Application of Water Mist to Extinguish Large Oil Pool Fires for Industrial Oil Cooker Protection

ZHIGANG LIU, DON CARPENTER, and ANDREW K. KIM
Fire Research Program, Institute for Research in Construction
National Research Council of Canada
Ottawa, Canada, K1A 0R6

ABSTRACT

Large oil fires occurring in industrial oil cookers are very challenging to extinguish due to their size and the large amount of hot oil involved. This paper reports a study to use water mist for large industrial oil cooker protection. The extinguishing mechanisms of water mist and corresponding criteria required for extinguishing large pool cooking oil fires were investigated both theoretically and experimentally. Based on the extinguishing mechanisms and required criteria, two water mist systems were developed in the present work. A series of full-scale fire tests were conducted in a large industrial oil cooker mock-up. The study showed that the two water mist systems presently developed worked effectively to extinguish large cooking oil fires and prevented them from re-igniting. Their extinguishing performance was determined by the type of water mist system, discharge pressure and hood position in the oil cooker.

KEYWORDS: water mist, fire suppression, cooking oil fire, industrial oil cooker

NOMENCLATURE

A	spray coverage (m^2)
C_p	specific heat (J/mol.K)
d	Diameter of water drop (m)
ΔH_c	heat of fuel combustion (kJ/mol)
f_c	fraction of heat that is transferred from flame to fuel
L_v	latent heat of evaporation (kJ/mol)
$\dot{m}_f$	oil burning rate (kg/ m^2s)
$\dot{m}_w$	water mist discharge rate (kg/s)
$\dot{Q}_E$	external heating flux (kW)
$\dot{Q}_L$	heat loss from the fuel (kW)
T	temperature (K)
u	velocity (m/s)
x	fraction of water mist that is suspended in flame
Greek	
ρ	density (kg/m^3)
φ	stoichiometric air/oil ratio
Subscripts	
f	fuel
w	water

INTRODUCTION

Industrial oil cookers are major equipment used in food processing plants for chicken, fish, potato products, doughnuts and other food products. They are typically conveyorized fryers, or occasional batch kettles. Industrial oil cookers contain cooking oil, varying from a few hundred liters to tens of thousands of liters, and their cooking surfaces vary from 4.6 m^2 (50 ft^2) to several hundred square feet [1,2].

A very severe fire could occur in industrial oil cookers by overheated cooking oil reaching its auto-ignition temperature due to a system malfunction or simple human

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error. The fires are very challenging to extinguish as they ignite at a very hot oil temperature, spreads rapidly over the oil surface and forms a large fire involving a very large oil surface and tons of hot oil. It requires flame extinction over the entire surface at once, and at the same time, rapid cooling of the oil to prevent re-igniting.

Fire suppressants that contain chemical components are not allowed for use in the food processing industry due to food safety considerations. Carbon dioxide is the most commonly-used agent for the protection of industrial oil cookers. It is capable of extinguishing flames over the oil surface, but it cannot effectively prevent hot oil from re-ignition, because carbon dioxide does not have sufficient cooling capacity to cool the oil below its auto-ignition temperature. Carbon dioxide is being considered for phasing out for use in industrial oil cooker protection.

The feasibility of using sprinkler water sprays for industrial oil cooker protection has been previously studied [2]. A series of full-scale fire tests were conducted in an outdoor facility involving three large industrial oil cooker mock-ups. Test results showed that water sprays extinguished oil fires in 10 to 145 s, depending on the cooker size and the sprinkler type. However, fire flare-up generated in fire suppression was pronounced and the interaction between the fire and the water spray was very intense. An extensive amount of oil was spilled over the oil cooker and formed large fires on the ground, as coarse water droplets sank and boiled up in the hot oil.

Water mist that consists of small water droplets (D_{v99} < 1000 μm) has been used to successfully extinguish various types of fires [3-5] as well as cooking oil fires in a commercial deep fat fryer without causing significant fire flare-up and re-ignition [6]. However, no research on usage of fine water mist against large cooking oil fires associated with the industrial oil cookers has been reported.

In this paper, a study of the use of fine water mist for industrial oil cooker protection is reported. The extinguishing mechanisms of water mist and corresponding criteria required for extinguishing large cooking oil pool fires are analyzed. A series of full-scale fire tests were conducted in a large industrial oil cooker mock-up. The performance of two water mist systems in extinguishing large cooking oil fires was evaluated in the full-scale tests. The impacts of the type of water mist system and their configurations, discharge pressure, oil quantity in the cooker, and hood position on the effectiveness of the water mist systems in suppressing large cooking oil fires were investigated.

EXTINGUISHING MECHANISMS AND CRITERIA REQUIRED FOR EXTINGUISHING LARGE COOKING OIL POOL FIRES

An oil fire in an industrial oil cooker is a pool fire situated in an open environment. When water mist is discharged onto a fire, as shown in Fig. 1, some fine water drops, $x\dot{m}_w$, are suspended in the flame and absorb the heat from the flame. Other water drops, $(1-x)\dot{m}_w$, penetrate through the flame and reach the oil surface. They cool the oil as water drops evaporate and absorb the heat from the oil, and produce a large amount of steam.

The flame that is directly hit by water mist can be extinguished, when the flame is cooled down to its low adiabatic temperature limit, resulting in the termination of the combustion reaction of the fuel-air mixture [4]. The energy balance of the flame at the low adiabatic flame temperature, T_{fl}, during fire suppression can be given as:

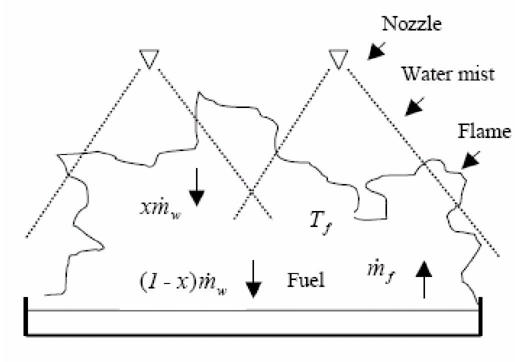

Fig. 1. Schematic of a pool fire suppressed by water mist.

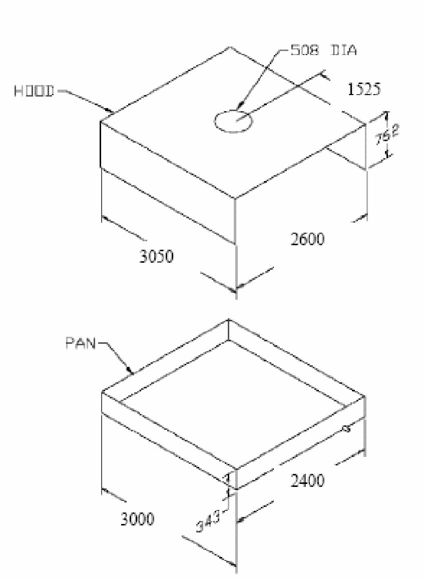

Fig. 2. Schematic of an industrial oil cooker mock-up.

$$\dot{m}_f \Delta H_c = x\dot{m}_w (L_{vw} + C_{pwL}(373 - T_w) + C_{pwv}(T_{fl} - 373)) + \dot{m}_f (C_{pf}(T_{fl} - T_{f0}) + \phi C_{pa}(T_{fl} - T_{a0}) + L_{vf}) \tag{1}$$

The left side of Eq. 1 is the heat released from the combustion of the fuel and the right side of Eq. 1 is the heat required for heating water and gas mixture to the flame temperature, T_{fl}. It is generally accepted that the low adiabatic temperature limit, T_{fl}, in which combustion cannot be sustained is around 1500 K [7].

An oil fire can also be extinguished when water droplets reach the oil surface and cool the oil below its fire point, as oil vapour generated from the oil is not sufficient enough in supporting the flames. The energy balance of the oil surface at the fire point during fire suppression by water mist is:

$$f_c \Delta H_c \dot{m}_f + \dot{Q}_E = L_{vf} \dot{m}_f + \dot{Q}_L \tag{2}$$

The left side of the Eq. 2 includes the energy transferred from the flame back to the oil surface and the external heating flux transferred to the oil that can be ignored for the present case. The right side of the Eq. 2 includes the energy required for gasification of the oil and the energy lost from the oil surface. During fire suppression, the heat loss from the oil surface is mainly caused by heating and evaporating water. Eq. 2 can be rewritten as:

$$S = (f_c \Delta H_c - L_{vf})\dot{m}_f - (1 - \mathrm{x})\dot{m}_w (L_{wv} + C_{pwL}(373 - T_w)) \tag{3}$$

When $S \geq 0,$ sufficient heat is available to maintain the flame on the oil surface and the combustion continues, however, when $S < 0,$ the heat will not be sufficient to produce fuel vapour to support the flame, resulting in the extinction of the flame. Normally, the fire point of a combustible material is higher than its flash point but lower than its ignition temperature [7]. The fraction of heat of combustion of the oil, f_c, that is transferred from the flame to the fuel is in the range of 0.1 to 0.4 [8].

Water flux, spray coverage and spray momentum are considered to be the three most important characteristics of water mist required for extinguishing a cooking oil fire [6]. As indicated in Eqs. 1 and 3, the fire cannot be extinguished unless the water quantity discharged from a water mist system is sufficient enough to extinguish the flame by removing sufficient heat from the flame, or to cool the oil below its fire point. The critical water mist flux required for extinguishing the flame, ($x\dot{m}_w$), and cooling the oil surface, ($(1-x)\dot{m}_w$), are given, respectively:

$$x\dot{m}_w = \frac{\dot{m}_f(\Delta H_c - C_{pf}(1500 - T_{f0}) - \phi C_{pa}(1500 - T_{a0}) - L_{vf})}{L_{vw} + C_{pwL}(373 - T_w) + C_{pwv}(1500 - 373)} \tag{4}$$

$$(1-x)\dot{m}_w = \frac{(f_c\Delta H_c - L_{vf})\dot{m}_f}{L_{vw} + C_{pwL}(373 - T_w)} \tag{5}$$

They suggest that critical water flux required is mainly determined by oil property, such as their heat of combustion, burning rate and adiabatic flame temperature.

Since a certain amount of water is required to extinguish a fire, water mist coverage must be large enough to cover the entire oil surface, which enables water mist to attack the flames and cool the oil over the whole oil surface. Those flames that are not directly attacked by water mist will not be extinguished and the heat released by the non-extinguished flames will counteract the cooling effect of the water mist on the oil, maintaining the flame on the oil surface. The water mist coverage, A_w, is determined by the spray angle, α, and discharge distance, *L*, to the fuel surface:

$$A_w = \pi(L\tan\frac{\alpha}{2})^2 \tag{6}$$

Water mist momentum is the third criterion required in extinguishing an oil fire. It must be sufficient enough to allow water droplets to penetrate the fire plume and reach the fuel surface. Water mist with low momentum will be carried away by the fire plume. To overcome the fire plume, the water mist momentum must be at least equal in magnitude, and opposite in direction, to the fire plume momentum.

The fire plume momentum is mainly determined by the heat release rate of the fire. The maximum upward velocity in a fire plume, $u_{f\max}$, is achieved in top of the flame [9]:

$$u_{f\max} = 1.9\dot{Q}_c^{0.2} \tag{7}$$

where $\dot{Q}_c$ is the convective heat release rate of the flame. Normally its relationship with the total heat release rate of the flame, $\dot{Q}$, can be expressed as [9]:

$$\dot{Q}_c = 0.7\dot{Q} \tag{8}$$

The water droplet momentum is mainly determined by the exit velocity of a water droplet at the nozzle, droplet size and discharge distance. Under non-evaporation conditions, the velocity of a water droplet, u_w, at the end of the discharge distance can be given [10]:

$$u_w = \frac{u_{wo}}{\exp(\frac{0.33\rho_g L}{d\rho_w})} \tag{9}$$

where u_{wo} is the exit velocity of the water droplet at the nozzle.

TEST FACILITY AND PROCEDURE

An industrial oil cooker mock-up that consisted of a pan and a hood was built (Fig. 2). The pan was 3.0 m long, 2.4 m wide and 0.343 m deep. The hood was 3.05 m long, 2.6 m wide, and 0.76 m deep. Both ends of the hood were open. There was a 0.51 m diameter hole on top of the hood to simulate the connection with the exhaust duct. A burner was centered beneath the pan in which the heat was distributed relatively uniformly throughout the pan surface. The propane gas was used in the burner to provide heating.

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 at the hood-up position and 0.05 m at the hood-down position.

Three thermocouple trees were placed in the pan to measure oil and air/flame temperatures. Tree #1 was placed in the center of the pan and 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. Their elevations were 51 mm, 100 mm, 124 mm, 165 mm, 254 mm, 381 mm, 681 mm and 981 mm, respectively, above the bottom of the pan, when the oil depth was 125 mm.

Two pressure gauges were used to monitor the discharge pressure of the mist system. The first one was located at the inlet of the mist system and another was located near one of the nozzles. A flow meter located at the inlet of the water mist system was used to measure the water flow rate. Two heat flux meters (air cooled) were placed, respectively, at the north and south sides of the cooker to measure the heat release rate of the fire, and possible fire flare-up.

Three video cameras were used in the experiments to record the testing process. One was located at the southeast side of the cooker, the second one at the west side of the cooker, and the third one was an aerial-view camera and elevated 7 m from the ground of the east side of the cooker.

Fresh cooking oil was introduced into the pan and then heated continuously at 3-5^{o}C/min until it auto-ignited. After the flame had spread over the whole oil surface, the fire was allowed to burn freely for 30 s, which ensures that there is sufficient time for people to evacuate from the oil cooker before the activation of a suppression system, according to requirement of the test protocol [1]. Heating was provided during the pre-burning until the start of the water mist discharge. At the end of the pre-burning period, the water mist discharge was activated manually. After the fire was extinguished, the water mist discharge was maintained for a certain time period to cool the oil and prevent them from re-ignition.

WATER MIST SYSTEMS AND THEIR SPRAY PERFORMANCE

Two water mist fire suppression systems with single fluid nozzles were developed and evaluated in the experiments. The spray performance of both single and group nozzles of two systems was studied. To measure the spray performance in the oil cooker, 23 sampling cups were placed on the bottom of the pan to measure water density distribution in the pan. They were distributed from the center of the pan along the longitudinal, transverse and diagonal axis of the pan. The distance between the cups was 20 cm. The amount of water collected in the cups was weighted after the water mist discharge. The total amount of water collected in the pan was determined by measuring the water depth in the pan. The water collection ratio in the pan was defined as the ratio of total water collected in the pan to the total water discharged by the mist system.

Water mist system I consisted of four MistShield nozzles. The nozzles were installed inside the mock-up and placed 0.93 m above the bottom of the pan. The spacing of the nozzles was 1.22 m x 1.52 m. The distance from the nozzles to the side walls of the pan was 0.6 m and to the ends of the pan was 0.75 m.

The water flow rate of a MistShield nozzle ranged from 28.2 L/min at 414 kPa to 40.9 L/min at 862 kPa discharge pressure. Water drops generated were relatively fine. Under a pressure of 552 kPa (80 psi), 50 and 90 percentages of the spray volume were in drops smaller than 250 and 380 μm, respectively. The spray angle of the nozzle was 150 degrees and not changed with an increase in discharge pressure.

Water mist generated by system I covered the whole oil pan surface. Fig. 3 shows the water density distribution over the pan under 552 kPa discharge pressure. Higher water density was distributed underneath the nozzles and the areas where water sprays overlapped. The water density at the corner of the pan was the lowest, while water density at the center of the pan was two times higher than that at the corner of the pan.

Under 414 kPa discharge pressure, the total water flow rate of water mist system I was 112.8 L/min and approximately 84.2% of the water discharged from the system was collected by the pan. The average water density in the pan was 13.2 L/m^2.min. With an increase in discharge pressure, the water densities in the pan increased but its spray coverage pattern did not change due to no change in the spray angle, as shown in Fig. 3.

Water mist system II consisted of six swirl type nozzles. The nozzles were installed inside the cooker mock-up and placed 1.03 m above the bottom of the pan. The spacing of the nozzles was 1.22 m x 1.00 m. The distance from the nozzles to the side walls of the pan was 0.6 m and to the ends of the pan was 0.5 m.

The water droplets generated by water mist system II were relatively coarser, compared to water mist system I. Under a pressure of 552 kPa, 50 and 90 percentages of the spray volume were in drops smaller than 300 and 540 μm, respectively. Its water flow rate varies from 19.1 L/min at 414 kPa to 24.3 L/min at 862 kPa discharge pressure. Its spray angle was substantially decreased with an increase in discharge pressure. Its spray angle was 120 degrees at 207 kPa of the discharge pressure, but decreased to 80 degrees at the discharge pressure of 896 kPa.

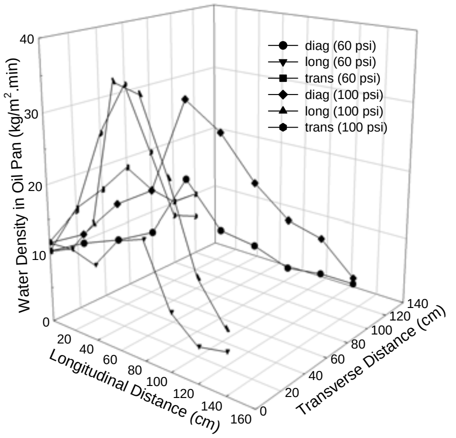

Fig. 3. Water density distribution of water mist system I in the oil pan.

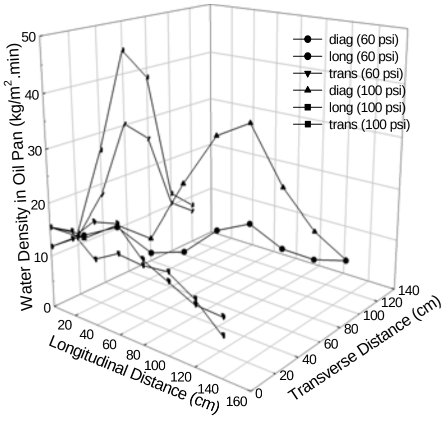

Fig. 4. Water density distribution of water mist system II in the oil pan.

The water collection ratio of water mist system II in the pan was lower than that with water mist system I. Under 414 kPa discharge pressure, the total water flow rate of system II was 114 L/min and its water collection rate was 80.4%. Its average water density in the pan was 12.7 L/min.m^2. With increasing discharge pressure, the water collection ratio and the average water density in the pan were increased.

Figure 4 shows water density distribution of water mist system II over the oil pan under 414 kPa discharge pressure. Its water spray also covered the whole oil pan, however, its spray pattern was different from that observed in water mist system I. High water density appeared underneath the nozzle, and the water density near the edge of the pan was higher than that with water mist system I, but the water density in the center area of the pan along the longitudinal direction was low. The water distribution pattern was also changed with discharge pressure. The water density along the longitudinal direction was reduced and tended to be uniform, while the peak water delivery density along the diagonal direction was shifted towards the edge of the pan, when the discharge pressure increased. These changes were caused by the reduction in the spray angle with increasing discharge pressure.

FIRE EXPERIMENTS

Canola oil was used as the cooking oil in the experiments. The properties of the canola oil at the room temperature are listed in Table 1.

Table 1. Physical property of canola oil [2,11].

Oil	Flash Point (K)	Auto-ignition temperature (K)	Density (kg/L)	Specific heat (kJ/kg.K)	Heat release rate (MW/m^2)
Canola	505-563	603-633	0.914	1.91	1.81

Seven full-scale fire experiments were conducted. The effect of hood position, discharge pressure, the type of the water mist system on water mist performance were examined. During the fire experiments, discharge pressures employed were 414 and 689 kPa, respectively, for water mist system I, and 689 and 827 kPa, respectively, for water mist system II. Testing conditions and results are listed in Table 2.

Table 2. Fire experimental conditions and results.

Test No.	Mist system	Discharge pre. (kPa)	Hood position	Pre-burn period (s)	Ignition temp. (K)	Ex. Time (s)	Discharge duration (s)
T-1	#1	689	up	38	629	4	20
T-2	#1	414	up	34	629	7	25
T-3	#2	689	up	35	633	15	29
T-4	#2	827	up	40	629	18	27
T-5	#1	414	down	35	630	5	22
T-6	#1	414	down	36	623	5	24
T-7	#1	414	up	42	624	7	23

Fresh canola oil was introduced in the pan in each experiment and heated continuously until it auto-ignited. After the oil was heated over 523 K, oil smoke appeared over the oil surface, and became very dense near the auto-ignition temperature. During seven experiments, the oil auto-ignited at temperatures ranging from 624 to 634 K. The flame consumed all the fuel vapour over the oil surface that was generated in the heating period and quickly spread to the whole oil surface once the oil auto-ignited.

During free burning, the fire was fully developed, filling inside the cooker and reaching outside the oil cooker. A large amount of dark smoke was produced. The fire size generated in the experiments was approximately 13.03 MW, based on canola oil’s property and the size of the oil pan used in the experiments. Experiments also showed that at the "hood-down" position, the fire grew more quickly than those at the “hood-up” position, because more heat was confined inside the cooker. Also, under the same heating source, the fire with shallow oil depth grew more quickly than that with deep oil depth and its oil temperature in the pan was relatively high due to higher heating rate.

Both water mist systems extinguished all the large cooking oil fires very effectively without substantial fire flare-up and burning oil being splashed outside the cooker. As observed in the experiments, with the discharge of water mist, the flame below the nozzle tip was extinguished quickly by flame quenching and oxygen dilution as the flame was hit directly by water mist and a large amount of steam was produced. 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 two ends of the hood. After a few more seconds of discharge, the entire flames were completely extinguished as the oil vapour generated from the oil was reduced, and more steams were produced to dilute oxygen and fuel available for the flame.

Figure 5 shows variation of temperatures measured above the oil surface at three different locations of thermocouple trees with time in Test 7. Once the water mist discharge was activated, the temperatures below the nozzle tip were quickly dropped as fine water drops cooled the flame, while the temperatures above the nozzle tip suddenly increased as some flames were pushed up. After the fire was extinguished, the temperatures far from the oil surface were cooled down to 323–353 K and tended to be uniform. However, the temperatures near the oil surface were still high, ranging from 473 to 613 K, as significant hot steam was produced. It also showed tha the temperature in the center of the pan was lower than that at the corner of the pan due to a difference in the water density distribution over the pan.

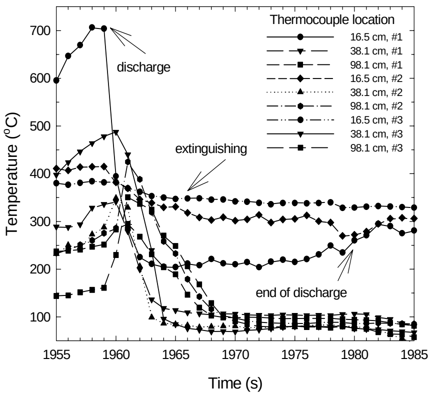

Fig. 5. Variation of temperatures above oil surface with time.

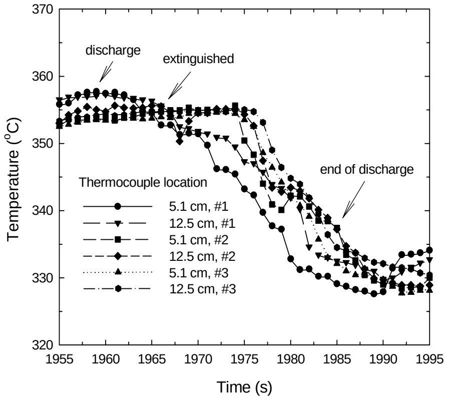

Fig. 6. Variation of oil temperatures with time.

During the experiments, the extinguishing times ranged from 4 to 18 s, depending on the type of water mist system, discharge pressure, and the hood position. Mist system I was more effective in extinguishing an oil fire than the system II. Under a discharge pressure of 689 kPa, water mist system I extinguished the fire in 4 s, while it took 15 s for water mist system II to extinguish the same size of oil fire. The excellent performance of water mist system I was attributed to its high water density, high water drop's velocity to reach the oil due to short penetration distance and large spray angle, compared to system II.

According to Eqs. 7 and 8, the maximum oil fire plume velocity was:

$$u_{f\,\max} = 1.9\dot{Q}_c^{0.2} = 1.9(0.7\times 13030)^{0.2} = 11.76 m/s \tag{10}$$

The maximum fire plume velocity is achieved at the tip of the flame height as the velocity is increased in the proportion to $Z^{0.5}$ of the vertical distance above the oil surface [7]. The fully developed oil flame height is much higher than the nozzle location of two water mist systems, based on its fire size. It suggests that the fire plume velocity encountered by water drops should be lower than its maximum velocity. The velocity of water droplets, on the other hand, decreases with an increase in penetration distance as they are shrinking and encountered with the upward fire plume. Approximate water droplet velocities reaching to the oil surface under non-evaporation conditions, discharged from two water mist systems, are listed in Table 3. The water droplet velocity is low for small droplets (<100 μm) but it substantially increased with an increase in droplet size and discharge pressure. The droplet velocity discharged from the system I is higher than that from the system II, when they reach the oil surface, due to their short penetration distance. Considering heavy mass density of water drops, their high discharge velocity and nozzle location in respect to the oil surface, the momentum of most water droplets discharged from two water mist systems under given working pressure were strong enough to overcome the fire plume momentum, and drops could penetrate through the fire plume and reach the oil surface. As shown in Fig. 5, the gas temperatures that were measured around 2 mm above the oil surface almost simultaneously dropped with activation of the water mist discharge, indicating that fine drops did reach the oil surface.

Table 3. Droplet velocity at the oil surface generated by two water mist systems.

Drop size		50 (μm)	100 (μm)	200 (μm)	300 (μm)	400 (μm)	500 (μm)
Velocity from System I (m/s)	414 (kPa)	0.14	2.04	7.66	11.8	14.8	16.9
	689 (kPa)	0.18	2.63	9.91	15.2	19.2	21.8
Velocity from System II (m/s)	689 (kPa)	0.09	1.91	8.42	13.8	17.6	20.5
	827 (kPa)	0.10	2.08	9.22	15.1	19.2	22.4

The critical water quantity required to extinguish the oil fire by cooling the flame or by cooling the oil can be approximately estimated from Eqs. 5 and 6. Based on the known properties of other cooking oils and hydrocarbon fuels [2,12,13], the heat of combustion and the burning rate of canola oil are given as 39,200 kJ/kg and 0.0462 kg/m^{2}s. The heat of gasification of canola oil is assumed to be 970 kJ/kg, the same value as ethyl alcohol in consideration of their similar burning rate (0.04 kg/ m^{2}s) [13]. The fraction of heat of combustion of the oil that is transferred from the flame to the fuel is assumed to be 0.1 in consideration of fine water drops and their vapors in the flame. The stoichiometric air/oil ratio of canola oil, like most of hydrocarbon fuels, is assumed to be 14.7 [7,13]. Heat capacity of the canola oil, steam, air and water is given, respectively to be 1.3, 2.1, 1.15, 4.2 kJ/kgK [13]. The oil surface temperature is assumed to be its ignition point, since its pre-burning period is very short. Thus, the critical water quantities required for extinguishing an oil fire are given, respectively, as:

$$x\dot{m}_{wc} = \frac{0.046(39200 - 1.3\times(1500-630) - 14.7\times 1.15\times(1500-298) - 970)}{2580 + 4.2\times(373-298) + 2.1\times(1500-373)} = 8.6 kg/m^2 \min \qquad (11)$$

$$(1-x)\dot{m}_{wc} = \frac{0.046(0.1\times 39200 - 970)}{2580 + 4.2\times(373-298)} = 2.8 kg/m^2 \min \qquad (12)$$

They are suggested that to extinguish an oil fire, more water is needed to cool the flame than to cool the oil due to the existence of fine water drops and vapor in the flame as well as the oil property. In the current work, the average water densities of two systems over the pan were 13.2 and 12.7 kg/m^2.min, respectively, under the lowest discharge pressure of 414 kPa employed in the experiment. They both were higher than the critical water quantity required for extinguishing a canola oil fire. In addition, the critical water flux required is reduced during fire suppression as the fire and its burning rate are reduced.

Increase in the discharge pressure resulted in an increase in the water flow rate and spray momentum. However, it did not mean that the performance of the water mist system would be improved with an increase in discharge pressure. For water mist system I, an increase in discharge pressure from 414 to 690 kPa reduced extinguishing time from 7 s to 4 s. However, for water mist system II, an increase in discharge pressure from 689 to 827 kPa resulted in increase in extinguishing time from 15 to 18 s. This is because an increase in discharge pressure did not change the spray angle of system I and its spray distribution pattern, but reduced the spray angle of system II, resulting in the reduction in the spray coverage area and changes in water density distribution. Some local water densities were reduced with an increase in discharge pressure. As observed in the experiments, during the fire suppression with water mist system II, the flame was pushed out only from two ends of the hood under low discharge pressure, while under higher discharge pressure, the flame was pushed out, not only from two ends of the hood, but also from two sides of the cooker due to the reduction in spray coverage.

Hood position in the oil cooker also had an impact on the extinguishing performance of the water mist system. For water mist system I under a discharge pressure of 414 kPa, the extinguishing time was reduced from 7 s to 5 s, when the hood was placed from the ‘up’ to the ‘down’ position. This is because the clearance between the nozzle tip and the hood ceiling was reduced in the “down” position, resulting in reduction in the amount of hot gases and flames near the ceiling that were not hit by water mist.

Water mist also demonstrated a strong cooling capability in fire suppression. Large amount of hot oil was quickly cooled below its auto-ignition temperature. Fig. 6 shows the variation of oil temperatures measured in Test 7 with 1000 L of oil. The average oil temperature was cooled down to 603 K from the burning temperature of 628 K during 23 s of water mist discharge. The oil cooling rate by water mist was approximately 65 K/min. The oil temperatures measured at the center of the pan cooled down more quickly than those at the corner of the pan due to the difference distribution of water density. In other experiments, the average oil temperature with 300 L of cooking oil in the pan was cooled down to 488–575 K from its burning temperature during 20–29 s of water mist discharges. The average oil temperature with 1000 L of cooking oil in the pan was dropped to 603–606 K during 23 to 24 s of water mist discharges. As the hot oil was quickly cooled down, no oil re-ignition was observed in the experiments. Experiments also showed that near the end of the water mist discharge, some water droplets sank into the oil and started to boil in the hot oil. However, no oil was spilled over the oil cooker in the experiments, since the bubbles generated in the boiling of fine water droplets were very small. The steam quickly disappeared from the oil after the end of water mist discharge, indicating that there was no more water in the oil.

The results obtained from the experiments were consistent with the theoretical analysis, showing that cooling of the flame and cooling of the oil were the primary extinguishing mechanisms of cooking oil fires by water mist. To extinguish a cooking oil fire, it must have sufficient water flow rate to cool the flame and oil, sufficient coverage area to cover the whole oil surface and sufficient spray momentum to penetrate through the flame.

SUMMARY

Flame and oil cooling are two dominant extinguishing mechanisms of water mist for large cooking oil pool fires. It requires that the employed water mist systems shall have sufficient spray coverage, water flow rate and spray momentum. Both water mist systems developed in the current work were effective in extinguishing the cooking oil fires. Their extinguishing performance was determined by the type of water mist system employed, discharge pressure, and the hood position. Water mist system I had a better performance than water mist system II due to their fine drops and large spray angle. Increase in discharge pressure improved the performance of system I but resulted in longer extinguishing time for system II due to the changes in the spray coverage and water density distribution. Water mist extinguished the cooking oil fire more quickly at the hood ‘down’ position than at the ‘up’ position due to a reduction in the amount of hot gases and flames near the ceiling of the hood. Water mist also effectively cooled hot oil and prevented it from re-ignition. No oil splashing was observed in the experiments. The current work also studies the flame quenching by water mist, the critical water quantities and spray momentum required for extinguishing a fire and more future works on these analyses are needed.

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