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COOLING CHARACTERISTICS OF HOT OIL POOL BY WATER MIST DURING FIRE SUPPRESSION

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ABSTRACT

Generally water is not favored for use in suppressing hot liquid fuel fires due to concerns of vapour explosion and boil-over, which could present potential danger to nearby personnel or firefighters. This paper reports on a series of full-scale fire experiments in which water mist was used in extinguishing large hot cooking oil fires. It was revealed that water mist not only extinguished large fires effectively but also cooled hot oil from its ignition point (up to 360°C) to below its flash point (200°C) and prevented the fire from re-igniting. No vapour explosion was observed in the experiments when water droplets touched the hot oil whose temperature was higher than the superheat-limited temperature of water. The boiling of water in the oil occurred during water mist discharge and a boiling layer with bubbles was generated and expanded in the oil pan. No boil-over or spillage of the oil over the container was observed in the experiments when water mist was discharged into the oil at high temperature (>300°C) but boil-over did occur in experiments when the water mist was discharged into oil at a

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relatively moderate temperature (~200^{o}C). In this paper, the mechanisms of cooling hot oil by water mist are investigated, and the formation and development of the bubble layer and boil-over during cooling are analyzed both experimentally and theoretically.

Key Words: water mist, fire extinguishment, cooling, hot liquid fuel fire, boiling, bubble and boil-over

NOMENCLATURE

A – fuel surface area (m^2),
c_p – Thermal capacity (J/mol.K),
D – Diameter of bubble (m),
H – Depth of oil or bubble layer (m),
ΔH_v – Enthalpy of vaporization,
k – Thermal conductivity of liquid (W/m.K),
L_{vw} – Latent heat of evaporation of water (kJ/mol),
m – Mass (kg),
$\dot{m}$ – Mass flow rate (kg/s),
P – Pressure (kPa),
$\dot{Q}_c$ – Cooling rate (kW),
r – Radium of bubble (m),
T – Temperature (K),
t – Time (s),

Greek symbols
α – thermal diffusivity,
ρ – density (kg/m^3)
σ – Surface tension

Subscripts
B – *Bubble*
b – *boiling*
oil – oil
w – water
v – vapour,

1. INTRODUCTION

Fire incidents, involving hot fuels/materials that have a temperature higher than the boiling temperature of water, can occur in many areas, such as crude fuel fires in hydrocarbon processing plants [1], cooking oil fires in food processing industries, households and restaurants [2-7] and asphalt fires in the roofing industry [8, 9]. Their size ranges from a small household cooking pan oil fire to a very large industrial oil cooker fire involving several hundred square feet of oil surface and tons of hot oils. The fuel or material during a fire incident can be heated to a few hundred degrees Celsius. Many commonly used fire suppressants can extinguish flames over the fuel surface but cannot effectively cool the hot fuel and prevent the fire from re-igniting [4, 5, 8].

Water has favorable thermal properties for extracting heat from fires and fuels. However, water is often avoided for use in suppressing hot liquid fuel fires due to concerns of vapour explosion and boil-over generated in firefighting, which could present danger to nearby personnel or firefighters [1, 4, 8, 9]. Vapour explosion can occur when water is introduced with a hot liquid. This phenomenon is often observed in our daily life and has been studied for many years [10 -13]. It is believed that the vapour explosion occurs when the water is superheated and vaporized very rapidly, without boiling, to its homogeneous nucleation temperature. Rapid vapour explosion can also occur in water-solid contact as reported by Manzello et al [14] in their tests when a water droplet penetrated a pool of hot peanut oil and reached the bottom of the container, while the temperature of the peanut oil (200°C) was lower than the superheat-limit temperature of water.

Boil-over can also occur, when water is introduced into the hot liquid. They are heated, generate large steam bubbles and expand in the hot fuel, which expels hot liquid over the top of the container and spreads on the ground [1]. This phenomenon was observed when fire-fighters tried to extinguish hot fuel or asphalt fires in hydrocarbon processing and the roofing industry. The fire can be intensified by a violent eruption and spreading of burning material, when the boil-over occurs. The spilled fuels can ignite and form a large surface fire when they meet hot objects. Unlike significant studies on the boil-over related to a fuel burning above a water layer [15-20], the investigation on the boil-over generated in fire suppression by water spray is very limited, and its behaviors and key factors affecting the phenomenon are not clear. The current recommendation for preventing such a boil-over is: don't use water to fight hot liquid fires.

However, water spray and water mist recently became favorable suppressants for providing protection for food processing industries and restaurants where hot cooking oil fires can occur, because of a lack of other appropriate suppressants for combating the hot oil fires as well as non-pollution requirements for the working environment [21]. During fire incidents, the cooking oil can be heated up to 400°C. It is required that not only the fire on the oil surface be extinguished, but also the oil must be cooled down to below its ignition point in the protection for commercial deep fat fryers [22] or below to 200^{o}C in the protection for the industrial oil cookers [23] from the burning point of the oil.

Nam [24] conducted a series of full-scale fire tests in which water spray was used to suppress large cooking oil fires associated with large industrial oil cookers. Test results showed that water spray was capable of extinguishing large oil fires and no vapour explosion was observed during suppression. However, massive boil-over occurred in every test and the oil was spilled onto the ground, resulting in a large surface fire. There was no detailed analysis on the oil boil-over generated in fire suppression by water spray, although this phenomenon was further reported in another his article [25].

The current authors have conducted a series of full-scale fire experiments and water mist was used to extinguish cooking oil fires in both commercial deep fat fryers and industrial oil cookers [26-30]. Fine water droplets effectively extinguished the fires and cooled the oil to prevent it from re-igniting. The boiling of water in the hot oil was observed but no oil was spilled outside of the equipment during fire suppression. The water mist system developed by authors has been approved for use in industrial oil cooker protection. During previous authors' studies, the extinguishing capability and mechanisms of water mist on the hot cooking oil fires were investigated, but the oil cooling process by water mist was not studied systematically.

This paper focuses on the cooling characteristics of the hot oil by water mist during fire suppression involving large industrial oil cookers. The effect of water mist parameters (water droplet size, flow rate, discharge pressure, etc.), different nozzles, oil pool size, oil depth and hood position on the oil cooling processes are investigated. Vapour explosion, the occurrence of boiling, the generation and development of the bubble layer and boil-over that occur in the cooling process are analyzed both experimentally and theoretically. Information obtained will be useful for designing water-based fire suppression systems, developing guidelines or standards for approving these systems, and in reducing injuries to personnel in the vicinity of the equipment or firefighters when fighting hot liquid fuel fires.

2. EXPERIMENTAL SETUP

Figure 1 is a schematic of the experimental setup. It includes an industrial oil cooker, a burner, various instrumentations, and a water mist system.

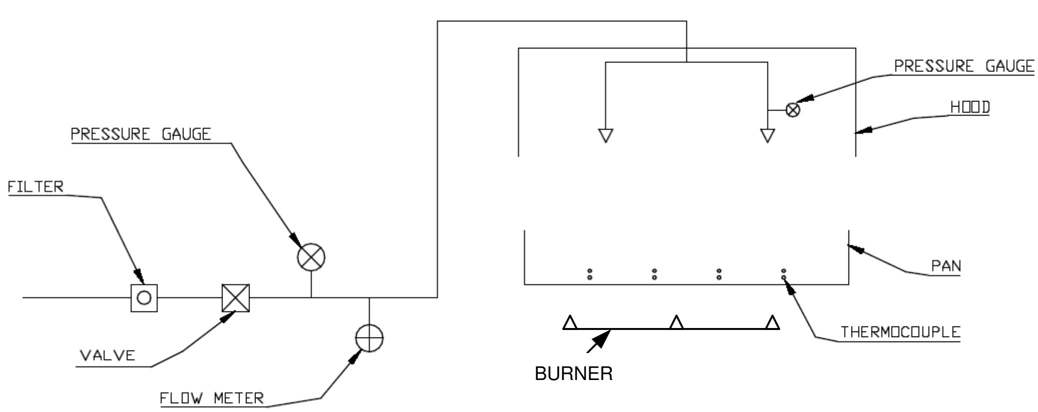


Figure 1. Schematic of experimental setup

2.1. Oil Pans

The industrial oil cooker consisted of a pan and a hood. A burner was centered beneath the pan in which the heat was distributed relatively uniformly throughout the pan surface. Four different sizes of oil cookers were constructed and used in the experiments. The pans of the oil cooker Mock-ups #1 to #3 had the same width (1.22 m) and depth (0.343 m), but their lengths were 1.22 m, 3.0 m and 4.5 m respectively. The pan for Mock-up #4 was 3.0 m long, 2.4 m wide and 0.343m deep. The detailed information on the construction of four mock-ups is provided in reference [29].

During experiments, the hood was placed in two different positions: namely a hood-up and a hood-down position. The clearance between the hood and the pan was 0.46 m for the hood-up position and 0.05 m for the hood-down position.

2.2. Oil

Canola oil was used as the testing oil in the experiments. The properties of the canola oil are listed in Table 1.

Table 1. Physical Property of Canola Oil [24, 31]

Flash Point (K)	Auto-ignition temperature (K)	Density (kg/L)	Viscosity (Kinematic at 20^{o}C, mm^{2}/s)	Specific heat (kJ/kg.K)	Thermal Conductivity (W/m.K)
505-563	603-633	0.914	78.2	1.91	0.179-0.188

Two depths of oil, 5.2 cm and 12.7 cm deep respectively, were used in the experiments. The oil surface to the edge of the pan for the two oil depths was 29.1 cm and 21.6 cm at room temperature. Approximately oil masses in the four cooker mock-ups at two oil depths are listed in Table 2.

Table 2. Oil mass in the mock-ups

Oil depth (cm)	Mock-up #1 (kg)	Mock-up #2 (kg)	Mock-up #3 (kg)	Mock-up #4 (kg)
5.2	–	–	–	342.4
12.7	173.6	420.4	694.6	836.3

2.3. Water Mist Systems

Two water mist fire suppression systems with single fluid nozzles were used in the experiments. Their spray performance, water density distribution over the pans and water collection rate in the pan were measured [30].

A single nozzle of water mist system #1 has a water flow rate ranging from 28.2 L/min at 414 kPa to 40.9 L/min at 862 kPa discharge pressure. Under a pressure of 550 kPa, 50 and 90 percentages of the spray volume are in drops smaller than 250 and 380 microns, respectively. The spray angle of the nozzle was 150 degrees and did not change with an increase in discharge pressure. The spray coverage area per nozzle was 1.22 m (4ft) wide x 1.22 m (4 ft) long for a single nozzle application and was extended to 1.22 m (4 ft) wide x 1.52 m (5 ft) long, when a multiple number of nozzles were used for a large oil surface. The number of nozzles installed in the four cooker mock-ups were 1, 2, 3 and 4, respectively, based on the sizes of the cooker pans. Each nozzle was installed in a vertically downward orientation inside the protected oil cooker. It was located at the center of its coverage area. The discharge distance from the nozzle tip to the bottom of the pan was maintained to be 0.93 m in the experiments. The water collection ratio of the system over the oil pan was changed with the discharge pressure and the size of the pan. The water collection ratio, under 689 kPa of discharge pressure, was approximately 65.8%, 81.2%, 88.3% and 85.2% for mock-ups #1 to #4.

Water mist system #2 consisted of a piping system with a number of swirl type nozzles. Its water droplets were relatively coarser, compared to water mist system #1. Under a pressure of 552 kPa (80 psi), 50 and 90 percentages of the spray volume in drops are smaller than 300 and 540 microns, respectively. Its water flow rate varied from 19.1 L/min at 414 kPa to 24.3 L/min at 862 kPa discharge pressure. Its spray angle was 120 degrees at 207 kPa of the discharge pressure and decreases to 80 degrees as the discharge pressure increases to 896 kPa. The nozzles were placed 1.03 m above the bottom of the pan. The spacing of the nozzles was 1.22 m x 1.00 m. Six nozzles were installed to cover the oil surface in Mock-up #4. Approximately 80.4% of discharged water from the system was collected by the pan.

2.4. Instrumentation

A number of thermocouple trees were placed along the centerline of the mock-up to measure fire and oil temperatures in the experiments. The number and locations of the thermocouple trees in the pan were determined by the size of the oil cooker mock-up. In addition, the number of thermocouples and their locations on each thermocouple tree were also changed in the experiments. For experiments involving Mock-up #4, three thermocouple trees were placed in the pan to measure oil and air/flame temperatures. Thermocouple tree #1 was placed in the center of the pan and thermocouple trees #2 and #3 were located 0.7 m apart from each other along the direction from the center of the pan to the southeast corner of the pan. Eight thermocouples (Type K, 18 gauge) were attached to each tree. The elevation of each thermocouple was 51 mm, 100 mm, 124mm, 165 mm, 254 mm, 381 mm, 681 mm and 981 mm above the bottom of the pan, when the oil depth at room temperature was 12.7 cm.

Two pressure gauges were used to monitor the discharge pressure of the water mist system. The first one was located in the inlet of the water mist piping system and another was located near one of the nozzles. One flow meter was used to measure the water flow rate of the system.

Two heat flux meters (air-cooled) were used to measure the radiant heat from the fire. The heat flux meters were located 0.5 m away from the pan and 1.2 m and 1.90 m, respectively, above the floor.

Two video cameras were used in the experiments to record the testing process and to assist in the identification of water mist discharge time, fire extinguishing time and water boiling in the oil. The first video camera was located 6 m away from the south side of the cooker to view the detailed suppression process, and the second one was placed 12 m away from the northwest side of the cooker to view the entire testing process.

The sound that was recorded by the video camera located at the south side of the cooker was also used for analyzing the fire suppression and cooling process in the experiments. A Norwegian Electronics real-time analyzer type 830 with a 0.3 Hz filter was used to analyze the sound pressure level (dB) and frequency (Hz) of the recorded sounds.

3. EXPERIMENTAL RESULTS AND DISCUSSION

During the experiments, fresh cooking oil was introduced into the pan. The oil was heated continuously at 3-5^{o}C/min until it auto-ignited. After the flame had spread over the entire oil surface, the fire was allowed to burn freely for more than 30 sec. At the end of the pre-burning period, the water mist discharge was activated manually. After the fire was extinguished, the discharge of water mist was maintained for a period of time to cool the cooking oil and to prevent it from re-ignition.

20 full-scale fire tests were conducted. They involved various testing conditions (oil pan size, hood position and fuel depth), two types of water mist systems and various operating conditions (discharge pressure, duration and discharged water quantity). For tests #1 to #13 involving Mock-ups #1 to #3, water mist system #1 was used and the oil depth in the mock-ups was maintained at 12.7 cm. However, the discharge pressures in the tests ranged from 595 kPa to 835 kPa and discharge durations from 65 s to 95 s. For tests #14 to #20 with Mock-up #4, two water mist systems and two oil depths were

involved. Their discharge pressures ranged from 414 kPa to 863 kPa and discharge durations from 22 s to 30 s. Detailed experimental conditions and results are shown in Table 3. The discharged water quantity that is listed in Table 3 is the total discharged water quantity of the system during fire suppression. The water quantity that reached the oil pan can be estimated, based on the total discharged water quantity and the collection rate of water in the pan.

The oil underwent a significant expansion in volume during heating. The oil depth was raised approximately from 12.7 cm at room temperature to higher than 16.5 cm at the ignition point [30]. The expansion in oil volume also resulted in a decrease in its density. Other changes in the oil properties included an increase in the specific heat or heat capacity, and a decrease in its viscosity. The specific heat of canola oil, C_p, at room temperature is 1.91 kJ/kg.K, but its average value at the temperature range of 20^{o}C to 160^{o}C increases to 2.5 kJ/kg.K [24].

Table 3: Fire Experimental Conditions and Results of Water Mist Systems

Test No.	Cooker No.	Ext. system	Oil depth (cm)	Dis. press. (kPa)	Hood position	Ignition temp. (^{o}C)	Ending temp (^{o}C)	Ext. time (s)	Dis. Duration (s)	Dis. Water quantity (kg)	Cooling rate (^{o}C/s)
1	#1	#1	12.7	635	Up	362	200	30	95	52.7	1.71
2	#1	#1	12.7	595	Up	357	238	33	85	45.9	1.40
3	#1	#1	12.7	828	Up	361	223	10	76	49	1.81
4	#1	#1	12.7	835	Down	358	226	3	75	48.3	1.76
5	#1	#1	12.7	718	Up	356	220	11	79	46.5	1.72
6	#1	#1	12.7	704	Down	355	208	4	88	51.1	1.67
7	#2	#1	12.7	718	Up	358	240	8	65	83.9	1.81
8	#2	#1	12.7	683	Up	356	210	6	89	102	1.64
9	#2	#1	12.7	670	Down	348	205	4	82	93	1.74
10	#3	#1	12.7	718	Up	355	225	8	73	141	1.78
11	#3	#1	12.7	670	Up	358	205	9	92	156	1.66
12	#3	#1	12.7	670	Up	359	217	9	78	132	1.82
13	#3	#1	12.7	676	Down	356	203	3	90	152	1.70

14	#4	#1	5.2	689	Up	356	260	4	22	50.6	4.36
15	#4	#1	5.2	414	Up	356	280	7	25	47	3.00
16	#4	#1	5.2	414	Down	357	295	5	22	41.4	2.81
17	#4	#1	12.7	414	Down	350	327	5	24	45	0.95
18	#4	#1	12.7	414	Up	351	327	7	23	43.2	1.04
19	#4	#2	5.2	690	Up	356	221	15	30	54	4.50
20	#4	#2	5.2	863	Up	357	230	18	27	56	4.71

The bulk of the oil auto-ignited at 343°C~362°C in the experiments. The oil temperature continuously increased during free burning as the heat was transferred back to the oil from the flame. The fire size encountered in the experiments ranged from approximately 2,600 kW to 13,000 kW, depending on the size of the oil pan.

As observed in the experiments, with the discharge of water mist, the flame below the nozzle tip was extinguished quickly due to flame quenching and oxygen dilution by water mist. Fine water droplets reached the hot oil and generated a large amount of steam as water droplets evaporated in the flame and on the oil surface (Figure 2). No burning oil was splashed during suppression. However, the flames near the ceiling of the hood, that were not directly hit by water mist, were not extinguished immediately and a part of them was pushed outside the cooker from the two ends of the hood. After a certain period of discharge, the entire flames were completely extinguished as the oil vapour generated from the oil was reduced due to the cooling. Both water mist systems effectively extinguished all the

Figure 2. Fire suppression by water mist at its initial stage

large cooking oil fires in 4~30 s. The extinguishing times were determined by the type of water mist system, discharge pressure and hood position [29].

3.1. Cooling of Oil

After the fire was extinguished, the discharge of water mist was maintained for a period of time to prevent re-ignition of the oil. During the 20 full-scale fire experiments, the oil was cooled down from its ignition point (>360^oC) to either below its flash point (<200^oC) or 30-35^oC below its ignition point in the tests with Mock-up #4. No re-ignition of the oil was observed. Figure 3 shows a typical variation of gas and oil temperatures with time during suppression, which was measured at Thermocouple Tree #1 located at the center of the pan. The flame temperatures over the oil surface quickly decreased with water mist discharge but it took a longer time to cool the oil down.

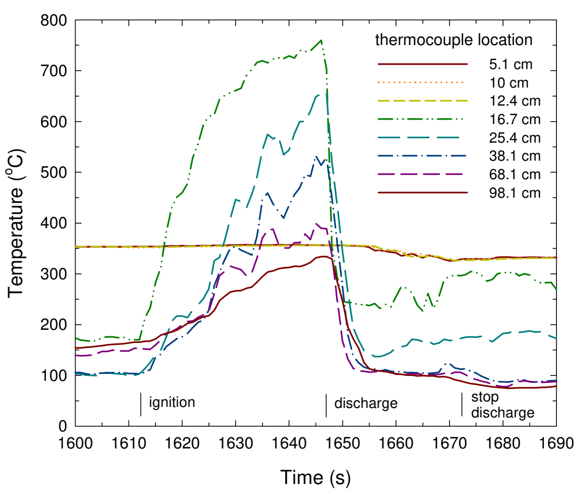


Figure 3. Variation of gas and oil temperatures with time (System #1, discharge pressure: 414 kPa, Mock-up #4)

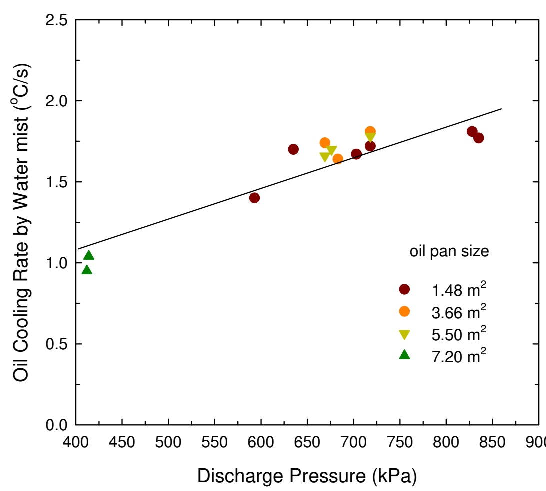


Figure 4. Variation of oil cooling rate by water with discharge pressure and oil pan size (System #1, 12.7 cm oil depth)

The oil cooling rate over the discharge of water mist, $\dot{Q}_{cwoil}$, is introduced to investigate the oil cooling by water mist and it is defined as:

$$\dot{Q}_{csoil} = (\frac{T_{oils} - T_{oile}}{t_w}) \text{ (}^{o}\text{C/s)} \quad (1)$$

where T_{oils} is the oil temperature at the end of pre-burn period, T_{oile} is the oil temperature after the end of water mist discharge, and t_w is the discharge duration of water mist.

The oil cooling rates under various testing conditions are listed in Table 3 and they change with the discharge pressure and oil depth or mass in the cooker pan. As shown in Figure 4 involving the same oil depth (12.7 cm) and extinguishing system in four mock-ups, the oil cooling rate by water mist tended to increase with an increase in discharge pressure, because more water was discharged into the pan. The oil cooling rate also significantly increased with the reduction in oil depth from 12.7 cm to 5.2 cm, as shown in Table 3 with Tests #15 to #18, since the ratio of water mass to oil mass in the pan increased with the reduction in oil depth.

The amount of water required for cooling the oil to a specific temperature can be approximately calculated from the energy balance between the oil and discharged water:

$$m_w(C_{pw}\Delta T_w + L_w) = m_{oil}C_{poil}\Delta T_{oil} \quad (2)$$

where the left side of the equation is the energy that water absorbs from the oil when it is assumed that the water droplets are heated from their room temperature to the boiling point ($\Delta \boldsymbol{T}_{water}$) and then fully evaporated into the steam ($\boldsymbol{L}_w$ - latent heat of evaporation of water), the right side of the equation is the energy that the oil loses when its cooling temperature difference is $\Delta \boldsymbol{T}_{oil}$.

Figure 5 shows the relationship between experimental and calculated water required for cooling different quantities of oil at a temperature difference $\Delta \boldsymbol{T}_{oil}$ =140^{o}C. For the calculated water in Figure 5, the specific heat of water used is 4.1 kJ/kg.K and the average specific heat of canola oil in the temperature range from 340^{o}C to 200^{o}C is estimated to be 3.1 kJ/kg.K, based on its values in the room temperature and its change in the range from the room temperature to 160^{o}C [24]. Figure 5 shows that both experimental and calculated water masses required for cooling demonstrate the same trend and linearly increase with an increase in the oil quantity in the pan. The water quantities required in experiments are close but higher than the calculated values, considering their losses in fire suppression and other error factors.

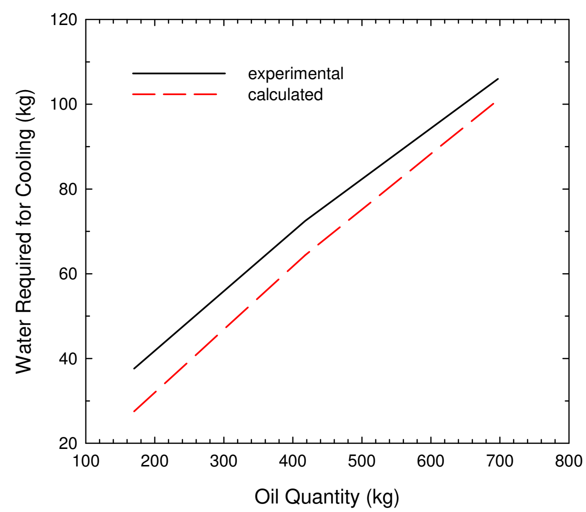


Figure 5. Relationship between experimental and calculated quantities of water required for cooling hot oil (at a temperature difference – 140^{o}C) with different quantities of oil

The detailed oil cooling process during fire suppression in Test #1 is shown in Figure 6, in which the oil temperatures were measured at three oil depths. Its experimental conditions were a 1.48 m^2 pan with an oil depth of 12.7 cm, and one nozzle of water mist system #1 with 635 kPa of discharge pressure and 95 s of discharge duration. The bulk of the oil was cooled down from 362^{o}C to 200^{o}C during the test. The oil cooling process can be divided into three phases during water mist discharge. Phase I occurred at the initial fire suppression stage, during which the oil temperature remained unchanged, because the fire was not fully controlled and the amount of water droplets that reached the oil surface was limited. Phase II of the cooling process occurred after the fire was controlled and extinguished. The oil temperature declined linearly as more water droplets directly hit onto the oil surface and absorbed heat from the oil. Phase III occurred at the water boiling period in the oil. The oil temperature sharply dropped with the onset of water boiling, and a bubble layer was formed in the oil, after then, the oil temperature in the bubble layer declined slowly. The occurrence and duration of each cooling phase changed with the oil depth, as shown in Figure 6. They also changed with the type and operating conditions of the water mist system as observed in the tests.

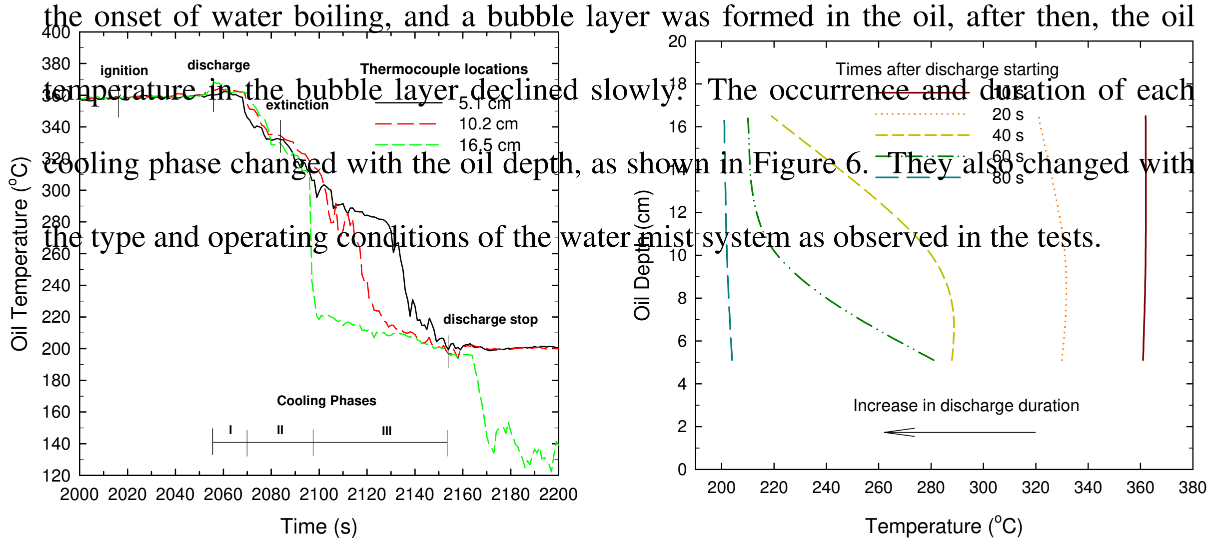
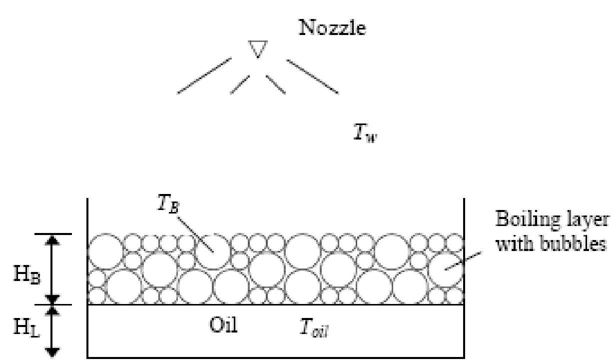


Figure 6. Variation of oil temperatures with time (System #1, discharge pressure: 635 kPa, 1.48 m^2 pan)

Figure 7. Variation of oil temperatures along oil depth with time after discharge starting (System #1, discharge pressure: 635 kPa, 1.48 m^2 pan)

Figure 7 further shows the variation of oil temperatures along the oil depth at different discharge times in Test #1. The oil cooling moved down from the oil surface to lower elevations with time as water droplets discharged from above and gradually sank into the oil. Two distinctive layers, one boiling layer with bubbles and one solid liquid layer, were formed in the oil once the boiling occurred, as shown in Figure 8. The boiling layer started from the upper layer of the oil and down to the deep oil. The temperature for the onset of the boiling decreased with an increase in the oil depth. For the experiment shown in Figure 6, temperatures for the onset of the boiling at oil depths

Figure 8. Schematic of oil cooling by water mist



of 16.5, 10.2 and 5.1 cm were 312°C, 307°C and 285°C respectively.

The temperatures in the bubble layer tended to be uniform both vertically and horizontally, as the hot oils were convectively mixed together with the generation, ascent and growth of the bubbles in the oil. The oil bubble layer rose up steadily in the pan as more water sank and expanded in the oil. The oil could be spilled outside the pan if the oil bubble layer continued to rise up beyond the edge of the pan. For Test #1, however, with the end of the water mist discharge, the rise of the bubble layer stopped before it reached the edge of the pan and the oil layer quickly faded. As shown in Figure 6, the temperature measured at 16.5 cm from the bottom of the pan significantly dropped at the end of the water mist discharge, because the thermocouple at this location was exposed to the air with the fading of the oil level in the pan. No oil spilled outside the pan or no boil-over occurred in Test #1.

3.2. Formation of Boiling Layer with Bubbles

The occurrence of the boil-over in the oil pan is dependent on the formation of bubbles, the expansion of the bubble layer in the oil, the gap between the oil surface and the edge of the pan and other factors. No violent vapour explosion was observed in the experiments when fine water droplets touched the hot oil at the initial discharge period. As indicated in the previous research [10], the temperature range for the occurrence of a vapour explosion is: $1 \le \frac{T_h}{T_{esl}} \le 1.1$, where T_h is the liquid temperature and T_{est} is its superheat-limit temperature. For the present experiments, the oil was heated to a temperature of 343°C~362°C, which was 14%~21% higher than the superheat-limit temperature of water (279 – 302°C). This is out of the temperature range for water vapour explosion. When water droplets touched the hot oil, a vapour film was quickly formed between two liquids, which shielded the water droplets from direct contact with the hot oil and prevented the vapour explosion.

With further water mist discharge, the oil was cooled down to near the superheat-limit temperature of water. The vapour blanket between two liquids collapsed, allowing water droplets to directly contact the hot oil. The nucleation then occurred spontaneously, leading to the onset of the boiling with formation of bubbles in the oil. Air/vapour entrained by the discharge of water spray could also act as the nuclei and increase the possibility of the formation of bubbles [10]. The formation or diameter of a bubble in the hot oil can be given [10]:

$$D_o = \frac{4\sigma(T_{oil})}{P_B(T_{oil}) - P_o} \qquad (3)$$

where P_o is the pressure in the bulk liquid, P_B is the bubble pressure and σ is the surface tension of bulk liquid. Both surface tension and the bubble pressure are directly related to oil temperature but they have opposite trends with the change in the oil temperature. High oil temperature leads to low surface tension, σ, but high bubble pressure, P_B.

As suggested in Equation (3), the bubble is either too small or not be formed if the liquid temperature is very high. This is consistent with the observation in the experiments: no boiling with bubbles occurred in Phase II of the cooling process in which the oil temperature was high. With continuously cooling , however, bubbles were generated in the oil. The temperature for the onset of boiling in the oil was in the range of 308°C to 315°C, as observed in present experiments.

Once the onset of boiling occurred, bubbles appeared and spread over the oil surface. At the same time, the temperature measured in the oil, as shown in Figure 6, dropped sharply and oscillated. One assumption for the change in the measured temperature is that with sudden formation of large bubbles in the oil, the temperature measured by the thermocouple was not the hot oil's but the vapour temperature inside the bubble that is much lower than the hot oil's temperature. The temperatures measured by thermocouples also oscillated with the formation of vapour bubbles, as the contacting interface of thermocouples oscillated between liquid and vapour. The oscillations in the measured temperatures during the formation of bubbles were also observed in the tests conducted by Nam [25].

Equation (3) further suggests that with a decrease in the oil temperature, the bubble will grow very quickly as bubble pressure decreases and the surface tension of oil increases. However, if the liquid temperature is too low, the pressure inside the bubble will not be sufficient enough to support the bubble growing or result in the collapse of the bubble. This suggests that there exists an optimum temperature region for fast bubble growth [10].

In order to understand the effect of oil temperature on the development of the bubble layer, an experiment (Test #4) was conducted in three phases at three different oil

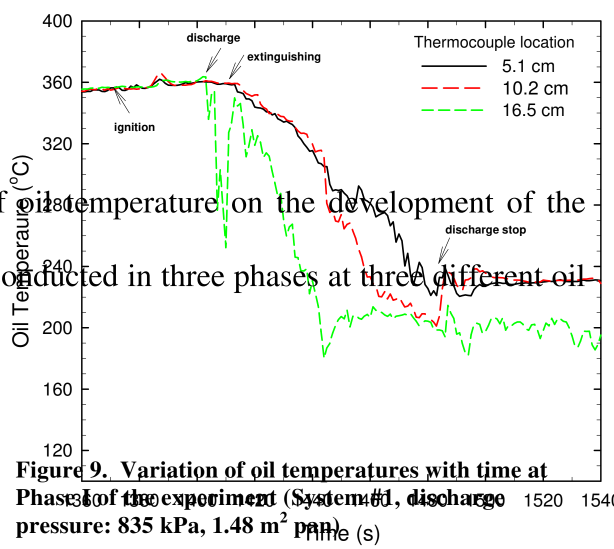


Figure 9. Variation of oil temperatures with time at Phase I of the experiment (System #1, discharge pressure: 835 kPa, 1.48 m² pan).

temperatures. The experimental conditions were a 1.48 m^2 pan with 12.7 cm deep oil, and one nozzle from water mist system #1, and its discharge pressure was maintained at 835 kPa during testing. As shown in Figure 9, in Phase I of the experiment, the fire was quickly extinguished and the oil was cooled down from a burning temperature of 358°C. The boiling of oil at a depth of 10.2 cm occurred when the oil temperature reached 311°C, after approximately 45 s of discharge. The bubble layer rose up steadily and reached the edge of the oil pan in 65 s from the beginning of boiling. However, no oil spilled outside the pan as the oil bubble layer quickly faded with the end of water mist discharge. The bulk of oil was cooled to approximately 230°C. No fire re-ignited on the oil surface.

Phase II of the experiment started at 134 s after the termination of the first water mist discharge (Figure 10). The oil temperature was 230°C and there was no fire on the oil surface. With discharge of water mist, the temperature measured at 16.5 cm from the bottom of the pan dropped to 57°C from 185°C as water droplets cooled the thermocouple, but it quickly bounced back, because the boiling spontaneously occurred in the oil, and the bubble layer expanded and rose up fast to reach the thermocouple. It took only 8 seconds for the oil at the depth of 10.2 cm to reach its boiling point. Temperatures at both oil depths of 10.2 cm and 16.5 cm tended to be equal. The

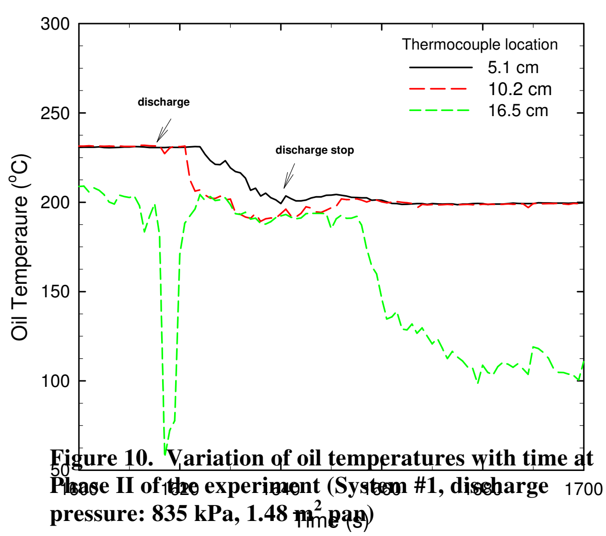


Figure 10. Variation of oil temperatures with time at Phase II of the experiment (System #1, discharge pressure: 835 kPa, 1.48 m^2 pan)

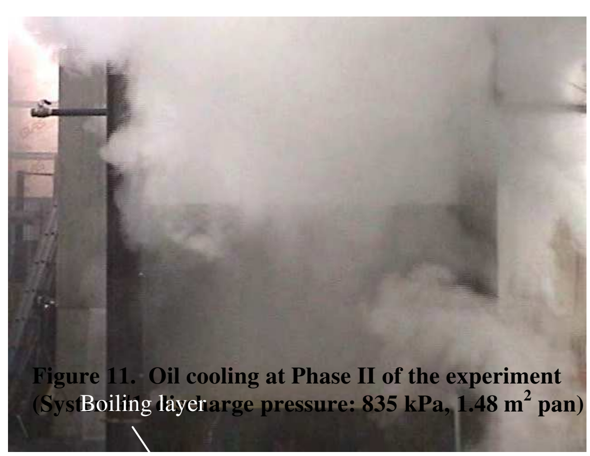


Figure 11. Oil cooling at Phase II of the experiment (System #1, discharge pressure: 835 kPa, 1.48 m^2 pan)

bubble layer rose up quickly and reached the edge of the pan in 5 s from the beginning of the discharge, as shown in Figure 11. With the termination of water mist discharge, the bubble layer did not quickly fade from the edge of the pan. Small amount of oils was expelled outside the pan during testing. During 18 s of the water mist discharge in Phase II, the bulk oil temperature was further cooled to 200°C.

Phase III of the experiment was conducted at 220 s after the termination of the second water mist discharge . The oil temperature was 200°C and there was no fire on the oil surface. The boiling with formation of bubbles occurred spontaneously with the discharge of water mist. It developed very quickly, and almost the entire amount of oil was involved in the boiling and temperatures at three different oil depths (5.1 cm, 10.2 cm and 16.5 cm) tended to be equal, as shown in Figure 12. The bubble layer quickly reached the edge of the pan in 3 seconds after activation of the water mist discharge and expelled massive oil outside the pan. As observed in the experiment and shown in Figure 13, the boil-over was vigorous and continued for a period of time even with the termination of the water mist discharge.

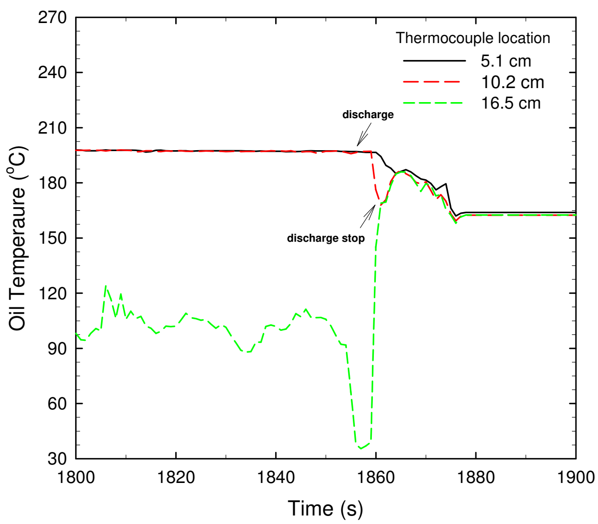


Figure 12c. Variation of oil temperatures with time at Phase III of the experiment (System #1, discharge pressure: 835 kPa, 1.48 m^2 pan)

Figure 13. Boil-over of the oil at Phase III of the experiment #4 (system #1, discharge pressure: 835 kPa, 1.48 m^2 pan)

3.3. Developing Rate of Boiling Layer in Oil

The boiling layer with bubbles will develop toward the deep oil, once the water droplets cannot be completely evaporated and sink in the oil. The developing rate of the boiling layer in the oil is determined by the energy balance between the oil and water, and can be expressed as:

$$\dot{m}_w (C_{pw} \Delta T_w + L_{vw}) - \rho_{oil} A_{oil} \frac{dH_{oil}}{dt} C_{poil} (T_{oil} - T_{Boil}) \geq 0 \tag{4}$$

or

$$\frac{dH_{oil}}{dt} = \frac{\dot{m}_w (C_{pw} \Delta T_w + L_{vw})}{\rho_{oil} A_{oil} C_{poil} (T_{oil} - T_{Boil})} \tag{5}$$

where T_{oil} is the oil temperature when water droplets reach the oil, and T_{Boil} is the temperature of the oil bubble layer in which the evaporation of water droplets is slowed down.

Equation (5) suggests the water quantity in the oil is one of the important factors to determine the development of the boiling layer. The more water in the oil, the faster the developing rate of the boiling layer with bubbles, as water droplets absorb more heat from oil. This conclusion was confirmed in the experiments, in which the developing rate of the boiling layer can be approximately calculated based on the oil depth and the time required to turn the oil into the boiling layer. As shown in Figure 14 involving tests with Mock-up #1, the developing rate of the boiling layer from the oil depth of 10.2 cm to 5.1 cm increases with an increase in the discharge pressure or water mass in the oil. , The developing rate of the boiling layer reduces with an increase in oil depth, as water available for cooling during sinking is reduced. In Test #1, as shown in Figure 6, the developing rate of the boiling layer is approximately 0.78 cm/s from the oil depth of 16.5 cm to 10.2 cm, but is reduced to 0.31 cm/s from the oil depth of 10.2 cm to 5.1 cm.

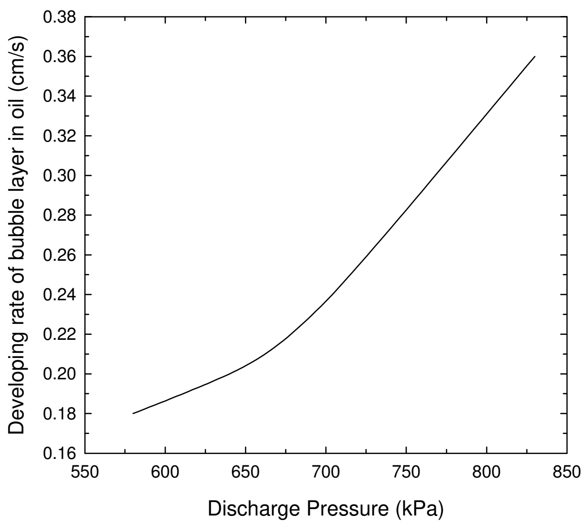


Figure 14. Variation of developing rate of bubble layer from oil depth of 10.2 cm to 5.1 cm with a change in discharge pressure (System #1, 1.48 m^2 pan)

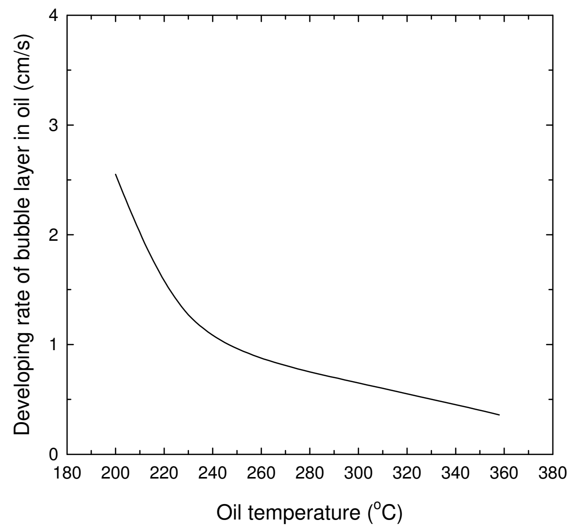


Figure 15. Variation of developing rate of bubble layer from oil depth of 10.2 cm to 5.1 cm with a change in oil temperature (System #1, discharge pressure: 835 kPa, 1.48 m^2 pan)

Equation (5) also suggests that when the water masses discharged into the oil are kept constant, the lower the oil temperature, the faster the development of the boiling layer in the oil, as the heat capacity of the oil is reduced and more water droplets cannot evaporate completely and penetrate more deeply into the oil. If the oil is close to its boiling layer temperature, the boiling could occur almost spontaneously throughout the oil with the discharge of water mist, depending on the sinking velocity of water droplets in the oil. These suggestions are consistent with experiment #4 with three different oil temperatures. As shown in Figure 15, the developing rate of the bubble layer from the oil depth of 10.2 cm to 5.2 cm is approximately 0.36 cm/s for the oil at the temperature of 360°C, but it then increases to 2.55 cm/s for the oil at the temperature of 200°C.

The developing rate of the boiling layer is not only determined by the discharged water flow rate and oil temperature but also by droplet size. For the same oil temperature, small droplets evaporate more quickly than large droplets before they sink into the oil. As observed in the present works and works conducted by Nam with sprinklers [24], the chance for the occurrence of boil-over during fire suppression with water mist was less than that with sprinklers. Further research is needed to study the effect of water droplet size on the boil-over.

3.4. Expansion Rate of Boiling Layer with Bubbles

Once the boiling layer is formed, it develops not only toward the deep oil but its level also expands in the pan as bubbles grow up and more water and oil are involved. The boil-over could occur if the boiling layer expands beyond the edge of the container. Potential boil-over and its intensity are determined by both developing and expansion rates of the bubble layer in the oil. The expansion rate of the bubble layer can be approximately expressed as:

$$\frac{dH_B}{dt} \propto (\dot{m}_{wb} + \dot{m}_{oilb})\frac{dr_b}{dt} \qquad (6)$$

where $\dot{m}_{wb}$ is the mass rate of water involving the bubble layer and given as:

$$\dot{m}_{wb} = \dot{m}_{wt} - \dot{m}_{we} \tag{7}$$

where $\dot{m}_{wt}$ is the total water mist discharge rate, $\dot{m}_{we}$ is the evaporation rate of water mist in the oil.

The mass rate of the oil involving the bubble layer in Equation (6), $\dot{m}_{oilb}$, is determined by the developing rate of the bubble layer in the oil that is expressed in Equation (5). The bubble growth rate in Equation (6), $\frac{dr_b}{dt}$, is given as [10]:

$$\frac{dr_b}{dt} \propto \frac{k(T_{oil} - T_b)}{\Delta H_v \rho_v (T_b)(\alpha t)^{0.5}} \tag{8}$$

Equations (6) to (8) suggest that the expansion rate of the bubble layer, like the developing rate of the bubble layer in the oil, is determined by both mass of water discharged and the oil temperature. At a high oil temperature, the bubble growth rate is high but the masses of water and oil involving the bubble layer are low as water droplets quickly evaporate, and at a low oil temperature, the bubble growth rate is low but the masses of water and oil involving the bubble layer are significant. This suggestion was supported by observations in the experiments: at a high oil temperature, it took a long time for the bubble layer to reach the edge of the pan, and the bubble layer quickly faded and disappeared from the oil surface with termination of the water mist discharge, as water droplets were quickly evaporated. At a low oil temperature, the bubble layer reached the edge of the pan quickly, and it faded slowly with termination of the water mist discharge, resulting in the boil-over, or spilling of a massive amount of oil outside the pan. As shown in Figure 16 involving three phases of experiment #4, the expansion rate of the bubble layer was approximately 1.6 cm/s at the oil temperature of 360°C in Phase I of the experiment, and it increased to 6.5 cm/s when the oil temperature decreased to 200°C in Phase III of the experiment, leading to massive boil-over. The expansion rate in Figure 16 is calculated based on the distance from the oil surface to the edge of the pan, and the time period from the start of the boiling in the oil to the time that the bubble layer reached the edge of the pan.

Figure 16. Variation of expansion rate of bubble layer with a change in oil temperature (System #1, discharge pressure: 835 kPa, 1.48 m^2 pan)

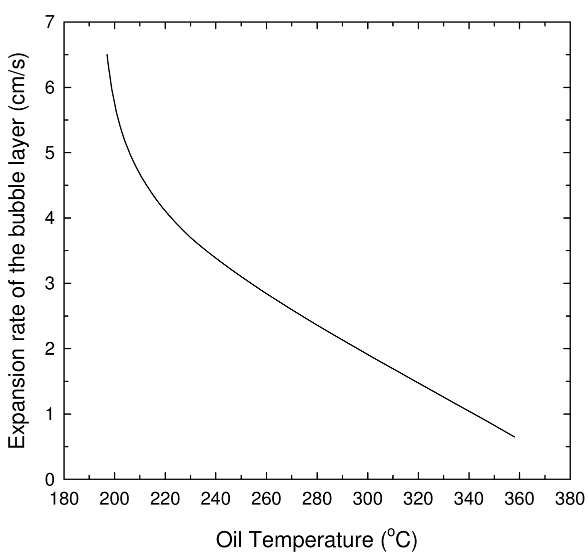
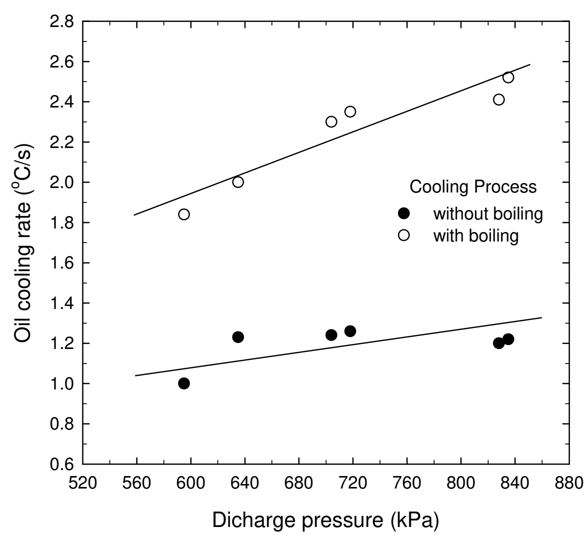


Figure 17. Variation of oil cooling rate with a change in discharge pressure of water mist (System #1, 1.48 m^2 pan)



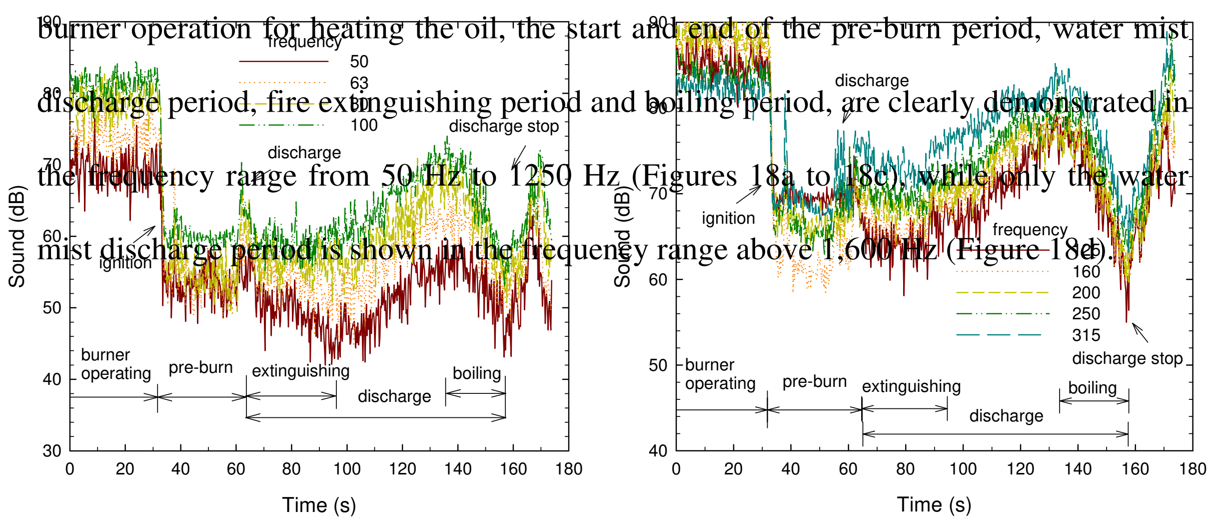
3.5. Effect of Boiling on Oil Cooling

For many present tests, the oil underwent the cooling processes with and without boiling. Figure 17 compares the oil cooling rates during cooling processes with and without oil boiling at different discharge pressures for Mock-up #1. Test results showed that the oil cooling rates in non-boiling period were lower than those in boiling period and they had also less increases with an increase in discharge pressure, compared to those in boiling period. This suggests that the boiling speeds up the oil cooling process and enhances heat transfer between hot oil and water droplets. This can be explained that the generation of the bubbles increases convective heat transfer in the oil and releases more hot vapour when the bubbles break up.

3.6. Sounds Generated in Fire Suppression and Cooling

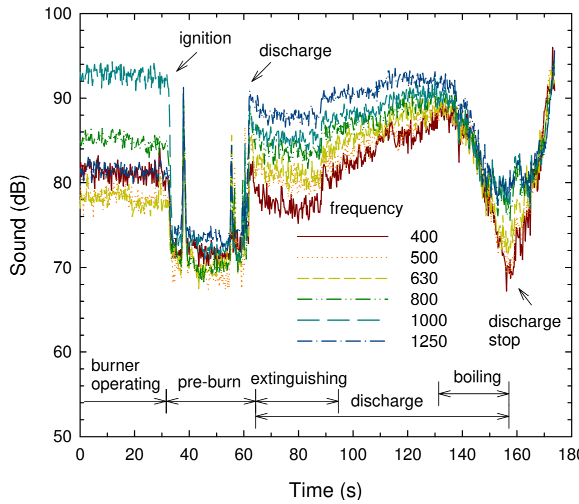
Various sounds were generated during the experiments and they can be used to describe the fire suppression and cooling processed, especially the occurrence of the boiling and expansion of the bubble layer in the pan. Figure 18 shows the variation of the sound pressure level and its frequency with time during Test #1.

As shown in Figure 18, each stage of the experiment, including the end of the burner operation for heating the oil, the start and end of the pre-burn period, water mist discharge period, fire extinguishing period and boiling period, are clearly demonstrated in the frequency range from 50 Hz to 1250 Hz (Figures 18a to 18c), while only the water mist discharge period is shown in the frequency range above 1,600 Hz (Figure 18d).

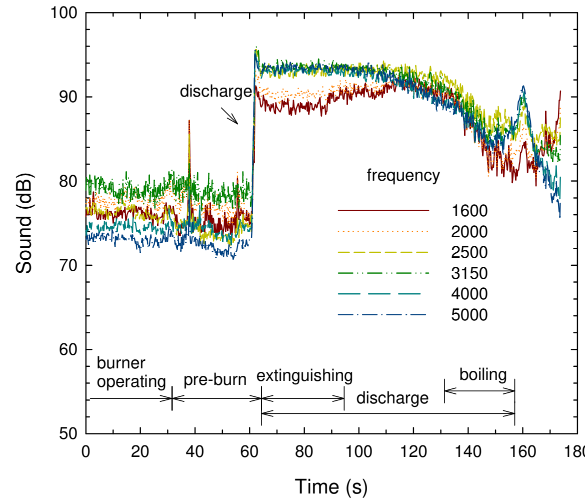


(18a). Frequency: 50-100 Hz

(18b). Frequency: 125-315 Hz



(18c). Frequency: 400-1250 Hz



(18d). Frequency: 1600-5000 Hz

Figure 18. Variation of sound pressure level and frequency with time in an experiment (System #1, discharge pressure: 635 kPa, 1.48 m^2 pan)

With the ignition on the oil surface, heating of the burner from the bottom of the pan stops, resulting in a relative silent pre-burn. The discharge of water mist from the nozzle at the end of the pre-burn period, as well as the evaporation of water in the flame and hot oil surface dramatically increases the sound level. The sound level is then reduced as the fire size is controlled and extinguished. After the fire is extinguished, numbers of water droplets that directly hit on the oil surface increase, resulting in an increase in sound, as the droplets vigorously vaporize in the hot oil. The occurrence of bubbles in the oil can be identified with characteristic bubbling sounds generated from the formation and break-up of the bubbles. The sound pressure level is also decreased with the growth of bubbles and the rising-up of the bubble layer in the pan, as the water droplets hit elastic bubbles. Reduction in the sound pressure level during the rising of the bubble layer is significant (approximately 30 dB difference from the formation of the bubble layer to the time when the bubble layer reaches the edge of the pan at a frequency of around 400 Hz), which can be used as a sign for preventing boil-over during fire suppression. Compared to the changes in the temperature measured in the oil, the occurrence of boiling measured by the sound pressure level is a few seconds later than that sensed by the thermocouples, because it takes a few more seconds for bubbles to grow and spread to the whole oil surface. After the termination of the water mist discharge, the bubble layer quickly faded and disappeared from the oil surface. Residual water droplets in the hot oil vapourized vigorously, resulting in an increase in the sound level.

4. CONCLUSIONS

The cooling of hot oil during fire suppression by water mist was investigated both experimentally and theoretically. Some findings from the present work are summarized as follows:

- Fine water mist showed effective extinguishing and cooling capability for large hot oil fires and they cooled very hot oil from its burning temperature (up to 365^{o}C) to the flash point (200^{o}C) in a short period of time. No fire re-ignited from the oil.
- The oil cooling rate by water mist increases with an increase in discharge pressure, and with the reduction in oil depth, as mass of water in the oil increases.

- No violent vapour explosion was observed in the experiments when water droplets touched the hot oil whose temperature was higher than the superheat-limited temperature of water. A vapour film was quickly formed between two liquids and shielded the water droplets from direct contact with the hot oil, preventing the vapour explosion.
- Bubble boiling occurred in the oil when the oil was cooled to a critical temperature. In the present work, critical oil temperature for the occurrence of bubble boiling was in the range of 308^{o}C to 315^{o}C.
- A boiling layer was generated and spread on the oil surface, once the bubble boiling occurred. This could be identified from a change in the sound pressure level and from a sharp drop in temperature. Two distinctive layers, one boiling layer with bubbles and one solid liquid layer, were formed in the oil after the occurrence of bubbles. The temperature in the bubble layer was much lower than the oil temperature and tended to be uniform throughout the whole bubble layer, as the hot oils were convectively mixed together with the generation, ascent and growth of the bubbles in the oil.
- The boiling layer with bubbles developed toward the deep oil and at the same time rose up in the container, as more bubbles were generated and expanded, and more water and oil were involved. The development of the bubble layer and its intensity were mainly determined by the water quantity involved and the oil temperature. The more water involved and the lower the oil temperature, the quicker the expanding speed of the bubble layer, resulting in the boil-over in the container, while the higher the oil temperature, the slower

the development of the bubble layer; in addition, the bubble layer also quickly faded with the end of water mist discharge, as water quickly evaporated in the hot oil. The developing rate of the boiling layer changed with the oil depth. The deeper the oil, the slower its developing rate. In addition, the water involved in the bubble layer is also associated with the size of water droplets and other factors, in which further research is needed.

- The boiling of the water in the hot liquid enhanced the heat transfer for the cooling by increasing convective heat transfer and releasing hot vapour on the oil surface.

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