ISSN 2616-5767 Vol.4, Issue 3: 6-15, DOI: 10.25236/AJETS.2021.040302

The effect of the four fire walls to the center pool

Jialong Qi, Gonghui Zhang

College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, China

Abstract: *According to the characteristics of burning rate of multiple oil pool fire, designing a four fire walls burning model. Influence of the central oil pan height, the fuel volume (oil film thickness) and the distance h between adjacent fire walls on fuel burning rate of central oil pool was studied. The results indicated that: Compared with single oil pool fire, the burning rate of central oil pan is enhanced by the four fire walls and the fire whirls also appears; define three regimes of flame reaction according to the flame shape, including initial state, incline state and merging state; when the gap width between 13cm-16cm, the center pool fire needs the lowest burning time and up to the highest average burning rate.*

Keywords: *four fire walls, fire rotation, flame merging, burning rate*

1. Introduction

Two or more fires burning simultaneously is termed as multiple fires. When multiple fires are located sufficiently close, they will influence each other and lead to flame merging and quick burning rates etc [1]. Multiple fires are usually occurred in urban and forest, leading to more sever disasters. In order to study the interaction of the multiply fires, several models have been created during the past years. In 1960s, multiple fires was first studied by Putnam and Speich [3] and interaction among multiple fires was first put forward at that time. Gaseous fuels were used to establish modeling partially and fully merging flames and the flow conditions and nozzle diameters producing single turbulent flames controlled by buoyancy were discussed. Analytical and experimental approaches were also applied to predict the important parameters affecting the merging phenomena and the expression of flame height was give finally. Baldwin and Thomas [4] did research with two rectangular fuel beds and four square fuel beds to deduce a critical condition that the flames tend to merging, causing change of the flame height and radiation when in the nearby fuel beds, the linear dimensions of the fuel beds D (width) and W (length) are both factors in determining the condition for flame merging. Different from the previous studies, Huffman[5] etc. studied the multiple fires with liquid fuels including methanol, acetone, hexane, cyclohexane and benzene to analyze the burning rates and the flame height varying with the diameter of the fire as well as the distance between the fire points. In their study, the burning rate of the center pool up to the maximum at the beginning of flame merging; then the formula to study the flame height of wood crib from Thomas was used in liquid fires and found that it were about the same as or slightly larger than those of Thomas. Liu [6] research the interaction of two parallel rectangular flame and divide the burning process to five states containing with Ⅰ) no interaction; Ⅱ) the two flames have interaction; Ⅲ) the intermittent regime; Ⅳ) partly merged flame and Ⅴ) completely merged flame. And give the normalized expressions in the different five states. Meanwhile, he uses 3*3 to 15*15 arrays to study the interaction of multiple fire from burning rates [7]. For n=3-7, the burning rate was speed up, when n=7-9, the burning rate was decreased, with n increase, the burning rate continues to increase.

Well, in the study of multiple fires, a typical flame shape like fire whirls also be observed, fire whirls was first researched in the forest, but in 2016, M.J. Gollner found the “blue whirl” over water, presents a small and stable state, and the processing of the transform from initial burn to the “blue whirl” was shown. Wu [9] first put out the four fire walls model to research the conditions of fire whirls and the influence of fire whirls to the flame height by numerical simulation, experimental observation and simplified physical analysis. They change the gap fraction $\frac{A}{A+B}$ (where A is the gap length and B is the length of oil container, they negligent the width of the container) and the number of edges to study the influence of the air flow to the center fire, the condition of fire whirl formation were obtain and the flame height of fire whirl due to rotation speed were measured in their study. As we all know, fire merging and fire whirls may occur in both urban and wildland areas, usually accompanied with great damage, in the other hand, it will also accelerate the burning rate effectively with a correct size, it will reduce the harmful too such in the oil spill in the ocean.

From the previous studies, we know, the research emphasis is burning rates, flame height and flame merging behaviors, in our study, the three points are also researched. In multiple fire, physically, the interaction of fires are two main mechanisms. The heat feedback enhancement and air supply restriction. When the two burning fires adjacent to each other, the fuel surface not only receives the heat from itself, but also from the other. When the fires are close, the air supply for inner fires may be significantly restricted [7] [8]. The burning rates would be speeded up due to the air entertainment and it would also be restricted for flame merging, we combine the air entrainment and flame merging behaviors together to explain their competition mechanisms by the burning rates, flame height and flame merging behaviors. We aim to study the burning rate through the gap width, pool height and oil mass, in the study, the gap width changed to alter the air entrainment processing to gain an optimum width that the burning rates go to the maximum or the burning times go to the minimum. The relations between the width and burning rates may be used for oil spill to gain less reaction time between oil and water and reduce the damage of the marine environment.

2. Experimental

Fig.1 shows the experimental setup, located in a closed room. Four identical rectangular oil containers around the oil pool, denoted as pool A, B, C and D, the center oil pool are placed on an electronic balance in order to record the mass change to reflect the burning rates of the center pool, and the oil containers on the board fireproofing to ensure the same height with the oil pool. The electronic balance was XA32001L series and it collect the data 1.1 seconds a time. Four rectangular oil containers are arranged to form four gaps, and the gap width are identified as 10cm, 13cm, 16m, 19cm and 22cm, the gap width from 10cm to start for the relative oil containers distance is 70cm and the tank width is 60cm, We define a fraction called $w = \frac{h+A-B}{h}$ to analysis model better and enhance its practicability, where h is the gap length of the neighbor oil container, A is the length of the length of it and B present the distance of the opposite oil container, it is obviously in our study w=0, 0.3, 0.6, 0.9, 1.2. Well, in our tests, two kinds of oil pools are used, size 20cm diameters with 10cm heights and 20cm diameters with 5cm heights, n-heptane with purity of 98% were used as the fuel with 50ml (31g) and 100ml (50g), 62g (100ml) n-heptane is belonging to one of the 20cm diameter with 5cm height oil pool. The flame was recorded by a high-speed video camera (SVSI, Inc., GigaView) at 25 fps with a frame size of 3840 ×2160 pixels to illustrates the flame height and flame merging.

After the data acquisition by the camera and the electronic balance, we choice the data helpful to data processing, in this part, we manage the mass data by the most common software like Excel and Origin, Excel to convert initial data to regular data, Origin was used to convert data to figure. The matlab were used to calculate the flame height from the video taken by the camera.

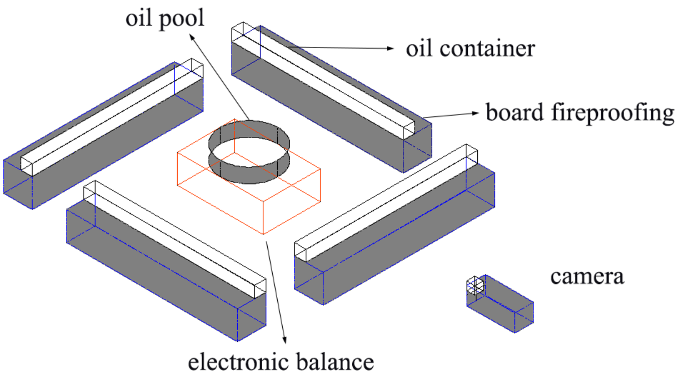

Figure 1: Schematic of experimental setup.

3. Result and discussion

Multiple fire burning is more complicated than single fire for the interaction among fires may induce special burning phenomena such as fire merging and fire whirl, of course including flame height change [9] and the interaction of multiple pool fires might lead to higher burning rate and flame higher than single pool fire [2]. in this chapter, we aim to study the flame shape in multiple fire pools and the burning rates in single and multiple pool fires respectively.

ISSN 2616-5767 Vol.4, Issue 3: 6-15, DOI: 10.25236/AJETS.2021.040302

3.1 Flame shape

3.1.1 Fire rotation

In multiple fires burning, the flame interactions may cause restriction of air entertainment, resulting in a pressure drop in the space among the flames [6]. In the past study, a generating eddy, a fluid sink within the eddy, and some friction or drag offered to the movement of air in the ground boundary of the eddy were the three conditions for the formation of fire whirl[12]. And for the intense fire whirl are dominate by rotation only rather than the hot burning products under the influence of gravity [13]. Well. In our study (Fig.1), we use four fire walls format a square range, with the fire burning, the air in the range was consumed, the hot-air tend to upwards for it is lighter than the normal air, the pressure in the range will lower than the outsides, as the exist of four fire walls, the air will be forced into the range from the sides gap and result in the tangential velocity(Fig.2), then the fire rotation was displayed, with the air entertainments, the rotational velocity will increase and result high velocities for the conversation of angular momentum[14]. Well, in this model, four fire walls may have two functions, one is to form a range of fire and consume the internal air, the other is to take four gap to accelerates the air entertainment. It can be observed in Fig. 3 that the rotation fire showing a higher and swirling shape.

Rotation fire and fire whirls are two special flame shape, similar with the rotation fire, fire whirls form in the presence of ambient swirl and heat [15]. Compared with the fire whirls and fire rotation, we know, fire rotation only a typical phenomenon of fire whirls, but without a quickly air entertainment, it isn’t easy to form the fire whirls. In our study, only the rotation fire was observed but steady rotation fire did not appear, so the fire whirls phenomenon inconspicuously. It may be called “the small fire whirls”.

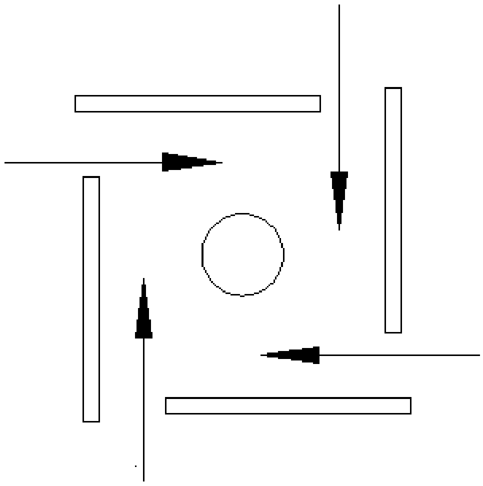

Figure 2: Air entertainment in the four fire walls model. example as h=16cm.

Figure 3: Typical rotation fire observed in experiments. Left: rotation fire for the pan‘s height is H = 5cm; right: rotation fire for the pan’s height is H = 10 cm

3.1.2 Flame merging behaviors

The flame merging behaviors means the process from the independence of the multiple fire to connected with each other, and in the multiple pool fire, flame merging behaviors is a typical burning phenomenon. In our experiment, the flames of the rectangular pools show a strong leaning toward the

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center, but the center pool still stay a vertical form for the surrounded fire walls has the identical force to it. Additionally, when fire merging occurred, the flame height will significantly increase [16]. Liu [6] etc. defines three regimes of flame reaction, namely “independent regime”, “intermittent regime” and consistent regime” by discuss the two rectangular flames with constant w/d and can be identified by visual observation. The three regimes are also divided as five States. State *I* indicate the two flames has no interaction, but the interaction flames on independent regime represents *State II*. When two flames being in consistent touch with each other, then it was called *State III* and included in the intermittent regime. The consistent regime was also divided into two States, so *State IV* refers partly merged flame and *State V* means completely merged flame. Well , Wan divide the flame shape into three regions with the difference of S/D, named fully merging region; intermittent merging region and fully separating region, and corresponding to 0≤S/D≤2, 2<S/D≤4, and S/D>4.

The four fire walls have some different with the two rectangular flames model, and the parameter w/d not applicable in our model. So, we may divide the combustion process into three States according to the four fire walls shape. When the flame stayed the initial condition, means a minor change but the flame shape and height still calm, we called “initial state”. Then the four fire walls reflect a strong incline towards to the Centre pool but the merged flame still not appear, we called it “incline state”. When the fire walls have touch with the pool flame, the “merging state” was putted up.

Taking the pools of D=20 cm (pool diameter), H=5cm (pool height), h=10cm (gap width) with 100ml u-heptane as an example, the flame images with burning progress increasing are shown in Fig. 4.

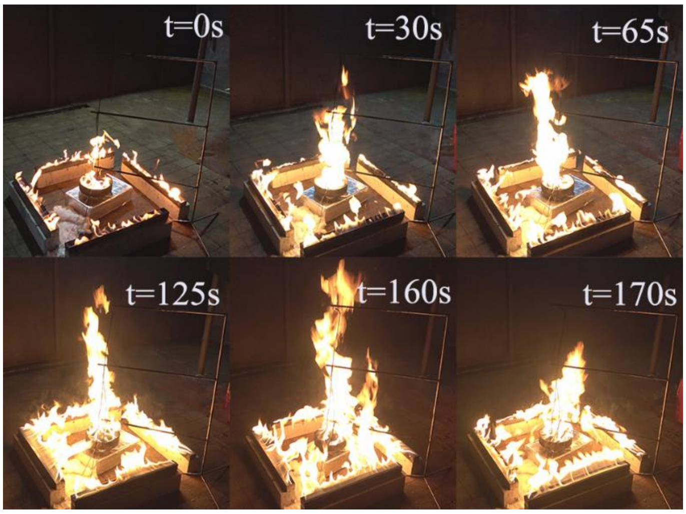

Figure 4: The flame images with burning progress increasing

It is observed that the flame shape was becoming higher and higher with burning and it arrived the highest when the time gone to 160s, then it goes to decline. We must be notice that in the initial burning time from 0s to 65s, four fire walls stayed a peaceful shape for cold-air in the circle of the walls and had not been burning out yet, we know it stayed in “initial state”. In the 125s, cold-air was burning out and under the influence of air pressure, fire walls have a strong inclined to the Centre pool but did not have any contact with it, we can also easily observe that fire height was increasing, that is the second condition “incline state”. In the 160s, fire walls have connected with the Centre fire including partly merging and completely merging and fire height up to the highest, it was considered as “merging state”. Then the center flame became smaller and smaller until the fuel used up.

3.2 Burning rates

3.2.1 Burn-out time with the gap width change

Burn-out time refer the process from the flame start to the end, Liu[17] first developed the burn-out time data analysis to research the interaction effect of the multiple fire, he confirms that it is reasonable to regard the burn-out time as the measurement for the average burning rate. We use the burn-out time to reflect the rates of burning too, with the same oil mass, less time means the quick mean value rates of burning. We need it to save our time to reduce the harmful may be caused by the longer burning time. Table.1 and Fig.5 displays the burn-out time of different oil mass, pool height and gap width. We control the burning in a same work conditions and change the w=0, 0.3, 0.6, 0.9 and 1.2 respectively, it is not

ISSN 2616-5767 Vol.4, Issue 3: 6-15, DOI: 10.25236/AJETS.2021.040302

suit for our formula when h=0, so we study it alone. We have find in our experiment that when the fuel was burned up, the flam also stays burning, that is to say, when the flame put out, the electronic balance reading below the initial pool mass, we define the burning time as the flame burning to the flame extinguished. We can learn from the Table.1 that when h=0cm, the burning time in the different three work conditions emerge a longer time than other width, then the w up to 0, time lower than h=0cm obviously and there exist a big time difference, the burning time always reaching the bottom at the w=0.6, and we may also say that at the range of w=0.3-0.6 the burning time achieving the minimum value. In the other words, oil with the same mass could be burning clearly with a shorter time when w=0.3-0.6. It is useful to deal with the oil spill in case of emergency, after w=0.6, burning time showing an upwards trend but still lower than h=0, we know the promoting effect for burning are restricted but still exists. Besides, Fig.4 also shows the burning process with time change that flame shape presents an irregular but regular changes, means the flame up to the highest height takes about 160s but from that time to the lowest just several seconds, however, the flame height presents a regular change from the lowest to the highest gradually, and then goes to the lowest progressively either.

Table 1: Burning time with different gap width

Gap width	Burning time (20*10+5)	Burning time (20*5+50)	Burning time (20*5+100)
0	172	142	225
10 (w=0)	155	124	174
13 (w=0.3)	149	122	170
16 (w=0.6)	147	118	168
19 (w=0.9)	165	130	177
22 (w=1.2)	168	131	181

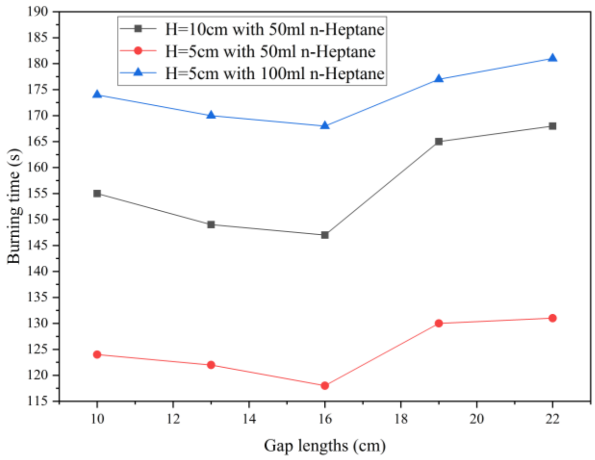

Figure 5: Burning time with different gap width

3.2.2 Burning rates of single burning fire

Burning rate is considered as the most important factor in pool fire research [18]. Pool fire burning is closely related to the heat transfer between the flame and the liquid surface, and the liquid fuel evaporation rate was influenced by the heat transform [19], that is to say, the nature of combustion is the fuel steam burning, so the burning rate was determined by the fuel evaporation rate. In this part, for comparison with multiple fire, we start to discuss the burning rates of signal fire, we test the burning rates of the pool size 20*10 with 50ml n-heptane and 20*5 with 50ml and 100ml n-heptane. In Fig.6, burning rates shows the form of fluctuation, in the first 10 seconds, the three different burning all share one thing in common that a peak value occurred and the highest height is H=10cm, then H=5cm with 100ml n-heptane, the lowest is H=5cm with 50ml fuel. After the mutation stage, the burning rates curve tend to be stable. Compare the mean value of the three curve, H=5cm with 100ml n-heptane get the highest value, then goes to the H=5cm with 50ml fuel, and the last is the H=10cm with 50ml n-heptane. Use the mean value of the burning rates reflect the burning efficiency, it is obviously that the burning efficiency raising with the pool diameter increasing, and the oil mass affect the burning rates yet, more oil burns faster. Summary of the burning rates of the pool without four fire walls, pool height (H) and oil mass are both influence factor for it, well, with the same oil mass, H determines the burning rates and with the same pool size, oil mass is the determinant for burning rates. In a word, H=5cm with 100ml n-heptane presents the best burning effect.

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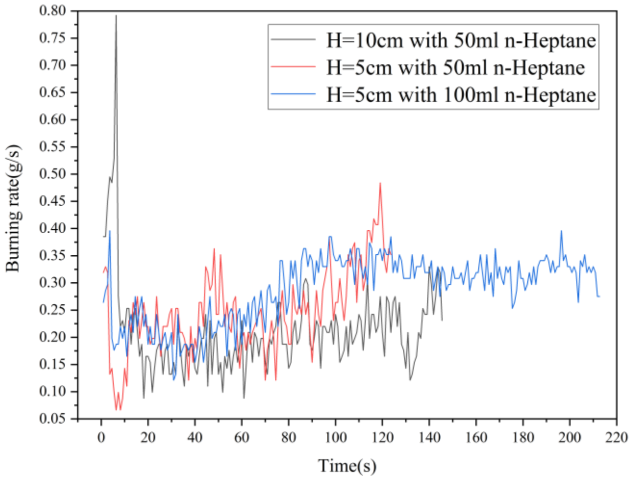

Figure 6: Burning rates of single burning fire.

3.2.3 Burning rates of the center pool with difference gap width of four fire walls

In section 3.2.2, we know the essence of burning. For multiple pool fire, it is more complicated for fuel evaporation because the heat feedback between the different pools existing and might lead to higher burning rate than single pool fire [2]. In our study, Fire gap width h is a key parameter for the burning rates of center pool fire. When h increase to another width, the heat feedback will also change, it means the mass loss rates will be transformed since the center pool will receive heat from the four fire walls, and the gap width change must alter the quantity of heat exchange. On the other hand, the air supply may be restricted or promoted. So, on the combined action of heat feedback and air supply, burning rates of the center pool must be changed, and the two fire interaction mechanisms may have competitive effects on the burning rates of the center pool [7].

Fig. 7- Fig. 9. shows the variations of burning rates in different gap width from 10cm to 22cm and the tolerance was 3, the mean value of burning rates is displayed. We have discussed in section 3.1.1 that when the data go to zero, the burning is still going on, and when the data reach the lowest, the burning still continue, but the data will raise. Different with the burning time study, we use the time which from the burning start to the data up to the lowest within the burning process to analysis, for the raising of data will gain the burning rate negatively and increase the error of average value. Obviously three different work conditions have the same rule that the burning rates up to the highest when w=0.3 or w=0.6. Fig. 7 presents the burning rates with the gap width change when D=20cm; H=10cm with 50ml n-heptane; it shows that when the gap width arrived 16cm, the mean value of mass loss rates reach to the highest. And from w=0 to w=1.2, the mean value of mass loss rates presents a tendency from low to high to low. Then we study the pool size D=20cm; H=5cm with 50ml n-heptane (Fig. 8), it delivery a different message that when w=0 and w=0.3, the value burning rates arrived to the highest. And it presents a tendency from high to low. Well, Fig.9 is the figure of D=20cm; H=5cm, with 100ml n-heptane, it shows that the mean value of mass loss rates goes to the highest at w=0.6. And deliver that in the first 70s, the actual value always less than the mean value.

From another perspective, the burning rates has different rule in picture. In D=20cm, H=10cm with 50ml n-heptane pool, the burning rates picture present a stable change, Obviously, the burning rates change around the mean value of the burning rates in the whole process, and it wave more and more strident with the increasing of gap width. Then in D=20cm, H=5cm with 50ml n-heptane pool, another phenomenon shows that the burning rates has several peak value and with the gap width change, the peak value was pushed back apparently. The mean value of the burning rates higher than the front pool. D=20cm, H=5cm, with 100ml n-heptane pool has a distinct appearance with the two front. Fig.9 presents that with the time raising, the burning rates gradually increase and present an upward trend, in the first several minutes, almost all of the actually burning rates are lower than the mean value of the burning rates.

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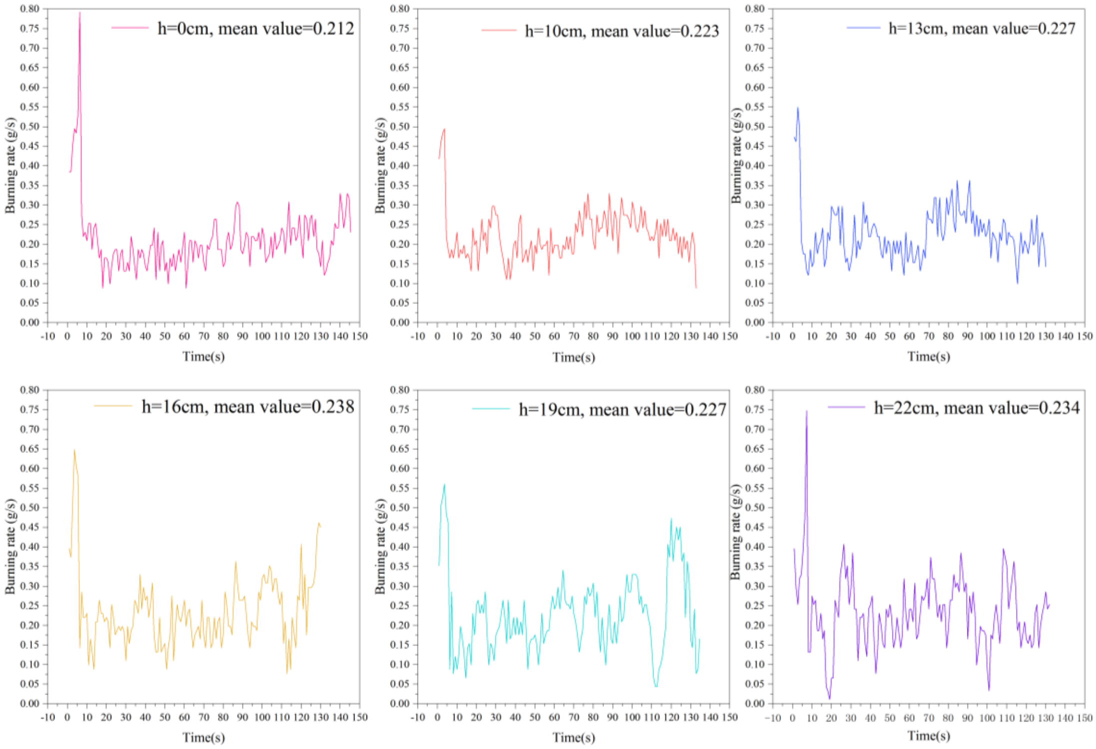

Figure 7: D=20cm; H=10cm; with 50ml n-heptane; h=10,13,16,19,22cm

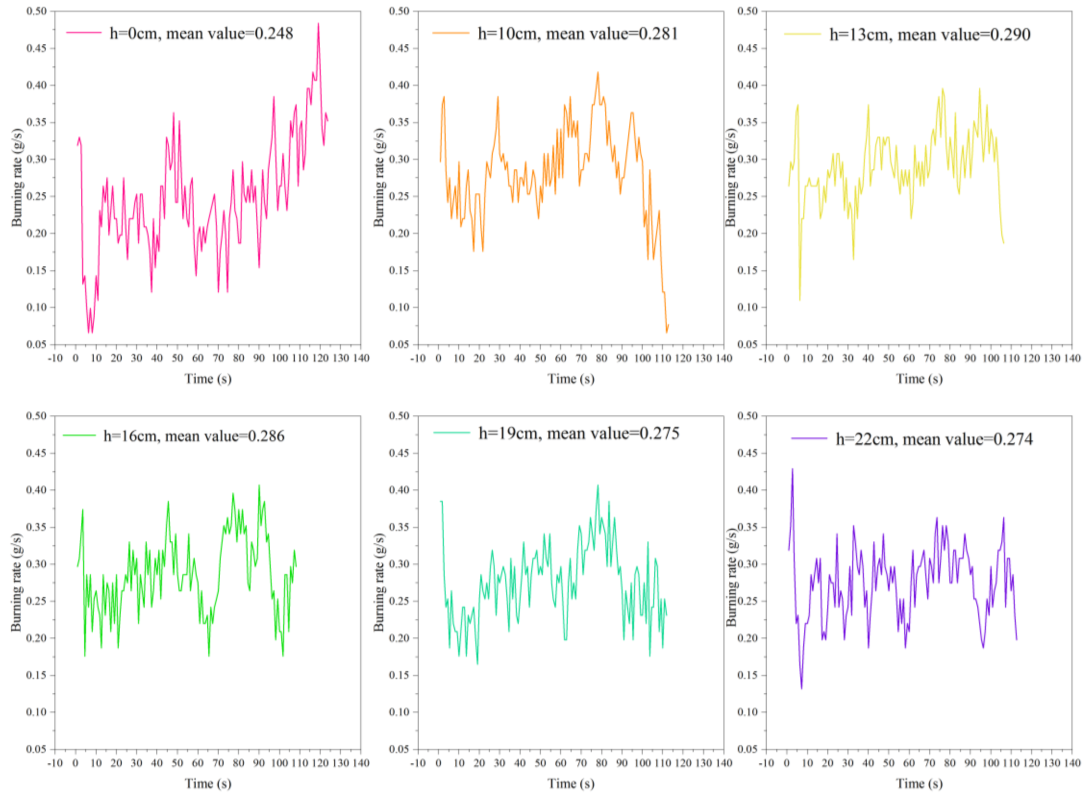

Figure 8: D=20cm; H=5cm; with 50ml n-heptane; h=10,13,16,19,22cm

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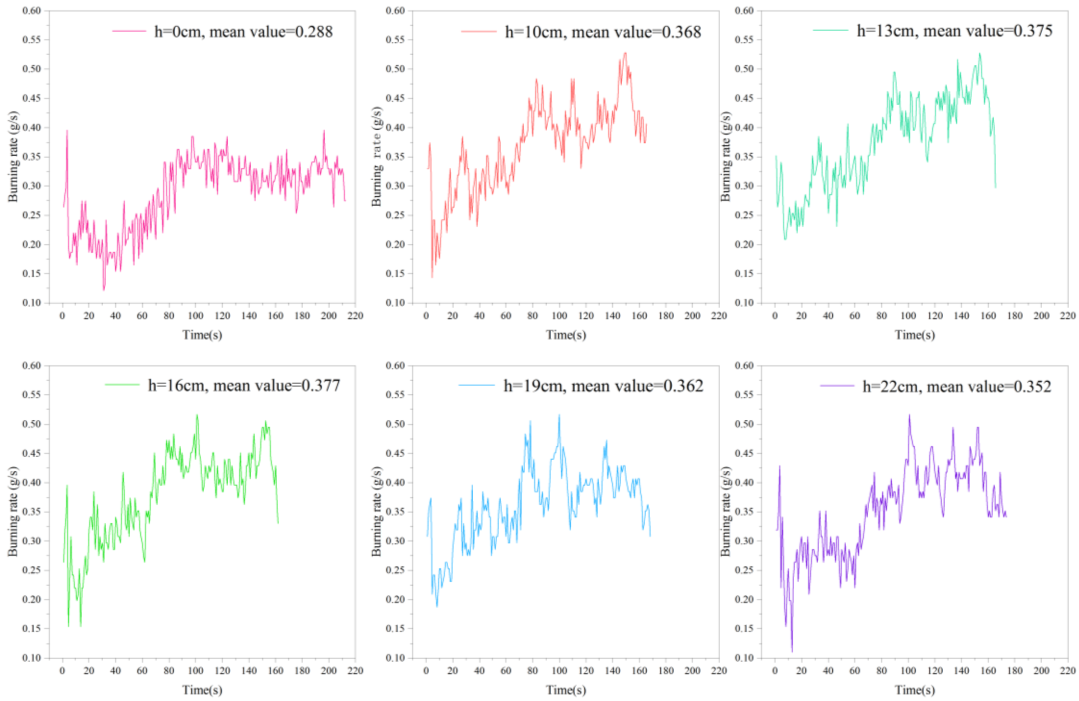

Figure 9: D=20cm; H=5cm; with 100ml n-heptane; h=10,13,16,19,22cm

Fig.10 and table.2 shows the mean value of the mass loss rates, compared the mean value of the burning rates in the same h, we choice w=0 as an example, the different three conditions have the mean burning rates are 0.223, 0.281 and 0.368, respectively, it is clearly that the H=5cm with 100ml n-heptane received the faster burning rates, then H=5cm with 50ml n-heptane are lower than the front but higher than H=10cm with 50ml n-heptane, and the message might be delivering that with the pool diameter increasing, the mean value of the mass loss rates will be lower due to the air cannot be supplemented in time, so it restricts the burning process. And with the oil mass increasing twice, the mean value has not arrived at twice over change. In addition, Table.1 presents a regular that in the same work condition, 16cm gap width implies the quickest average burning rates, it means when w=0.6, the same mass of oil will be burned up quicker than other width, it is prospective to development in oil spill.

Table 2: Average burning rates different gap width

w	Average mass loss rates (20*10+50)	Average mass loss rates (20*5+50)	Average mass loss rates (20*5+100)
0	0.223	0.281	0.368
0.3	0.227	0.290	0.375
0.6	0.238	0.286	0.377
0.9	0.227	0.275	0.362
1.2	0.234	0.274	0.352

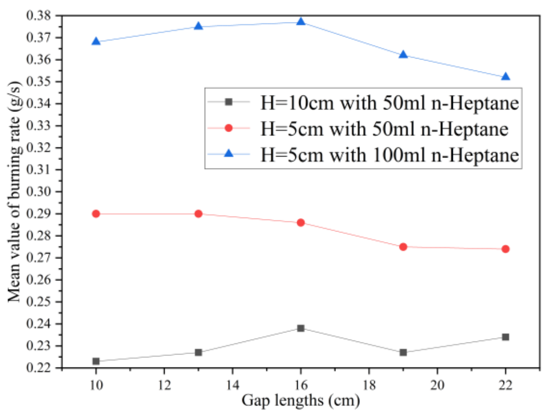

Figure 10: The mean value of the burning time with gap width change

ISSN 2616-5767 Vol.4, Issue 3: 6-15, DOI: 10.25236/AJETS.2021.040302

4. Conclusions

This paper presents the multiple pool fires burning, we use the four fire walls as the model to study the flame shape, the effect of the four fire walls to the center pool. The model design concept and the experiment findings are summarized as follows.

1) The four fire walls combine the air entertainment and the fire merging together to research the competition mechanism of the burning promotion and restriction. When the promotion is dominant, the burning will be speeded, contrarily, when the restriction is dominant, the burning will be slowed down, we reflect the competition mechanism through the burning rate.

2) The gap width of the four fire walls is altered to adjust the air entertainment and a relation of the gap width, oil containers width and the relative oil containers distance are given, it is possible to change the size with the same ratio to apply to the oil spill.

3) The rotation fire is found in our study. With the burning of the fire, air pressure difference in four fire walls, air entertainment mostly through the gap for the four fire walls restrict the air get into the inside directly and only the four gap left. The rotation fire in our study unstable, it is a little difficult from the fire whirls, so we call it “the small fire whirls”.

4) We divide the multiple pool fire burning process and define three regimes of flame reaction according to the flame shape, including initial state, incline state and merging state, as we have discussed in section 3.1.3, both four fire walls and the center pool fire keep clam called initial state, after the first state, the arrange and center fire showing a strong fluctuation and the surrounding fire have a strong incline towards to the center pool but the flame merging still not appear, then the center pool fire have connect with the four fire walls, we called this regime as merging state.

5) The most suitable gap width h=13cm – 16cm is found in our work, not only the lowest burning time, but also the highest mean value of burning rate it presents, a phenomenon showing that the four fire walls can accelerate the burning rate effectively and with the gap width increasing, the burning rate rising gradually and reach the pinnacle when the gap width reach 16cm, then it will go down but still higher than no-fire-walls.

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