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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПОВЕДЕНИЯ ГОРЕНИЯ n-ГЕПТАНА В БАССЕЙНАХ РАЗЛИЧНОГО РАЗМЕРА ПРИ НИЗКОМ ДАВЛЕНИИ

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Проведен анализ температуры пламени, скорости горения, теплового потока на разных стадиях горения резервуаров с нефтью на высокогорном плато и на равнине. Скорость выделения тепла, скорость горения, распределение температурного поля и излучения были зафиксированы и проанализированы. Было определено соотношение размеров нефтяного бассейна и массовой скорости горения. Оказалось, что массовая скорость горения варьирует линейно в зависимости от размеров нефтяного бассейна. Было обнаружено, что классическая теория не подходит для корректного предопределения скачка температуры вследствие низкого давления и низкой концентрации кислорода. Анализ также показал, что чем больше площадь бассейна, тем больше тепловой поток. Отношение размеров нефтяного бассейна к тепловому потоку было представлено графически.

Ключевые слова: высокогорное плато; пожар в нефтяном бассейне; скорость горения; температура пламени; тепловое излучение.

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EXPERIMENTAL STUDY OF DIFFERENT SIZE n-HEPTANE POOL FIRE BEHAVIOR UNDER LOW PRESSURE

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To analyze the high plateau affected by the difference of air pressure, such as flame temperature, mass burning rate and radiation flux have a great difference in every burning stage compared to the oil pool fires in plain region. The experiments were conducted in High plateau air laboratory with different oil pool diameters. Heat release rate, burning rate and flame temperature field distribution and flame radiation heat flux were recorded and analyzed in these experiments. The relationship between oil pool size and mass burning rate was deduced, and which was found that the mass burning varies linearly with oil pool size. Was found that implementing the classical theory assessment the flame temperature cannot correctly predict temperature rise for the influence of low pressure and low oxygen concentration. Analysis also shows that the bigger oil pool area, the greater the radiation fluxes. By the curve fitting method, the relationship between the oil pool size and the heat radiation flux was also obtained.

Keywords: high plateau; oil pool fire; burning rate; plume temperature; thermal radiation.

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Introduction. With the One Belt, One Road summit held in China, which will accelerate the infrastructure construction and economic development in western region. As is known to all, the height of elevation directly affect atmospheric pressure, air density and oxygen partial pressure, which have a direct impact on the fire behavior of material. The scholars at home and abroad have done a lot of researches in this field, at different altitudes. Wieser et al. [2] conducted small size multi-material experimental study and found exponential relationship between the burning rate and pressure. Fang et al. [3-4] made a n-heptane pool fire contrast study in Lhasa and Hefei and found that the burning time in Lhasa increased by 45 %, the burning rate was significantly lower, than in Hefei. Li et al. [5] contrasted the crib fires and n-heptane pool fire behavior in Lhasa and Hefei and summarized fire behavior in high-altitude area, i.e. low burning rate, low radiation coefficient, uniform flame temperature distribution and small flame width. Hu et al. [6-7] conducted the study at a higher altitude, Dangxiong, which verified the experimental conclusion of Li et al. and suggested that the radiant heat of the flame decreases with the increasing altitude. Zhou et al. [8-9] conducted aviation fuel and n-heptane experiments in low-pressure tanks with small-sized rectangular flasks and found the flame temperature was related to the radiation fraction parameters, the flame temperature will increase, while the pressure decrease.

Former scientists conducted contrast study of oil pool fire behavior in Lhasa, Hefei and other places and summarized some combustion rules under low pressure, but ignored the study on different size n-heptane pool fire behavior under low pressure.Thus, the author carried out the study on oil pool fire in Safety Laboratory in Kangding High Plateau to measure fire characteristic parameters under specific environment ,such as burning rate, heat release rate, plume temperature distribution and thermal radiation flux .The fire behaviour in high plateau are obtained and can be used to provide theoretical support for fire prevention and fighting.

1 Experimental design. In the common fire accident, the liquid fire accident occupies a certain proportion, its burning form is extremely complex, its macroscopic characteristics include fuel evaporation, burning rate, flame temperature, thermal radiation intensity and others, while micro-characteristics include flow field disturbance, flame vortex structure, smoke particle structure and so on, has always been the focus of fire accident research.

The experiment was carried out on the standard 9705 experimental platform in Aviation Safety Laboratory of Kangding high Plateau. The n-heptane was used as the combustible medium with stable purity of more than 99%. The oil pool was round and made of stainless steel with dimensions of 10 cm, 20 cm, 30 cm. The fuel thickness was guaranteed to 2 cm every time and the liquid surface was closed to the pool. Electronic scales (Ohaus EX35001ZH) was used to measure the loss of fuel quality and the scale accuracy is 0,01 g. The temperature difference between the centerline temperature of the oil pool and the temperature distribution of surrounding temperature is measured by a 1 mm *K*-type (nickel-chromium-nickel-silicon) thermocouple. The thermocouples spacing 5 cm, a total of 18 arranged. The TS-10C series of water-cooled thermal flux sensor was used to measure the thermal of the oil pool, from the edge of the oil pool at 1m arranged at the three heat flow meter, the first R1 from the ground 0,4 m, upward spacing 20 cm, R2, R3 were arranged. The highest elevation full-scale low-pressure heat release rate tester (ISO-9705) was used to measure real-time determination of the heat release rate. The concentrations of CO, CO_2 and O_2 were analyzed by collecting flue gas samples in the built-in sensors. According to the size of the oil pool, it can be divided into four groups of experiments, each group repeat three times, the experimental arrangement shown in Figure 1.

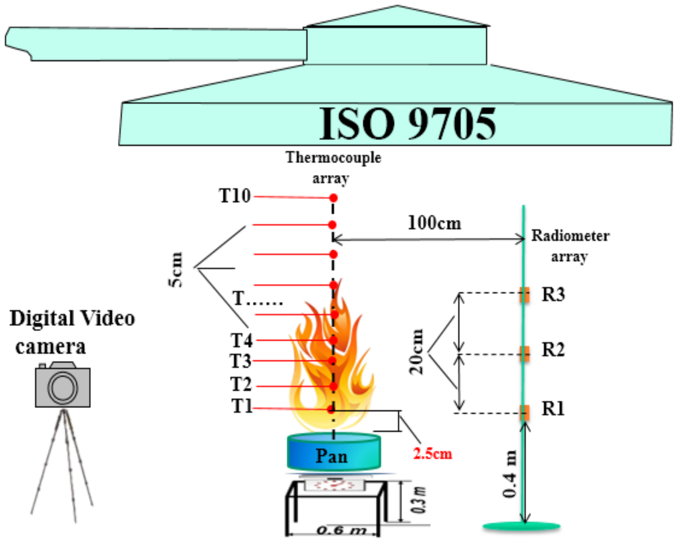

Figure 1. – The experimental arrangement

In order to reduce the effect of experimental error and the accidental factors, the experiment of each group of n-heptane oil pool was repeated for three times. The experimental results of the three experiments were basically the same, and the average of the three experiments was compared and analyzed.

Table 1. – Design of the experiment conditions

Pan size, cm	Atmospheric presure, kPa	Air density, kg·m^{-3}	Environment temperature, °C	Burning quality, g	Burning time, s
10	60,10	0,756	15	32	702
20			16	202	758
30			20	600	700

2 Results analysis and discussion.

2.1 Burning rate change rule. The burning rate of the oil pool refers to the loss rate of mass per unit area, which is the main parameter of reflecting the burning behaviour of the flames. The change of fire power can be seen by the change of burning rate. According to the experimental results, the quality change curve of different size oil pool with time can be obtained, as shown in Figure 2.

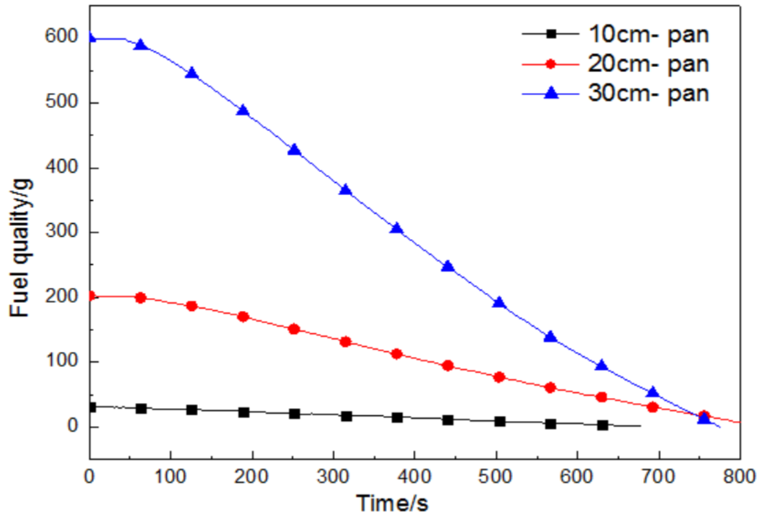

Figure 2. – Relationship between quality and time

It can be seen from Figure 2 that the quality reduction process is constantly changing ,and the initial quality stage is not obvious. With the burning continues, the mass loss gradually increases and tends to stabilize, and finally decreases to zero. Different sizes of oil tank quality loss is different, the greater the size of the oil tank changes in the quality of the more intense, in the middle stage of the quality of change is relatively stable. The data curve fitting in stable stage can be conducted to obtain the relationship between quality of different size oil pool and time changes, as shown in Figure 3.

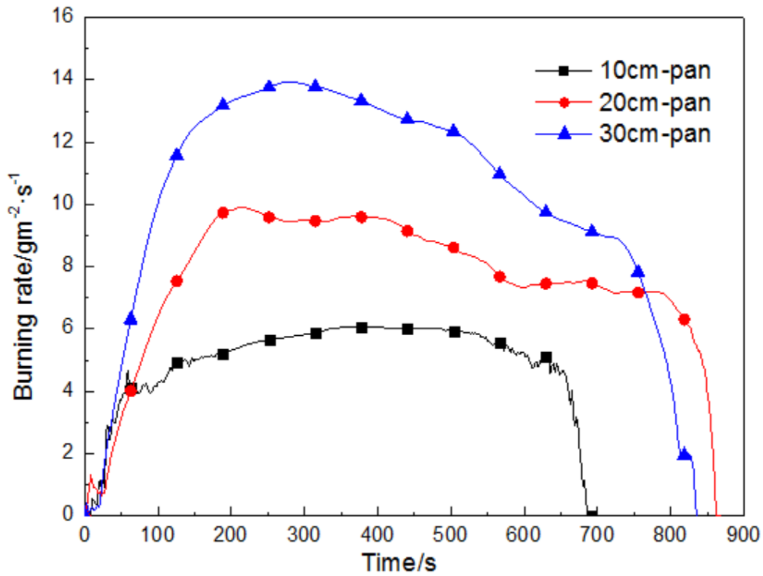

Figure 3. – Relationship between burning rate and time

It can be seen from the figure that the process of quality loss can be divided into three stages, the initial burning, stable burning and recession burning. In the initial stage, the n-heptane vapor and the air are mixed before ignition, and the premixed burning is formed after the ignition. The burning speed is gradually accelerated. The burning flame acts on the oil sump through heat radiation to keep the n-heptane vapor, N-heptane vapor and oxygen in the air gradually stabilize the state of combustion, with the combustion reaction, n-heptane continue to reduce consumption, the flame gradually extinguished, the combustion rate gradually reduced. Different size of the oil pool per unit area burning rate is different, the larger the area of the oil pool, the greater the burning rate per unit area. In the experiment, it was found that the burning rate per unit area reached the maximum when the combustion was stable, the burning rate was 5,52 g/(s·m^2) in the 10 cm oil pool, 9,67 g/(s·m^2), in 30 cm oil pool is 13,35 g/(s·m^2).

According to Babrauskas et al. [10] the burning rate empirical formula per unit area at atmospheric pressure was summarized:

$$\dot{m} = \dot{m}_\infty[1 - \exp^{(-\kappa\beta D)}], \tag{1}$$

where $\dot{m}$ is the burning rate per unit area, kg/(m^2·s), $\dot{m}_\infty$ is the burning rate of the oil pool with infinity diameter kg/(m^2·s), κ is the radiation emission coefficient, β is the average correction coefficient, D is oil pool diameter, m. Based on experimental and theoretical analysis Babrauska et al. [10] summarized some of the fuel data for n-heptane:

$$\dot{m}_\infty = 0{,}101\ (\pm\ 0{,}009), \quad \kappa\beta = 1{,}1\ (\pm\ 0{,}3).$$

According to Wieser et al. [1], at different altitudes of the experimental results and the same experimental conditions, the burning rate $\dot{m}$ in proportion to atmospheric pressure p_∞:

$$\dot{m} \propto p_\infty^\alpha, \tag{2}$$

Where α is a constant, through the table [1] shows that heptane: $\alpha \approx 1{,}3$, according to Tu's [11] burning rate contrast in Lhasa and Hefei, there is a proportional relationship between burning rate and air pressure. The atmospheric pressure of the Kangding high plateau is 60,1 kP. It can be seen that according to (2), the burning rate of n-heptane in Kangding high plateau is about 0.507 times of normal pressure. Through (1) and (2), it can be known that Kangding plateau n-heptane theoretical burning rate:

$$\dot{m} = 0{,}507\dot{m}_\infty[1 - \exp^{(-\kappa\beta D)}]. \tag{3}$$

The burning rate of different size oil pool: 10 cm oil pool is 5,33 g/(m^2·s), 20 cm oil pool is 1,11 g/(m^2·s), 30 cm oil pool is 14,39 g/(m^2·s), the theoretical contrast curve between predictive value and experimental value was made as shown in Figure 4.

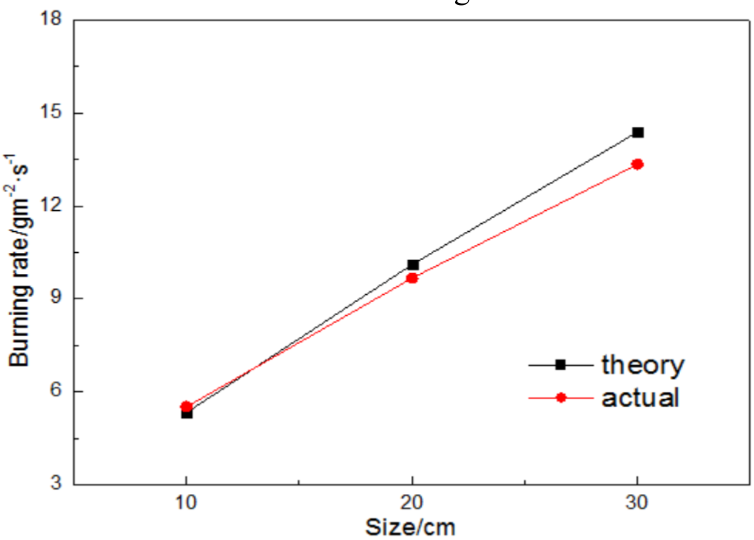

Figure 4.− Compared with the actual theory of burning rate

Shown as in Figure 4, with the increasing of oil pool size, the gap between measured value and the theoretical value gradually increased. The burning of the oil pool fire is actually the burning of the mixture of n-heptane steam and oxygen in the air. With the thermal feedback of the upper side flame from the upper side fuel in oil pool, the constant formation of n-heptane steam, and then swept around the ambient air, keep uninterrupted combustion process. Kangding plateau low pressure environment, the air density of the standard atmospheric pressure of 0,756, the oxygen content is relatively small, n-heptane combustion is not sufficient, the flame temperature is relatively low, resulting in more smoke particles, relative to normal pressure situation n-heptane. The volatile steam is smaller, prolongs the burning time and reduces the burning rate. According to Tu et al. [11], it can be seen that with the increasing of burning area, the influence of heat radiation will be bigger, and probably, the burning rate will be larger than the theoretical value, further experimental verification is needed.

2.2 Flame temperature distribution. Fire plume temperature is an important parameter to study the flame and its flue gas, which directly affects the formation of smoke particles. The temperature fluctuation of the plume in different sizes is measured. The temperature is fluctuating up and down due to the flame intermittent at the measuring point, but the whole is relatively stable. Fig. 5 shows the temperature change curve of the oil pool with different sizes at 7,5 cm.

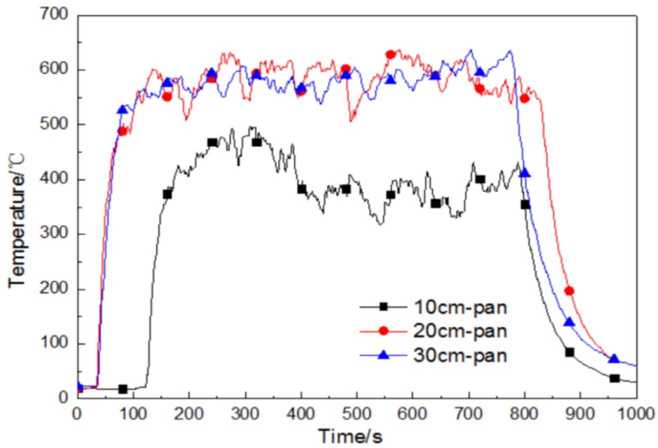

Figure 5. − Thermocouple temperature vs time

Shown as in Fig. 5, it is found that the temperature rises rapidly after the ignition of the oil pool, 150 s later, reaching the stable state. Compared with the mass burning rate of Fig. 2, the stable time approached. After burning for 600 s, the fuel of different size oil pool exhausted, the temperature gradually reduced. The temperature of the stable burning stage of each size oil pool is taken as the average temperature of the fire plume axis, and the curve of the temperature of the fire plume is changed with height.

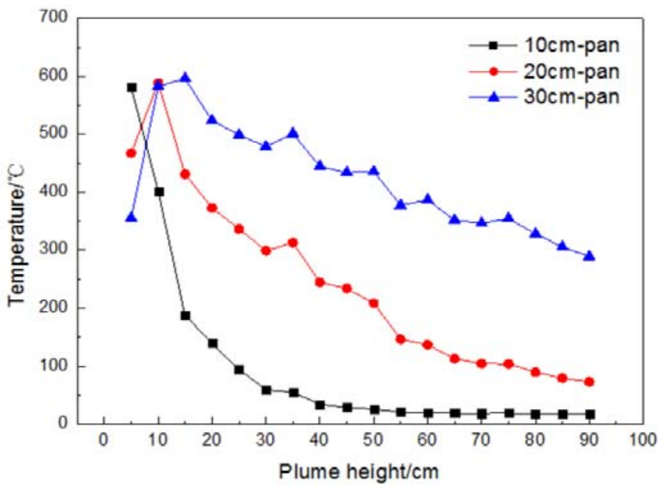

Figure 6. − Different sizes of oil pool steady state temperature vs height

From the analysis of Figure 6 found that different sizes of oil pool axial temperature is different, the larger is the maximum height of the oil pool, through observing the temperature change rule found that oil pool of more than 10 cm, the temperature of 0 to 20 cm gradually increased, about 20 cm. Temperature, with the increase in height, the temperature continues to decline, the larger the trend of decreasing the trend. 10 cm oil tank at 5 cm measured the highest temperature, with the height increases, the temperature quickly reduced. The plume temperature rise and fall rate of each size of the oil pool is different, but the whole is in accordance with certain rule.

In the classic fire plume model, McCaffrey et al. [12] conducted many experiments on methane combustion in a 30 cm square burner and obtained a low power diffuse fire model

$$\frac{2g\Delta T}{T_\infty} = \left(\frac{\kappa}{C}\right)^2 \left(\frac{z}{\dot{Q}^{2/5}}\right)^{2\eta-1} \tag{4}$$

where ΔT is central plume temperature, K; T_∞ is environment temperature, K; $\dot{Q}$ is total heat release rate, kW; C is specific heat at constant pressure, kJ/(kg·K); κ and η are the constants, different values in the three regions (Luminous flame area $\kappa = 6{,}8$ m$^{1/2}$/s, $\eta = 1/2$; intermittent flame $\kappa = 1{,}9$ m/(kW$^{1/5}$·s), $\eta = 0$; intermittent-plume $\kappa = 1{,}1$ m$^{4/3}$/(kW$^{1/3}$·s), $\eta = -1/3$). In equation (4), it is found that the plume axis temperature is related to the 2/5 th power ratio of the heat source heat release rate. Then, according to the burning situation, the plume center is divided into three areas: burning flame area, oscillation flame area and unburned plume zone.

$$\Delta T = \begin{cases} 2{,}91T_\infty & \text{if} \quad \frac{z}{\dot{Q}^{2/5}} < 0{,}08, \\ 0{,}227T_\infty \left(\frac{z}{\dot{Q}^{2/5}}\right)^{-1} & \text{if} \quad 0{,}08 < \frac{z}{\dot{Q}^{2/5}} < 0{,}2, \\ 0{,}0761T_\infty \left(\frac{z}{\dot{Q}^{2/5}}\right)^{-5/3} & \text{if} \quad \frac{z}{\dot{Q}^{2/5}} > 0{,}2. \end{cases} \tag{5}$$

The real heat release rate and total heat release can be measured by the 9705 laboratory equipment. The experimental data are brought into the McCaffrey model to obtain the theoretical value of the temperature rise of the fire center in Kangding high plateau. The theoretical value is compared with the temperature measured by the actual thermocouple. The results of the oil pools are similar. The comparison *chart of 20 cm and 30 cm oil* pool theoretical value and experimental value, as shown in Figure 7.

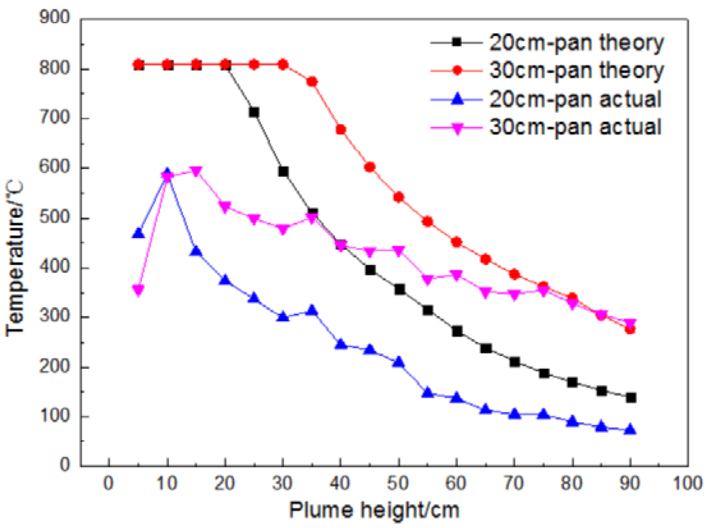

Figure 7. – The flame stability phase axis of the plume temperature contrast

It can be seen from the figure that in the experiment the temperature of visible flame is slightly smaller than that of the McCaffrey formula, but the temperature in the intermittent flame is different from that of the McCaffrey formula, and the variation is not the same, and the temperature of the unburned plume McCaffrey formula gradually close, 30 cm oil pool at 75 cm position and the theoretical calculation of the same value. Compared with the ideal plume, the experimental value is less than the calculated value, but the variation range is consistent. With the increase of the burning area, the difference between the experimental value and the calculated value is bigger. Mccaffrey's plume temperature model can not be applied to calculate the plume temperature in Kangding high plateau due to the pressure condition and the air density.

It was found that in the experiment the temperature measured by the thermocouple at less than 20 cm is the temperature of the combustible vapor, which is lower than the temperature of the visible flame and the maximum value of the temperature measured in the visible flame. In intermittent flame, unburned plume area, plume centerline temperature gradually reduced. The greater the burning area, the higher the flame height and the heat release rate, the greater the measured temperature maximum, the temperature rise is not the same, further study was needed on Kangding high plateau plume temperature rise.

2.3 Thermal radiant heat flux. Thermal radiation is one of the main indicators to evaluate the thermal damage of the oil pool. In the contrast of the thermal flux densities, the author have found that the same rules. The thermal radiation flux of different size measured by R2 thermal flowmeter was analyzed (Fig. 8).

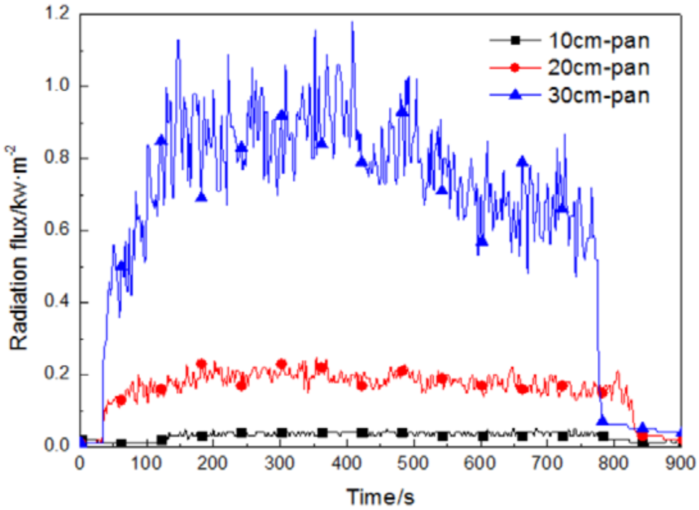

Figure 8. − R2 heat flux density meter measured thermal radiation flux vs time

It can be seen from the figure, that the thermal radiation flux is similar to the burning rate and can be divided into three stages, i.e., the initial stage, the stabilization stage and the attenuation stage. The thermal radiation flux increases rapidly after the ignition of the oil pool. 200 seconds later, the stabilization stage is reached and the radiation flux is no longer increased. After the stable burning, the flame is reduced to zero due to the reduction of the flame. Comparison of the thermal radiation density of the oil sump stage, 10 cm average 0,0269 kW/m^2, 20 cm average 0,1524 kW/m^2, 30 cm average 0,47537 kW/m^2. The same height of the heat radiation flux increases with the size of the oil pool, and the change is very obvious. Compared with R1 and R3 measured the two radiation radiation flux, have the same changes in the law, but the height of the measured heat radiation flux of the maximum and the average slightly different, take the measured thermal radiation. In the depth of 10 cm and 20 cm oil pool, for R1, the average thermal radiation flux measured the oil bath of the No. 1 heat flow densities, which is slightly larger than that of R2 and R3, but the values are close to each other. For R2, in the depth of 30 cm oil pool, the thermal flux density measured the average thermal radiation flux was significantly greater than the value of R1 and R3 (Fig. 9).

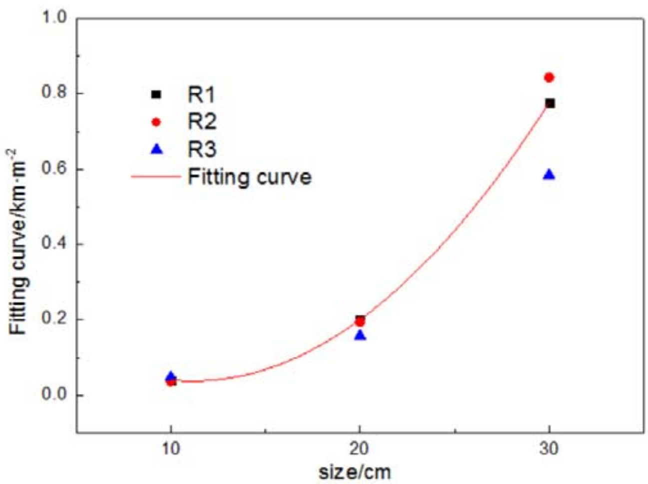

Figure 9. − The thermal radiation flux of different sizes of oil pool and the fitting curve

Assuming that the flame is a cylindrical gray body [13] with a certain temperature, then the model $r = \phi\varepsilon T^4$, where r is the radiation intensity at a distance away from the flame, ε is the emissivity, ϕ is the angle coefficient of emissivity, and T is the absolute temperature. It can be seen that the difference in heat flux is mainly related to the flame temperature and the flame height. The larger the size of the oil sump, the higher the temperature, the height of the flame, the greater the intensity of the radiation. The heat radiation flux is affected by the flame temperature, which is relatively small by the height of the flame. Regardless of the height of the flames, the relationship between the size of the oil pool and the thermal flux is considered in the position of 1m away from the oil pool. It is found that there is a certain linear relationship. The thermal radiation flux of the three sizes of the oil can be obtained:

$$E = 4{,}846D^2+1{,}429D-0{,}1833, \tag{6}$$

where E is stands for thermal radiation flux, D is stands for oil pool diameter. The thermal radiation flux of the 10 cm to 30 cm oil pool (1 m away from fire) can be predicted by fitting formula. Assuming that the thermal radiation flux of larger size oil pool conforms to this rule, the radiant thermal Flux of mild burning is 4 kW/(m^2·s), calculated by 80 cm oil pool can be found at the location of 1 m can cause burns.

3 Conclusions. With regard to the relationship between the combustion area and the combustion behaviour in low pressure environment, through the oil pool combustion experiments of different sizes, the following conclusions are obtained:

1. The burning rate is linear with the combustion area when the oil pool area is small and the burning rate is proportional to the atmospheric pressure under the experimental conditions in Kangding high plateau. It can be predicted that the burning rate of different size oil pool will be different under the condition of different atmospheric pressure through Wieser's formula.

2. The bigger is the burning area, the higher is the flame temperature, which is accord with the Kanding high plateau axis of the plume temperature rule, that is to rise at first, then to drop slowly and the difference between the lowest point of the axis and the highest one is smaller.

3. The atmospheric pressure in Kangding high plateau is low, and the temperature in visible flame and intermittent flame area is less than that of the atmospheric pressure. The classic plume temperature McCaffrey model does not consider the effect of atmospheric pressure on the flame temperature and can not be used to predict the plume temperature in Kangding high plateau.

4. The heat radiation flux is related to flame temperature. The larger is the burning area, the higher is the flame temperature and the greater is the heat flux. The heat radiation flux rule of different size oil pool while at distance of 1m away from fire can be obtained through curve fitting e.g. Formula (6).

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