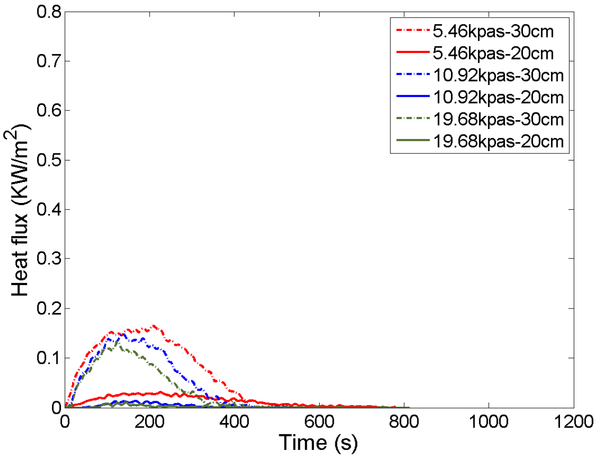
(a) R1



(b) R2



(c) R3



(d) R4

Figure 8. *The comparison of the average heat flux of R1, R2, R3 and R4 for all the pool fire tests.*

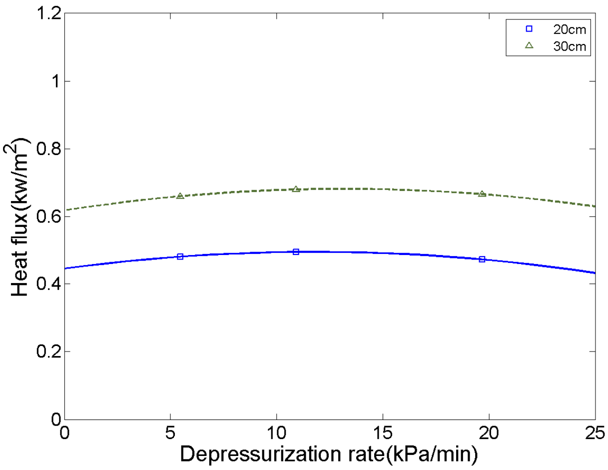


Figure 9. *Fitting for the relation between heat flux and the depressurization rates.*

3.4. Oxygen Concentration

Figure 10 shows the comparison of average oxygen concentration between the two sizes of pans under different depressurization rates.

In the combustion process under different depressurization rates, the oxygen concentration of altitude chamber decreased from 20.9% to a lower value in about 200 seconds. The oxygen concentration decrease later with the increase of the depressurization rate. In the same experimental conditions, the oxygen concentration of 20cm pan tests is higher than that of 30cm pan tests. It is found that the lower depressurization rates of environment and the larger the diameter of the pan, the more consumption of oxygen concentration.

The average lowest oxygen concentration of 20cm pan is 20.32%, 20.57% and 20.65% for the depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively. The average lowest oxygen concentration of 30cm pan is 18.26%, 18.57% and 18.78% for the depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively.

The fitting function is applied for the relation between the lowest oxygen concentration and the depressurization rate. Figure 11 shows the curves fitting for the lowest oxygen concentration versus depressurization rates for 20cm and 30cm pan pool fire tests.

For 20cm pan pool fire tests, the dependence relationship of the lowest oxygen concentration on depressurization rates can be expressed as,

$$C_{oxy} = -0.0026{v_p}^2 + 0.089v_p + 19.91 \tag{7}$$

For 30cm pan pool fire tests, the dependence relationship of peak oxygen concentration on depressurization rates can be expressed as,

$$C_{oxy} = -0.0022{v_p}^2 + 0.093v_p + 17.82 \tag{8}$$

Where C_{oxy} is the lowest oxygen concentration, v_p is the depressurization rate. Generally, the lowest oxygen concentration increases with the depressurization rates increases for the same pan tests.

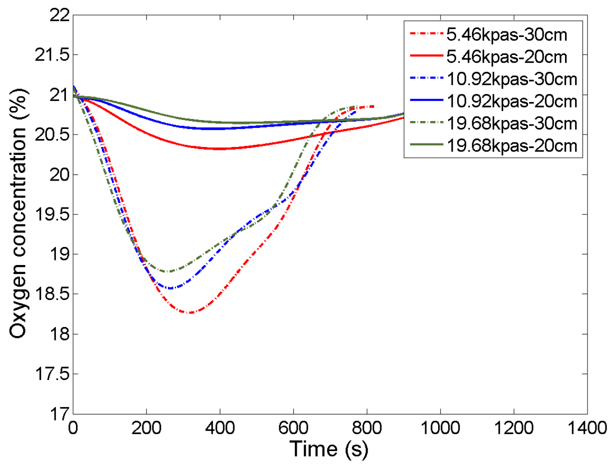


Figure 10. *The comparison of oxygen concentration for all the pan fire tests.*

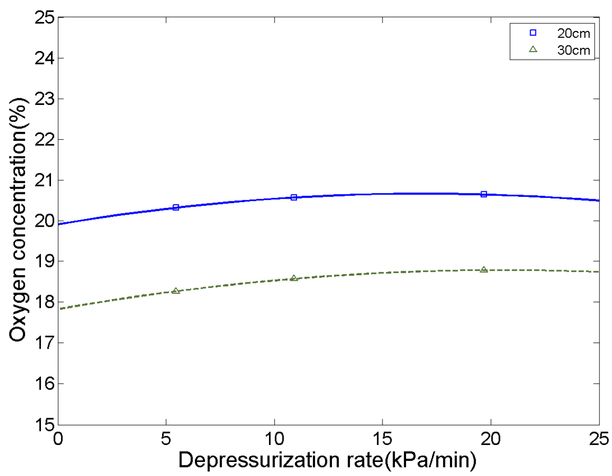


Figure 11. *Fitting for the relation between oxygen concentration and the depressurization rates.*

3.5. Heat Release Rate

Figure 12 shows the comparison of average heat release rate between the two sizes of pans under different depressurization rates.

In the same experimental conditions, all heat release rate of 30cm pan is higher than 20cm pan. The heat release rate of 20cm and 30cm pan both reach the peak in about 300 seconds.

The average peak heat release rate of 20cm pan is 18.49kW, 13.84kW and 11.67kW for the depressurization rates of 5.46 kPa/min, 10.92kPa/min and 19.68kPa/min, respectively. The average peak heat release rate of 30cm pan is 59.76kW, 67.0kW and 65.69kW for the depressurization rates of 5.46KPa/min, 10.92KPa/min and 19.68KPa/min, respectively.

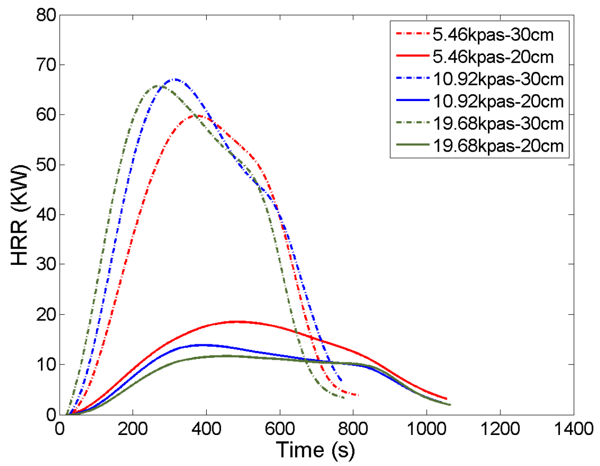


Figure 12. *The comparison of heat release rates for all the pan fire tests.*

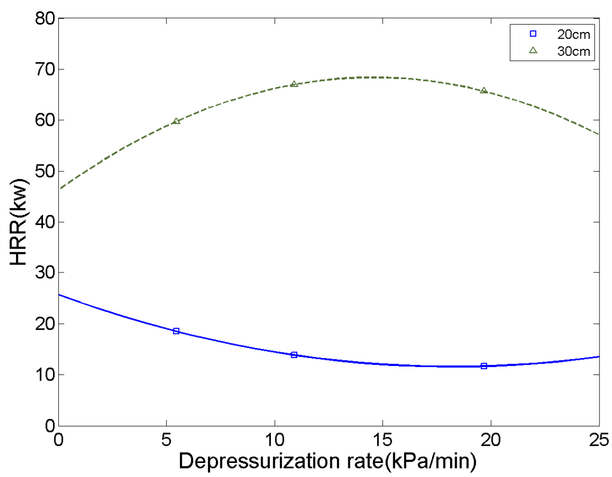


Figure 13. *Fitting for the relation between heat release rates and the depressurization rates.*

The fitting function is applied for the relation between peak oxygen concentration and the depressurization rate. Figure 13 shows the curves fitting for the peak heat release rates versus depressurization rates for 20cm and 30cm pan pool fire tests.

For 20cm pan pool fire tests, the dependence relationship of peak heat release rate on depressurization rates can be expressed as,

$$HRR_{Peak} = 0.042{v_p}^2 - 1.55v_p + 25.68 \quad (9)$$

For 30cm pan pool fire tests, the dependence relationship of peak heat release rate on depressurization rates can be expressed as,

$$HRR_{Peak} = -0.104{v_p}^2 + 3.03v_p + 46.33 \quad (10)$$

Where HRR_{Peak} is the peak heat release rate, v_p is the depressurization rate.

4. Conclusions

20cm and 30cm pan pool fire tests were conducted under three depressurization rates of 5.46kPa/min, 10.92kPa/min and 19.68kPa/min, respectively to investigate the fire behaviors under dynamic pressures. Some conclusions are as follows:

When the pan size is fixed, different depressurization rates of environment has little effect on the burning rate other than on the consumption of oxygen. The axial temperature and heat flux decrease sooner after reaching a peak. With the increase of the depressurization rate, the impact to flame transition zone is small at the bottom of the pan, Flame stable zone and plume zone at higher location of the pan are affected more evidently.

Burning characteristics of the burning rate, the axial temperature, heat flux, consumption of oxygen concentration and heat release rate for 30-cm diameter pan are higher than that for 20-cm diameter pan as for tests with the same depressurization rate.

Fire behaviors under dynamic pressures are influenced by many factors including the pan size, low pressure or dynamic pressure, ventilation/exhaustion, et al. The preliminary impacts of different depressurization rates on fire behaviors under dynamic pressures are obtained in the paper, which is very useful as a base for in-depth study about the effect of low pressure and varying pressure on fire behavior and suppression.

Acknowledgements

The work described in this paper were supported by Key Program of National Natural Science Foundation of China (No.: U1633203, No.: 91224008 and 91646201), the Scientific Research Fund Project of CAFUC (J2016-41) and major project funded by Civil Aviation Administration of China (MHRD20160103). The authors deeply appreciate the supports.

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