Study on Flame Expansion Phenomenon in Pool Fire Extinguished by Water Mist

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Abstract

The theoretical and experimental studies on the phenomenon of flame expansion in pool fire extinguishment with water mist are presented in the paper. Firstly, the theoretical analysis on fire expansion phenomenon is made. It’s found that, both the interaction of water mist with flame and hot fuel lead to the flame expansion phenomenon in liquid pool fire extinguishment with water mist. The impacting on fuel vapor by water mist jet flow, which corresponding to the interaction of water mist and flame, and the azeotropic effects, which corresponding to the interaction of water mist and hot fuel, are these two kinds of root causes for fire expansion phenomenon. And the theoretical analysis also indicates that the flame characteristics, the interaction of water mist and pool fire, the momentum of water mist are the key factors to leading to an expanded fire. Then, three groups of experiments are set to study the above factors. The experimental results show that the impacting effects of the water mist jet flow to fuel vapor and the azeotropic effects of the mixtures of water and hot fuel are the main causes for fire expanding. And the flame characteristics, the momentum of water mist are important to the size of expanded fire. The existence of a certain amount of fuel vapor rich core of pool fire and the impacting of water mist with adequately large momentum are the prerequisites for fire expansion. It’s also found in the experiments that the fire expansion start from the bottom of the pool fire and not much related to the far-end of the flame. The experimental results indicate that the theoretical analysis are fit the fire expansion phenomenon well.

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Keywords: Flame expansion, flame characteristics, azeotropic effects, momentum, pool fire, water mist

1. Introduction

In the process of water mist fire suppression the flame expansion phenomenon may be found, that is, the flame sharply expand instantly when the extinguished agents discharging to the flame. The phenomenon will go on only in a short time which about 1-2s or less. While, the fire is intensified seriously in this short time, and the flame enlarges to several times of the original one. Then, most of the time, the fire is soon suppressed or extinguished. However, the momentary expansion of the fire can bring the firefighter or the surrounding people into injury, or contribute the
surrounding combustible to fire. So, it is with great significance to study on the phenomenon and behavior of flame expansion in pool fire extinguished by water mist.

The phenomenon of flame expansion is common in experimental studies on pool fire extinguishment with water mist \[^1-8\]. Experimental tests carried out by Mawhinney \[^1, 2\] showed that the heat release rate of the fire extinguished by water mist was higher than that of a fire without the suppression by water mist. And the authors also indicated that the increase in the heat release rate of the fire may result from kinetic effects of water mist on flames. Liu et al \[^3\] conducted a study of portable water mist fire extinguishers used for extinguishment of multiple fire types, and they found that the fire expansion process could be divided to several stages. Atreya et al \[^5\] found that the water mist enhance combustion through the evaporative expansion which enhances the mixing of the fuel vapor and air, while the water vapor interacts with the chain reactions to suppress soot formation, and hence reduce the radiant heat loss. Kim \[^6\] and Kim \[^7\] observed a momentary increase in the liquid pool fire size at the beginning of the water mist discharge in the case of successful fire extinguishment. And they thought that the increase in fire size is attributed to the enlarged flame surface caused by the impingement of water sprays, as water mist impinged on the pool flame and increased the mixing area between the oxidizer and the fuel. Experiments on the interaction of a water drop impacting on hot liquid surfaces carried out by Wang \[^9\] found that the water droplet will fragmented and ultimately produced a vapor explosion. And the authors thought that the behavior of the water droplet is related to the flame expansion phenomenon in liquid pool fire extinguishment with water mist.

It’s not difficult to find that most of these researches mention the phenomenon only with a surmised point of view and few studies are focused on the phenomenon and behavior of flame expansion, and neither conclusion nor theoretical model has made until now for its complexity. However, the previous studies and experimental tests also reveal several key issues for fire expansion phenomenon as follows: (1) the flame expanded sharply once the extinguishing agent discharging and the duration is short \[^10\]; (2) The flame expansion phenomenon is also common in liquid pool fire extinguishment with gaseous agent such as steam, nitrogen and carbon dioxide in local application; (3) The fire expansion phenomenon observed in Class “A” fire and some pool fire such as ethanol pool fire is much less obvious; (4) The momentum of the extinguishing agent affects the behavior of the phenomenon a lot \[^1, 2\]. (5) A periodic flame expansion phenomenon may be observed if the momentum of the jet flow is not enough to extinguish a pool fire. Therefore, any theoretical analysis on fire expansion should not only explain the phenomenon well, but also answer the above key issues.

The previous studies also reveals that, both the interaction of water mist and flame and the interaction of water mist and hot fuel are serving to the flame expansion phenomenon in liquid pool fire extinguishment with water mist. These two kinds of interactions are complex. Hence, the attempt is made in the paper to study the behavior of the flame expansion phenomenon in pool fire extinguishment with water mist. And the theoretical analysis based on both the interaction of water mist and flame and the interaction of water mist and hot fuel, is proposed to study the fire expansion phenomenon. The conclusions reveal that the theoretical analysis could explain the fire expansion phenomenon well, and could also answer the above key issues.

2 The theoretical analysis

Both the interaction of water mist with flame and hot fuel are leading to the flame expansion phenomenon in liquid pool fire extinguishment with water mist. While, these two kinds of interaction are mainly dominated by the following factors: (1) the flame characteristics, which are decided by the fuel; (2) the momentum of water mist; (3) the distance from the nozzle to the fuel surface.

2.1 The pool fire model and the flame characteristics

The flame characteristics of pool fire are different for different fuel types. Hence, the pool fire model is studied firstly to analysis the flame characteristics.

Previous studies \[^11-14\] showed that, a fuel vapor rich zone existing in the bottom of some pool fire. Xiao\[^15\] built a simplified pool fire model as show in Fig. 1. In the pool fire model, the fuel vapor rich core, which with sufficient fuel vapor, exists in the bottom of the flame.
To the pool fire with sufficient fuel vapor in fuel vapor rich core, the fuel vapor will be convected when the water mist jet flow impacted the flame. The convected fuel vapor will keep burning when it is pushed out of the original place by the water mist jet, and lead to an expanded fire.

While, some pool fire is with different characteristics. Take methanol pool fire for example, the flame is burning more completely and seems to be a laminar flow flame. Hence, the fuel vapor rich core of these kinds of pool fire is not big enough to collecting sufficient fuel vapor to result in an obvious fire expansion. The Class ‘A’ fire, which without a big fuel vapor rich core, is also difficult to serving to an obvious fire expansion. It indicated that the pool fire model, which decided by the fuel type, affects a lot in fire expanding.

Therefore, the flame characteristic is the key factor for serving a fire expansion. And the existence of a certain amount of fuel vapor in the fuel vapor rich core is the prerequisite for serving to a flame expansion phenomenon impacting by water mist with sufficient momentum.

2.2 The interaction of water mist and pool fire

Both interaction of water mist and flame, and interaction of water mist and hot fuel may be generated after water mist discharging in the pool fire.

(1) The interaction between water mist and flame

Water mist jet flow soon impacts the flame after discharging, and decreasing the flame height firstly. Then, water mist reach the fuel vapor rich core and make the fuel vapor convected. As is introduced in the work of W. W. Bannister et al [16], water suspended in or vicinal to the fuel before the fire will not materially affect the flash point or flammability of the fuel. Hence, the fuel vapor will burn as in the process of diffusion and formed an expanded fire ball.

Fuel vapor diffusion caused by water mist jet flow is a key factor for water mist to result in the fuel vapor diffusion. The water mist jet flow, with sufficient momentum, will ‘push’ the fuel vapor out of the original area, and serving a fire expansion.

A round turbulent impact jet flow (the curve $OQ'K'P'$) as is show in Fig.2 is formed on the impacting of the water mist to the ground. According to the typical mechanism of jet flow [17], the round turbulent impact jet flow can be divided to three zones: the free round turbulent jet zone, the jet flow impact zone and the radial wall jet flow zone.

However, the ground is not smooth because there is a vertical edge of the fuel pan, and no radial wall jet flow formed. As is shown in Fig.2, the oblique and upward jet flow can be divided by the line $N'N'$ and line $K'P'$. While, the fuel vapors in this jet flow, is forced both by the drag force and the buoyancy. The convected fuel vapor burning and form a flame ball as curve $S_1S_2S_3$ in Fig.2, which displays as the fire expansion phenomenon.

(2) The interaction between water mist and hot fuel

The interaction between water mist and hot fuel is an important and complex issue. Bannister et al [15] with a viewpoint of that the azeotropic effects can serious increased the fire intensities and serves to a flame expansion. As is introduced in the paper, the application of water onto burning fuels, which are insoluble in water, will result in an increased rate of volatilization of the fuel, and, at least momentarily, increased fire intensity.

A large number of fuels are insoluble in water. Hence, once the water mist reaches the fuel surface, mixtures of two immiscible liquids is formed. While, both of the water and the fuel contribute to the overall vapor pressure of
the mixture. That is, the total vapor pressure $P_m = P^0_A + P^0_B$. Where, $P^0_A$ refers to the saturated vapor pressure of the pure water, and $P^0_B$ refers to the saturated vapor pressure of the fuel.

Liquids boil when their vapor pressure becomes equal to the external pressure, which is 101.325 kPa. Therefore, mixtures of immiscible liquids will boil at a temperature lower than the boiling point of either of the pure liquids. Their combined vapor pressures are bound to reach the external pressure before the vapor pressure of either of the individual components get there. This means that such a mixture would boil at a temperature just a shade less than the boiling point of each pure liquid.

In a well developed pool fire, the temperature of the fuel surface is much close to the boiling point. A mixture with lower boiling point is formed once water mist reaches the fuel surface, and the temperature of the liquid surface will be higher than the boiling point of the mixture instantly. Then, the fuel becomes boiling and much more fuel vapor is generated soon. The boiling of the fuel can intensify the fire and result in the fire expansion phenomenon.

2.3 The momentum of water mist

The experimental reveals that, the fire expansion phenomenon will not be obvious if the momentum of water mist is small. This is because that the water mist jet flow can’t reach the fuel vapor rich core and ‘push’ the fuel vapor out of the original area. Hence, the fire expansion phenomenon can be observed in cases of water mist with sufficient momentum to reach the fuel vapor rich core.

It’s important to notice that, the momentum of water mist discussed here is the momentum of water mist in the area of fuel vapor rich core. In other hand, if initial velocity of water mist keeps the same while the distance from the nozzle to the fuel surface become short, the momentum of water mist is increased.

Therefore, the momentum of water mist is also a key factor to the fire expansion phenomenon in a pool fire with sufficient fuel vapor in the fuel vapor rich core. An obvious flame expansion phenomenon can observed when the momentum of water mist is large enough to reach to the fuel vapor rich core and push the fuel vapor out of the original area.

3 Experimental Setup

Three groups of experiments are conducted to study the behavior of fire expansion in pool fire extinguishment with water mist, and to confirm the theoretical analysis above.

3.1 Pool fire extinguished by nitrogen in local application

The first-group experiments are set to study the effects between the extinguishing agent and the flame without the azeotropic effects between the extinguishing agent and the hot fuel. Hence, the high pressure nitrogen is discharging to the pool fire to make an analogy of the water mist jet flow, to study the effects between the extinguishing agent and the flame. The schematic diagram of the experimental setup is shown in Fig3.

The experiments were carried out in an indoor laboratory which is large enough to simulate a local application of the nitrogen for extinguishment of fire. The nitrogen, with a pressure of 8 MPa, was delivered through pipes of size DN 20 to the nozzle with a diameter of 8mm located at different height right above and at the central axis of the fire source. The diameter and height of the fuel pan are 42cm and 3cm respectively. And the methanol, gasoline and diesel are taken as the different types of fuel. The thermocouples and the thin radiation heat flow meter are set to record the change the temperature and the radiation heat flow. The test cases are shown in Table 1. A DV camera with a responding rate of 120 fps was used to record the procedure of fire extinguishing.
Table 1 Test cases of pool fire extinguished by nitrogen in local application

| Case No. | Fuel   | Volume (ml) | Nozzle height | Pre-burning time |
|----------|--------|-------------|---------------|------------------|
| 1-1      | methanol | 400         | 1.2           | 60s              |
| 1-2      | gasoline | 400         | 1.2           | 45s              |
| 1-3      | diesel  | 400         | 1.2           | 80s              |
| 1-4      | methanol | 400         | 1.5           | 60s              |
| 1-5      | gasoline | 400         | 1.5           | 45s              |
| 1-6      | diesel  | 400         | 1.5           | 80s              |
| 1-7      | methanol | 400         | 1.8           | 60s              |
| 1-8      | gasoline | 400         | 1.8           | 45s              |
| 1-9      | diesel  | 400         | 1.8           | 80s              |

Table 2 the parameters of water mist

| Pressure (MPa) | Flow rate (L/min) | K factor | Average droplet diameter (um) | The average vertical velocity (m/s) |
|----------------|-------------------|----------|-------------------------------|-------------------------------------|
| 0.8            | 0.948             | 0.335    | 189                           | 1.33                                |

Table 3 Test cases of Pool fire extinguished by water mist under ventilation

| Case No. | volume(ml) | Wind Speed (m/s) | Pre-burning time |
|----------|------------|------------------|------------------|
| 2-1      | 50         | 0.4              | 120s             |
| 2-2      | 50         | 0.4              | 120s             |
| 2-3      | 50         | 0.8              | 120s             |
| 2-4      | 50         | 0.8              | 120s             |
| 2-5      | 50         | 1.2              | 120s             |
| 2-6      | 50         | 1.2              | 120s             |

3.2 Pool fire extinguished by water mist under ventilation
The second-group experiments are set to study the interactions of water mist with the upper part and the lower part of flame respectively, the fire expansion phenomenon under ventilation, and the azeotropic effects of the water-heptane immiscible mixtures. A scale experimental bench of a tunnel, with a length of 6.5m and a Square cross-section of 0.6m×0.6m, was established. The schematic diagram of the experimental setup is shown in Fig5. And ventilation was set to supply wind with different velocity. Water mist was set to extinguish the pool fire, and the nozzle is located 0.5m above the pan. The water mist was generated by high pressure nitrogen, and with parameters as is shown in table 2.

The size of the fuel pan is 7cm×7cm×2cm, and the fuel used in the experiment was Heptane. The water mist can’t reach the fuel pan but the far-end of the flame when the fire source located in location 2. The thermocouples and the thin radiation heat flow meter are also set to record the change the temperature and the radiation heat flow. The test case is shown in Table 3.

3.3 Pool fire extinguished by water mist with different momentum

The third-group experiments are set to study the Pool fire extinguished by water mist with different momentum. The schematic diagram of the experimental setup is shown in Fig7. The momentum of water mist is changed as the changing of the working pressure. The parameters of water mist with different momentum are showed in table 4.

| Pressure (MPa) | Flow rate (L/min) | K factor | Average droplet diameter (um) | The average vertical velocity (m/s) |
|---------------|------------------|----------|------------------------------|-----------------------------------|
| 0.4           | 0.665            | 0.333    | 205                          | 1.26                              |
| 0.6           | 0.810            | 0.331    | 200                          | 1.29                              |
| 0.8           | 0.948            | 0.335    | 189                          | 1.33                              |

Three types of fuel, methanol, gasoline and diesel, are used in the experiments, and the size of fuel pan is 10cm×10cm×1cm. The thermocouples and the thin radiation heat flow meter are also set to record the changes of the temperature and the radiation heat flow. The test case is shown in Table 5.

Table 5 Test cases of Pool fire extinguished by water mist with different momentum

| Case No. | Fuel       | Working pressure (MPa) | Mass of fuel (g) | Pre-burning time |
|----------|------------|------------------------|------------------|------------------|
| 3-1      | methanol   | 0.4                    | 30               | 60s              |
| 3-2      | methanol   | 0.6                    | 30               | 60s              |
| 3-3      | methanol   | 0.8                    | 30               | 60s              |
| 3-4      | gasoline   | 0.4                    | 30               | 40s              |
| 3-5      | gasoline   | 0.6                    | 30               | 40s              |
| 3-6      | gasoline   | 0.8                    | 30               | 40s              |
| 3-7      | diesel     | 0.4                    | 30 (+5) *        | 180s             |
| 3-8      | diesel     | 0.6                    | 30 (+5) *        | 180s             |
| 3-9      | diesel     | 0.8                    | 30 (+5) *        | 180s             |

4 Results and discussions

4.1 The flame expansion behavior varied with the fuel type

The experimental results reveal that fire expanded size observed in methanol pool fire extinguishment both with nitrogen and water mist is much smaller than that of gasoline pool fire, diesel pool fire and heptane pool fire. Table 5 shows that the fire expanded size in almost all test cases of methanol pool fire extinguished by nitrogen and water mist is smaller than the other pool fires.

However, the fire expansion phenomenon is commonly observed in gasoline pool fire, diesel pool fire and heptane pool fire. The following shown in Fig. 9 are the pictures of gasoline pool fire extinguished by water mist. It could be found that the fire is intensified seriously when water mist impacting on the pool fire.

The experimental results indicate that the flame characteristic is a key factors that to the expanded fire size. As is discussed above, the flame is burning more completely and seems to be a laminar flow flame. Hence, the fuel vapor rich core of these kinds of pool fire is not big enough to collecting sufficient fuel vapor to serving a fire expansion.
However, the fuel vapor rich core is big enough to collecting enough fuel vapors in gasoline pool fire, diesel pool fire and heptane pool fire. The fuel vapor in these kind of pool fire will be ‘pushed’ out of the original area by water mist jet flow after water mist discharging, and leading to a expanded fire. And it’s reasonable to make a deduction that the existence of a certain amount of fuel vapor in the fuel vapor rich core is the prerequisite for serving to a flame expansion phenomenon impacting by water mist with sufficient momentum.

| Case No. | The first-group | The third-group |
|----------|----------------|----------------|
|          | 1-1 | 1-4 | 1-7 | 3-1 | 3-2 | 3-3 |
| Type of fuel | methanol | methanol | methanol | methanol | methanol | methanol |
| Expanded fire size | small | small | small | small | small | small |

The following shown in figure 8 are the pictures of methanol pool fire extinguished by water mist of case No. 3-1. And it’s not difficult to find that there is almost no obvious fire expansion phenomenon observed.

4.2 The flame expansion behavior under impacting of the extinguishing agent jet flow

The experimental results of pool fire extinguished by nitrogen in local application reveal that the flame expansion phenomenon is also common in liquid pool fire extinguishment with gaseous agent such as nitrogen in local application. Table 6 indicates that the expanded fire size of gasoline pool fire, diesel pool fire is large. While, different with the water mist, there are no azeotropic effects generated between nitrogen and hot fuel, and the behavior of the flame expansion phenomenon is mainly caused by the gaseous jet flow.

| Case No. | 1-2 | 1-3 | 1-5 | 1-6 | 1-8 | 1-9 |
|----------|-----|-----|-----|-----|-----|-----|
| Type of fuel | gasoline | diesel | gasoline | diesel | gasoline | diesel |
| Expanded fire size | Large | Large | Large | Large | Large | Large |

The pictures shown in Fig. 10 indicate that the nitrogen jet flow impacting the fuel vapor rich core of the pool fire, and ‘push’ the fuel vapor out of the original area. The convected fuel vapor burning in its expanding and then a fire ball is formed. The typical time curve of radiation heat flow of gasoline pool fire extinguishment with nitrogen in local application is shown in Fig. 11. And as is shown in the figure, the radiation heat flow sharply increased momentarily after the nitrogen discharging, and sharply decreased following the extinguishing of the fire.
The results of the second-group experiments also indicate that the water mist jet flow impact the fuel vapor and force the fuel vapor convected. As is shown in figure 12, the first five pictures indicate that fire expansion phenomenon is start from the bottom of the pool fire, and not much related to the far-end of the flame.

The picture shown in Figure 13 reveals that the flame is blown obliquely by the wind with a speed of 1.2 m/s. However, the water mist jet flow still pushes the fuel vapor to the opposite wind direction and forms an upwind flame. The picture indicates that the fuel vapor is impacted seriously by the water mist jet flow.

4.3 The mixtures of immiscible liquids

The heptane was used as the fuel to study the azeotropic effects in the second-group experiments. As is discussed above, mixtures of immiscible liquids will boil at a temperature lower than the boiling point of either of the pure liquids. Their combined vapor pressures are bound to reach the external pressure before the vapor pressure of either of the individual components get there. This means that such a mixture would boil at a temperature just a shade less than the boiling point of each pure liquid.

Figure 14 shows the time curve of temperature of the heptanes fuel surface. In the well developed heptane pool fire, the temperature of the fuel surface is 95.5°C, which is much close to the boiling point of pure heptanes which is 98.5°C. Figure 15 shows that the azeotropic point of the water-heptane mixtures is about 79°C which is much lower than that the boiling point of water 100°C and heptanes 98.5°C. In the experiment study, a mixture of water and heptane with lower boiling point 79°C is formed instantly once water mist reaches the fuel surface. While, the temperature of the liquid surface when is still 95.5°C, is higher than the azeotropic point of the mixture. Then, the fuel becomes boiling instantaneously and a large amount of fuel vapor is generated soon. Hence, the boiling of the fuel can seriously intensify the fire and result in the fire expansion phenomenon.
4.4 The effects of the momentum of water mist

As is discussed above, the momentum of water mist affects a lot to the fire expansion phenomenon. The maximum expanded fire size in third-group experiments are shown in Fig. 15 with different pressure. And it is found that the expanded fire size is increasing with the increasing of working pressure.

[Images of fire expansion at different pressures]

![Fig.15 The maximum expanded fire size with different pressure](image)

The typical time curves of radiation heat flow of pool fire extinguishment with water mist are shown in the figure 16 and 17. As is shown in the figures, the radiation heat flow increased sharply after the water mist discharging.

The table 7 shown that the maximum radiation heat flow of fire expansion phenomenon in gasoline and diesel pool fire extinguished by water mist with different work pressure. It’s found that the maximum radiation heat flow increased with the increasing of the working pressure of water mist.

Table 7

| Pressure (MPa) | 0.4       | 0.6       | 0.8       |
|---------------|-----------|-----------|-----------|
| gasoline      | 2526.213  | 2836.66   | 3457.025  |
| diesel        | 2860.94   | 2868.0    | 2867.0    |
| gasoline      | 3835.94   | 4818.578  | 6486.35   |
| diesel        | 2855.94   | 1816.4    |           |

The experimental results of the first-group are also shown that the longer the distance between the nozzle and the fuel surface is, the larger the expanded flame size is. Table 8 gives the maximum radiation heat flow of the fire expansion phenomenon in pool fire extinguished by water mist with different distance.

Table 8

| Distance (m) | 1.2       | 1.5       | 1.8       |
|--------------|-----------|-----------|-----------|
| gasoline      | 2982.0    | 2860.35   | 2868.0    |
| diesel        | 2855.94   | 2867.0    | 1816.4    |

Hence, the experimental results indicate that the momentum of water mist is also a key factor to the fire expansion phenomenon in a pool fire with sufficient fuel vapor in the fuel vapor rich core. An obvious flame expansion phenomenon can observed when the momentum of water mist is large enough to reach to the fuel vapor rich core and push the fuel vapor out of the original area.

5 Conclusions

The following conclusions are drawn from the theoretical analysis and the experimental studies reported in this paper:(1) Both the interaction of water mist with flame and hot fuel are serving to the flame expansion phenomenon in liquid pool fire extinguishment with water mist. The impacting on fuel vapor by water mist jet flow, which corresponding to the interaction of water mist and flame, and the azeotropic effects, which corresponding to the interaction of water mist and hot fuel, are these two kinds of root causes for fire expansion phenomenon. (2) The experimental results and the theoretical analysis indicate that the flame characteristic which decided by the fuel type, the momentum of water mist, and the distance from the nozzle to the fuel surface, are all the key factors that to the expanded fire size. (3) The experimental results indicate that fire expansion phenomenon is start from the bottom of the pool fire.(4) The momentum of the water mist is also a key factor to the fire expansion phenomenon in a pool fire with sufficient fuel vapor in the fuel vapor rich core.
While, much more experimental and theoretical analysis should be conducted to confirm the behavior of the fire expansion phenomenon as follows: (1) Further studies on the flame characteristics of the pool fire model; (2) Further studies on the azeotropic effects in pool fire extinguishing; (3) Further studies on the interaction between extinguishing agent jet flow and flame;

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