CHAPTER 4

RESULTS AND DISCUSSION

The results presented in the study were from the tests conducted in a simulated machinery space. The fire source is a pool fire, using diesel oil as fuel. The reason for choosing pool fires is twofold. Firstly, it can easily determine the heat release rate for such pool fire; that is, the nominal HRR of diesel is approximately 1.2 MW for $1m^2$ area [24]. Obviously, this is, however, only possible for the cases where the pool fire is obstructed from direct impingement of the water spray. Secondly, the pool fire is generally more difficult to extinguish for a given fire size, comparing to the spray fire.

The fire protection designs in tests can be divided into three categories: non-protection condition, conventional sprinkler system and high-pressure water mist system. For each fire test, the temperatures, smoke opacity, CO and O_2 concentration variations are measured by the instrumentation apparatuses, described in Chapter 2. Theses measurements are served as the evaluations and comparisons of fire extinguishing efficiencies for the different fire protection systems. Furthermore, in order to identify whether the pool fire is extinguished or not under the application of specific fire protection, a thermocouple, termed as S-F, is installed at an elevation of 50cm above the pan. It is not a requirement of FMRC protocol [18].

4.1 Non-Protection Condition

The test measurements, such as temperatures, O_2 and CO concentrations, and smoke opacity, for non-protection condition are served as the reference data for fire protection efficiency comparisons. By the way, the pool fire source is shield as mentioned in Chapter 2. It is a simulation of an engineering room fire.

The temperature history of S-F as shown in Figure 4.1 is described first. Note that in this figure, it contains all of the pool fire burning histories under the various fire protection designs. In the present case without any application of fires protection, the diesel is ignited at t=100sec., the temperature rises sharply and it reaches 800°C around t= 160sec. Then it drops a little and maintains an oscillatory trend around 700°C. Eventually, the fuel is burnout at t=250sec. and after that the temperature starts to decay monotonically. Therefore, the total burning time is 150 seconds.

The temperature histories for the specific heights at thermocouple trees #1, #2, #3 and #4 are shown in Figures 4.2, 4.3, 4.5 and 4.6, respectively. At t=100sec., the diesel is ignited, then, the temperatures rise quickly due to a great amount of heat releases. For thermocouple tree #1, as shown in Figure 4.2, the highest temperature always occurs at the height of 2.8m. The maximum one is 300°C at t=250 sec. It is because this tree is directly exposed to the ejected fire plume completely and it is not too far from the burner (see Figure 2.1), so the thermal plume can directly move upward without any obstacle. However, only this thermocouple tree shows the trend that the temperature increases with height. In addition, it has the largest temperature difference between the ceiling and floor.

For thermocouple tree #2, it is far from the burner and close to the vents. Figure 4.3 shows that the measured highest temperatures occur at the height between 1.5m and 2m. It is attributed to the heating in a room causes air to expand, pushing some air out of the room through all available vents. When the hot layer under the ceiling becomes deep enough to fall below the top of a vent, some hot gas will flow out through the vent. As the fire grows, the buoyant outflow will exceed the gas expansion by the fire. Thus the pressure in the fire room at the floor will fall below atmospheric pressure, and outside cold air will flow into the room at the bottom. The pressure difference, ΔP, at a height y is

$$\begin{aligned}\Delta P &= P_1 - P_2 \\ &= \Delta P_f + \int_0^y (\rho_2 - \rho_1) g \, dy \\ &= \Delta P_f + 3461 \int_0^y \left(\frac{1}{T_2} - \frac{1}{T_1}\right) dy\end{aligned} \tag{4.1}$$

where $P_1 = P_f - \int_0^y \rho_1 g \, dy$ is the pressure at height y inside the room,

$P_2 = P_a - \int_0^y \rho_2 g \, dy$ the pressure at height y outside the room,

$\rho_1 =$ the inside density,

$\rho_2 =$ the outside density,

$P_f =$ the pressure at the floor inside the room in front of the vent,

$P_a =$ the pressure at the floor level outside the room just beyond the vent,

$T_1 =$ the temperature inside the room (about one vent width in from the vent),

$T_2 =$ the temperature outside the room (well away from the vent flow).

The mean pressure drop at the interval between 2.5 and 2.8 m height (vent location) can be calculated by Eq. 4.1, and its result is presented in Figure 4.4. It shows that the pressure difference becomes greater and greater as the fire grows and eventually it becomes level-off as soon as the fuel is burnt out. It indicates that the smoke and combustion products in the upper layer near the vent flow out continuously after ignition in this case. As expected, the temperature in the neighborhood of vent is lower than those below its height.

Figure 4.5 is the temperature histories at the thermocouple tree #3. This thermocouple tree is quite different from the others that its thermocouple spacing is smallest and it is just located above the fire source. However, there is a horizontal shield plate existed just below its bottom, in other words, it is isolated from the pool fire. Therefore, the plume needs to soar along the perimeter of the 45^0-angle plate and go around the plate tip, making an upward wake flow. It enhances the momentum and energy transfers that make the temperature distribution to be somewhat concentrated. The highest temperature is at the bottom one, 30cm above the horizontal shield plate.

The thermocouple tree #4 is closer to burner than that of #1, but it is not directly exposed to the fire plume due to the partial blockage of a vertical side shield plate. Therefore, the temperatures, as shown in Figure 4.6, are relatively lower than the corresponding ones in #1.

However, the highest temperature occurs at the height of 1.5~2.5m, but not at the one closest to the ceiling.

The concentration variations of O_2 and CO in the compartment as a function of time can be seen in Figures. 4.20 and 4.21. The measurements are taken at the elevation of 1.8m and 1m, respectively. Note that, similar to Figure 4.1, both figures include the measured data for all fire scenarios and fire protection designs. In Figure 4.20, it can be seen that the oxygen concentration almost does not vary at the height of 1.8m, whereas at the 1m height, it drops substantially with time after ignition, even is lowered to unattainable condition. Apparently, the pool fire consumes a lot of oxygen around its nearby region. For CO concentration, from Figure 4.21, its production rate seems to relate with the consumption rate of oxygen. At the height of 1m, it has no production at all since no oxygen is consumed. However, its produce a lot of CO as O_2 is substantially consumed, even its quantity is out of the measurable range.

Figure 4.22 shows the resultant smoke opacity patterns under different protection designs. Apparently, all of the smoke opacity developing curves under different protection tests are almost identical.

4.2 Conventional Sprinkler System

In this case, the fire scenario is the same as that in the previous section (shielded pool fire), however, the convention sprinkler fire suppression system now is applied. There are six pendent sprinklers installed on the ceiling according to fire code requirement.

The activation time of the automatic sprinklers protection is about 60 seconds after ignition. The extinguishing time is defined as the duration between the activation time of the fire suppression system and the instant that the temperature of S-F (Figure 4.1) is cooled to 328 K. In the present case, the extinguishing time is 176 seconds as listed in Table 4.1, which includes the test results obtained from all of the experiments, such as non-protection, automatic sprinklers system with shielded pool fire and two water mist systems subjected to the shielded and unshielded pool fires.

Figures 4.7 to 4.10 show the resultant temperature histories for thermocouple trees #1 to #4 as the sprinkler system is activated in the compartment under natural ventilation. As shown in these figures, it can be seen that as soon as the automatic sprinkler system is activated at t = 60 sec., all of the temperatures in every thermocouple tree stop to rise immediately and commence to drop until the room temperatures are reached, indicating that the fire is suppressed completely. It also can be confirmed by Fig. 4.1 that the temperature at 50cm above the pan is dropped to room temperature after a period of sprinklers activation.

The gases in the room can be characterized in terms of two layers: an upper layer above the 1.5 m height with hot combustion products and a lower one under 1.5 m with the less affected air. The reason to pick 1.5m height as the border between these two layers is that it is the half height of the room. The corresponding temperature variations for these two layers under different protection designs are shown in Figure 4.11. The layer temperature is obtained by averaging the related ones in four thermocouple trees. From this figure, the operation of conventional sprinkler mitigates the temperature difference substantially between these two layers, reducing the fluid convention.

The pressure difference between the compartment and surrounding is also decreased, (see Figure 4.3) as the automatic sprinklers are operating. This leads to a reduction of mass exchange. The relationship between the mass exchange and pressure drop is expressed as follows.

$$\text{Flow out} \qquad \dot{m} = C\int_{h_n}^{h_t} bV\rho \, dy \,, \tag{4.2}$$

$$\text{Flow in} \qquad \dot{m} = C\int_{h_n}^{h_t} bV\rho \, dy \,, \tag{4.3}$$

where b = width of the vent,

C= experimentally determined flow coefficient,

ρ = density of the fluid approaching the vent,

V= Velocity of the fluid given by $V = 0.93\sqrt{\frac{2\Delta P}{\rho}} \; \left({}^{m}\!/_{\sec}\right)$.

It may conclude that the reduction of mass exchange makes an insufficient air supply to support the combustion in fire.

4.3 Water Mist System

The two fire scenarios, shielded and unshielded pool fires, and two protections, 4 nozzles and 6 nozzles, are carried out for the full-scale test series with high-pressure water mist system. The use of 4-nozzle and 6-nozzle protections is to identify whether an increase of mist nozzles can increase the cooling effectiveness. The averaged water density (W_d) per area is introduced to measure the quantity of water required for fire extinguishment. It is defined as the ratio of the total amount of water discharge (W_t) over the compartment area (A_c)

$$W_d = \frac{W_t}{W_c} \quad (L/m^2) \tag{4.4}$$

The values of W_d are 1.22 L/m^2 and 1.53 L/m^2 for 4-nozzle and 6-nozzle protections, respectively.

In order to make fair comparison, the activation of water mist system is fixed to take place at t = 60 seconds, the same as that in conventional sprinkler system.

4.3.1 Shielded Pool Fire

From Figure 4.1, it indicates that the extinguishing times for both 4-nozzle and 6-nozzle high-pressure water mist systems are less than that of conventional sprinkler system. The corresponding values can be seen in Table 4.1. From this, it may conclude that the fire suppression efficiency of water mist system is better than that of conventional sprinkler system if we just take the 6-nozzle cases into consideration. In addition, the required water quantity is much less in water mist system. Although the extinguishing time of 4-nozzle is longer than that of 6-nozzle, but it still shorter than that for 6-sprinkler system. Therefore, its performance is still acceptable.

Figures 4.12 to 4.15 shows the resultant temperature histories for thermocouple tree #1~#4 when 6 high-pressure water mist nozzles are employed, whereas Figs. 16 to 19 are the corresponding ones for 4 high-pressure water mist nozzles. From these figures, it clearly shows that the gas phase temperatures are still rising for a while after the water mist system takes action. They eventually drops, however, the final temperatures are not the ambient one before ignition. These phenomena are completely different from what we observe in the conventional sprinkler system. Apparently, the main fire suppression mechanism for water mist is the more like the gaseous agent, but not the direct cooling. As to the final temperature for the application of water mist system, it is believed to be the saturated temperature.

Form Figure 4.11 shown the calculated average gas temperature inside the test compartment which be characterized in terms of two zones, the calculation was based on the reading of the 24 thermocouples on the four thermocouples trees. As the above discussions, the whole cooling effectiveness of the 6 high-pressure nozzles protection is superior to other fire protection categories, but Fig. 4.11 indicated that average upper zone temperature pattern under 6 high-pressure nozzles protection is higher than other protections.

Figure 4.20 shows that with discharge of water mist, the oxygen and fuel vapor available for combustion are reduced due to the displacement by water mist, which is more obviously as 6 nozzles are employed. The explanation is believed that: (1) it increases the injection of a lot of fine water droplets into a hot environment to result in the rapid evaporation, expansion and displacement of air in the compartment by vapors, and (2) the expansion evaporation leads to an “gas shielded effect” that heat from the fire trapped in the compartment evaporates the finest portion of the mist, leading the expanding water vapors to push air out of pool fire.

In Figure 4.22, for the 6-nozzle discharge fire tests the smoke opacity curve begins to emerge after 170s the activation of water mist. This demonstrates the clean ability by water mist. It also shows that the more applied water mist nozzles, the better the cleaning effect.

4.3.2 Unshielded Protection

In the unshielded pool fire test series, the effect of obstruction in water mist system is examined as the shielded metal is removed. Like the shielded tests, pre-burn period for the unshielded tests are set for 60s. The tests results for water mist produced by 4 high-pressure nozzles directly on the pool fire are shown in Figures 4.23 to 4.26. From these figure, it takes more time to cool the room temperature to a constant value. For the application of 6 high-pressure nozzles in the unshielded pool fire tests also show the similar results. It is because that the heat of hot vapor is not absorbed by the obstruction and move up to the ceiling with the plume directly. Therefore, it results in the compartment having a higher temperature.

However, from Figure 4.1, it shows that the extinguishing effectiveness for water systems with the same number of nozzles seem to be almost the same under the shielded and unshielded pool fires. In other words, the obstructions have a minor influence on the fire extinguishing performance in the limited ventilation compartment.

Figures 4.27 to 4.30 show the temperature histories for thermocouple #1 to #4 by using 6 nozzles under unshielded pool fire tests. The room temperature responses are similar to these with 4 nozzles tests. The time needed to cool the hot gas temperature to a constant is more than that in the shielded tests. Like the shielded tests, increasing the number of nozzles can reduce the extinguishing time. From the two tests mention above, it is clear to find that the obstruction will not affect the fire extinguishing effectiveness of water mist obviously in the limited ventilation compartment.

What does the influence of obstruction on the oxygen and CO concentrations? The tests results are shown in Figures 4.20 and 4.21. Comparing the oxygen and the CO concentrations at the 1.8 m height for shielded and unshielded tests, it shows that the oxygen and the CO concentrations maintain the constant vales in the shielded tests, but in the unshielded tests, obviously the oxygen and CO concentrations change with time. The explanation is believed that the obstruction has an influence on the fluid movement. In the shielded tests, the fresh air is entrained in the compartment by pressure difference and the fire products are exhausted by the horizontal fan directly by moving along thin metal at 45^0, finally, it results in a diluted concentration at 1.8 m height.