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Extinguishment of Cooking Oil Fires by Water Mist Fire Suppression Systems*

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ABSTRACT

A series of full-scale experiments were conducted in a mock-up commercial cooking area to study extinguishing mechanisms and effectiveness of water mist against cooking oil fires. The impact of water mist characteristics, such as spray angle, droplet size, flow rate, discharge pressure and type of nozzle, on the effectiveness of water mist against cooking oil fires was investigated. A series of oil splash experiments were also conducted to determine if the oil was splashed by water mist. In addition, the change in oil composition during heating and fire suppression was determined using Fourier Transform Infrared (FTIR) technique.

The study showed that cooking oil fires were very difficult to extinguish, because they burned at high temperature and re-ignited easily due to changes in oil composition during heating and fire suppression. The water mist systems developed in the present work effectively extinguished cooking oil fires and prevented them from re-ignition. The spray angle, discharge pressure, and water flow rate were important factors to determine the effectiveness of water mist in extinguishing cooking oil fires.

Key Words: water mist, fire suppression, cooking oil fire, re-ignition, oil splash

NOMENCLATURE

C_{pw} - Thermal capacity of the water (J/mol.K),
 D - diameter of the drop (m),
 $D_{v0.9}$ - drop diameter such that 90% of the total liquid volume is in drops of smaller diameter,
 ΔH_c - Heat of combustion of the fuel (kJ/mol),
 f_c - Fraction of heat of combustion of the fuel (ΔH_c) that is transferred from the flame to the fuel,
 K - Thermal conductivity (W/m.K),
 L_{vf} - Latent heat of evaporation of the fuel (kJ/mol),
 L_{vw} - Latent heat of evaporation of water (kJ/mol),
 $\vec{M}_f$ - fire spray momentum,

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$\vec{M}_w$ - water spray momentum,
 $\dot{m}_f$ - oil burning rate,
 $\dot{m}_w$ - water mist discharge rate (kg/s) that reaches the oil,
 m_{fp} , m_{fg} , m_{fa} - mass of combustion products, fire gases and air entrained by the fire plume,
 m_{wl} , m_{wv} , m_{wa} - mass of water, water vapour and air entrained by the water mist,
 P - discharge pressure (Pa),
 $\dot{Q}_E$ - External heating flux transferred to the fuel (kW),
 $\dot{Q}_L$ - Heat loss from the fuel (kW),
 S - Rate of transfer of 'sensible heat' at the surface area of the fuel,
 T_{fs} - Fuel surface temperature (K),
 T_{fo} - Fuel temperature inside the fuel (K),
 T_w - Water droplet temperature (K),
 $\vec{V}_w$ - velocity vector of the water mist,
 $\vec{V}_f$ - velocity vector of the fire plume,
 V - drop velocity (m/s),
 ρ - water density (kg/m³),
 δ - Thickness of heating layer below the fuel surface (m),
 ε - Emissivity,
 σ - Stefan-Boltzmann constant (5.67 X 10⁻⁸ W/m².K⁴)

INTRODUCTION

In recent years, development of high-efficiency cooking equipment with high energy input rates and the widespread use of vegetable oils that have a high auto-ignition temperature, have increased potential risks to life and property loss by fire in commercial cooking areas. Statistics have shown that almost 50% of all accidental fires in hotels, restaurants and fast food outlets start in kitchens, and the majority of these involve liquid cooking oil or fat fires [1, 2]. In addition, cooking oil fires are also a primary cause of household fires [3, 4]. In 1997, nearly 30% of residential fires in Canada were related to cooking fires, which resulted in 51 deaths, 653 injuries and \$72.6 million property loss [5].

Commonly used cooking oils include canola, corn, cotton seed, palm, peanut and soybean oils. They have flash points in the broad range from 160 to 282°C and their auto-ignition temperatures vary from 315 to 445°C [6]. Average burning rates of cooking oils are higher than other hydrocarbon oils [4].

Compared to other types of fires, cooking oil fires are very difficult to extinguish. During cooking, the oil is heated to high temperature approaching its flash point. Once the oil auto-ignites, it is difficult to cool the bulk of the oil (up to 36.3 kg of oil in the commercial fryer) to below its auto-ignition temperature. Modern energy-efficient fryers are designed to retain more heat to minimize fuel costs, which retards the dissipation of heat from the hot cooking oil

in the event of a fire. The composition of cooking oil is also changed during heating, resulting in a new auto-ignition temperature that may be as much as 28°C lower than its original auto-ignition temperature [7]. Unless the oil is cooled below its new auto-ignition temperature, the fire would re-ignite after extinguishment. Since cooking oil fires have a different behaviour from other types of flammable liquid fires, they have recently been classified as a special class of fire (Class K) [8].

Previous research showed that foam, powder and carbon dioxide can effectively extinguish the flames over the oil surface but they are very difficult to cool the oil below its auto-ignition temperature and to prevent it from re-ignition due to their limited cooling capacity [1, 2]. Wet chemical agents are the most common agents used in commercial cooking areas. They are effective in extinguishing cooking oil fires, but it takes a long time for a wet chemical agent to cool the oil below its auto-ignition temperature, depending on agent quantity used [9]. They may cause irritation to the skin and eyes [10] and clean-up problems after fire extinguishment. The system cost of wet chemical agents is relatively high.

Water mist fire suppression systems have demonstrated their effectiveness in suppressing various types of fires, and presenting no toxic and environmental problems. There is very little clean-up after fire suppression using water mist, and the building can be re-occupied and become operational in a very short time, which is a great benefit for the occupants/owners of the facilities [11, 12]. Over the last decade, water mist suppression systems have been used to replace halons for the protection of machinery spaces, ships and electronic equipment [13-15]. Water mist has also been used for applications where traditional technologies have not been effective [16, 17]. For example, water mist fire suppression systems are used to extinguish flammable liquid fires that conventional sprinkler systems cannot extinguish due to splashing and spillage of the fuel.

A water mist system also has the potential to be a cost-effective suppression system for the cooking oil fires. However, currently there is little information available on the performance of water mist system in extinguishing cooking oil fires. The characteristics of cooking oil fire and depression of cooking oil's auto-ignition temperature in fire suppression are not understood.

The objective of the present work was to develop a water mist system to effectively extinguish cooking oil fires. In order to achieve this goal, the mechanisms of water mist in extinguishing cooking oil fires were investigated, and the impact of water mist characteristics (e.g., discharge pressure, flow rate, spray coverage area and nozzle location, etc.) on the effectiveness of water mist in suppressing cooking oil fires as well as on potential oil splashing were studied in the present work. In addition, characteristics of the cooking oil and its fire in the heating and burning periods were examined. Fourier Transform Infrared (FTIR) techniques were used to study the changes in oil composition, and their effects on the depression of cooking oil's auto-ignition temperature.

EXPERIMENTAL FACILITIES

A series of full-scale fire tests was conducted in a mock-up restaurant cooking area (see Figure 1), in accordance with UL 300 “Standard for Fire Testing of Fire Extinguishing Systems for Protection of Restaurant Cooking Areas” [18].

A deep fat fryer was placed directly under an overhead hood. Its frying area was 305 mm x 381 mm (12 in x 15 in) and it had a capacity ranging from a minimum of 15 L (30 lb) to a maximum of 20 L (40 lb) of shortening. The hood was constructed of stainless steel with a minimum thickness of 2 mm. A 254 mm diameter exhaust duct was installed and connected to the top of the hood. An exhaust fan was used to vent hot gases and vapours out of the cooking area. The installation of the deep fat fryer and the overhead hood as well as the distance between the two pieces of equipment, were based on manufacturers’ recommendations.

During each test, a fresh commercial vegetable oil (a mix of canola and soybean oils) with an auto-ignition temperature above 365°C (690°F) was used.

A water mist nozzle was located at the front of the hood and aimed at the centre of the cooking area. The distance of the nozzle from the fuel surface varied between 860 mm and 1100 mm in different experiments.

A thermocouple tree with four thermocouples was used to measure flame and oil temperatures (Thermocouples 1-4). As shown in Figure 1, Thermocouple #1 was located 25.4 mm below the surface of the oil and 80 mm from the side wall of the fryer to measure the cooking oil temperature. Three other thermocouples (Thermocouples #2 - #4) were located above the oil surface to measure air and flame temperatures. One additional

Figure 1. Experimental set-up of deep fat fryer, hood, duct, water mist system and temperature measurement

thermocouple (Thermocouple #5) was attached to the top of the fryer's metal surface to measure its temperature (see Figure 1).

A pressure transducer was installed in the pipe near the nozzle to monitor the discharge pressure of the water mist system.

All experimental data were recorded by a data acquisition system with 1 s sampling interval. Two video cameras were used to provide visual records of the cooking oil fire, water mist discharge, oil splashing and fire suppression.

A BioRad FTS 175 FTIR spectrometer was used to characterize the virgin cooking oil and to identify the functional groups of new components formed during the tests. The oil was sampled at different oil temperatures as well as after the fire was extinguished by water mist. The oil specimens were then analysed using the FTIR (0.5 cm^{-1} resolution).

WATER MIST FIRE SUPPRESSION SYSTEMS

Three water mist fire suppression systems with three types of commercially available single-fluid water mist nozzles were developed and evaluated in full-scale experiments. The discharge pressures of the three systems varied from low pressure (2 bar) to high pressure (70 bar) and water flow rates varied from 1.4 Lpm to 28.3 Lpm. The spray characteristics and performance data for each type of nozzles provided by the manufacturers are listed in Table 1. The droplet size produced by the nozzle #1 was $D_{v0.9}=120$ microns at discharge pressure of 35 bar, and the droplet size produced by the nozzles #2 and #3 was $D_{v0.9}=170$, and 200 microns, respectively, at discharge pressures of 21 bar, based on information provided by the manufacturer.

Table 1 Spray Characteristics and Performance Data of Three Types of Nozzles

Nozzle No.	Type	Discharge Pressure (bar)	Flow Rate (L/min)	Spray Angle	Spray Characteristics
No 1	Single-fluid	2 to 70	1.42 to 8.1	67° at 20.5 bar discharge pressure	Small flow rate, very fine spray and hollow cone
No 2	Single-fluid	2 to 27	2.62 to 16.5	60°	Clog-free, and fine atomization
No 3	Single-fluid	2 to 27	4.76 to 28.7	90°	Fine spray and high flow rate

A stainless steel pipe, with a uniform diameter of 19.1 mm outside and 16.2 mm inside, was used to connect the nozzle with a water cylinder and three compressed air cylinders. The total length of the pipe was approximately 5.5 m. The water cylinder had a maximum capacity of 45 L of water. Three compressed air cylinders were used to provide stable discharge pressures of up to 70 bar. The water mist system and its piping network are shown in Figure 2.

In addition, one cylinder containing both water and compressed air was also used in a test to investigate the effect of descending discharge pressure on the performance of water mist.

EXPERIMENTAL PROCEDURES

Two types of full-scale fire experiments were conducted. In the first type of experiments, the fresh liquid cooking oil was heated in the rate of 8 to 12°C/min. When the cooking oil auto-ignited, the fire was allowed to burn freely with the heating source remaining on for an additional 2 minutes. At the end of the free burning period, the heating source was shut off and 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 cooking oil and to prevent the oil from re-ignition.

In the second type of experiments, the fresh cooking oil was heated to around 190°C and a splash experiment was conducted to determine if the oil would be splashed out of the fryer as a result of the discharge of the water mist. A 5 s water mist discharge period was allowed in the splash experiment, with the heating source remaining on. The changes in cooking oil temperature and any potential splash of oil caused by the water mist discharge were recorded. After the water mist discharge was stopped, the water in the hot oil quickly evaporated. As observed in the experiments, the cooking oil was not affected by the short period of the water mist discharge. It was heated continuously and the subsequent testing procedures involving fire extinguishment by water mist was the same as the first type of experiments.

RESULTS AND DISCUSSION

Table 2 summarizes experimental conditions and results with three water mist systems. Characteristics of cooking oil fires, oil splash caused by the water mist discharge as well as the effectiveness of water mist against cooking oil fires under different operating conditions were investigated in the full-scale experiments.

Table 2 Full-Scale Fire Test Conditions and Results

Test No	Water mist system	Nozzle Height (m)	Discharge Pressure (bar)	Splash Test	Extinguishing Test
K-1	No 3	0.86	24	no	Fire was extinguished at 1 s with short water mist discharge but re-ignited twice after the discharge was stopped.
K-2	No 3	0.86	24	no	Oil was sampled at different temperatures and analyzed by FTIR. Fire was extinguished at 1 s
K-3	No 1	1.1	Increased from 27 to 48	yes	Fire was not extinguished during 90 s discharge.
K-4	No 2	1.1	13	yes	Fire was extinguished at 15 s after discharge and no re-ignition
K-5	No 3	1.1	Increased from 4 to 13	no	Fire was not extinguished until the discharge pressure reached 13 bar.
K-6	No 3	1.1	13	no	Fire was extinguished at 15 s after discharge and no re-ignition.
K-7	No 3	1.1	28.5	yes	Fire was extinguished at 1 s and no re-ignition
K-8	No 3	1.1	16.5	yes	Fire was extinguished at 6 s after discharge and no re-ignition.
K-9	No 3	0.86	28.5	yes	Fire was extinguished at 1 s and no re-ignition
K-10	No 3	0.86	13	yes	Fire was extinguished at 2 s after discharge and no re-ignition
K-11	No 3	0.97	13	yes	Fire was extinguished at 8 s after discharge and no re-ignition.
K-12	No 3	1.1	Reduced from 17.2 to 11.5	no	Fire was extinguished at 2 s after discharge and no re-ignition.

Characteristics of Cooking Oil Fires

The cooking oil auto-ignited when it reached its auto-ignition temperature with continuous heating. The auto-ignition temperature of the cooking oil measured in the 12 full-scale experiments varied from 365°C to 372°C. During the subsequent 2 min free burning period, the fire developed from a small fire attached to the oil surface to a fully developed fire

reaching the overhead hood (see Figure 3). The fire growth rate accelerated after the first minute of free burning.

Figure 3. A cooking oil fire at 1 min 50 sec of the free burning

Figure 4 shows the variation of the cooking oil temperature with time in an experiment. The rate of oil temperature rise was $8^{\circ}\text{C}/\text{min}$ during the heating period. The oil auto-ignited at 368°C . With the large flame over the oil surface, the rate of oil temperature rise increased to $14^{\circ}\text{C}/\text{min}$, and the oil was further heated to 396°C at end of the free burning period. The highest oil temperature measured in the free burning period among the 12 full-scale experiments was 403°C , which was 38°C higher than its initial auto-ignition temperature.

Figure 4 The variation of cooking oil temperature during free burn period

With water mist discharge, the cooking oil fire was extinguished and the oil was cooled down. However, the oil compositions were changed during free burning and fire suppression periods, resulting in the decrease in its auto-ignition temperature. The oil tended to auto-re-ignite at a lower temperature. In the experiment (Test K-1) with short periods of water mist discharge, auto-re-ignition of the cooking oil occurred twice, shortly after the water mist discharge was discontinued. The change in the auto-ignition temperature of the oil in the experiment is shown in Figures 5a and 5b, respectively. Figure 5a shows the oil and flame temperatures during both the free burn and fire suppression periods, while Figure 5b shows the oil and flame temperatures in detail during the fire suppression period at the same experiment. During the free burning period, the flame temperature near the oil surface was approximately 800°C and the cooking oil was heated to approximately 400°C. With a 15 s water mist discharge, the fire was extinguished and the cooking oil in the fryer was cooled down. The temperature measured at the upper level of the oil (25.4 mm below the oil surface) decreased from nearly 400°C to 280°C. However, the oil in the lower portion of the fryer was still very hot.

With stop of the water mist discharge, the oil in the fryer was quickly mixed and oil temperature near the oil surface increase from 280°C to 330°C. An oil fire auto-re-ignited in the fryer. As water mist was discharged for 3 s, the re-ignited fire was extinguished. The upper level's oil temperature was decreased to below 290°C. However, after the water mist discharge terminated 15 s, the oil in the fryer was well mixed again and increased to a temperature of 300°C. The second oil auto-re-ignition occurred in the fryer. This new auto-re-ignition temperature was approximately 65°C lower than its original auto-ignition temperature, and approximately 100°C

lower than the oil temperature at the end of the free burn period. The fire was extinguished again using 5 s water mist discharge and the oil temperature dropped to below 200°C, and no further auto-re-ignition occurred.

Figures 5a and 5b also show that the body of the deep fat fryer becomes very hot during the heating and burn periods. The maximum temperature of the fryer's top metal surface was about 180°C. Due to the good heat retaining capability, the body of the deep fat fryer was cooled down slowly and the heat was difficult to disperse from the fryer even under water mist discharge.

Figure 5a The variation of oil and fire temperatures with time, when the cooking oil fire was suppressed by water mist with short discharge periods

To examine changes in the cooking oil's composition during heating and fire suppression by water mist, an additional full-scale experiment (Test K-2) was conducted. In the experiment, the oil was sampled at various temperatures (100°C, 200°C, 300°C, and 350°C) during heating, as well as after the cooking oil fire was extinguished using water mist (the oil temperature dropped to approximately 270°C). The oil samples were then analysed using the FTIR. The spectral features of the sampled oil were compared with library/literature spectra of appropriate standards or model compounds. To identify new functional groups produced in the oil during the experiment, the differential spectra of the oil were obtained by the subtraction of the

normalized spectra of fresh oil (at room temperature) from the spectra of the oil specimens sampled during the experiment.

Figures 6a, 6b and 6c show the differential spectra of the oil in three spectra regions at different oil temperatures. There was no substantial change in the oil's spectra when the oil was heated up to 300°C, indicating no formation of new component in the oil. However, when the oil was heated to near the auto-ignition temperature (350°C), the spectra/composition was significantly changed. As shown in Figure 6a, a strong and broad peak of associated O-H groups appeared in the region of 3700 to 3100 cm^{-1} with a maximum at $\sim 3450 \text{ cm}^{-1}$. This band indicates that hydroperoxides and hydroperoxide-degradation products, such as low molecular weight acids, alcohols, aldehydes and ketones, were formed in the heated oil [19]. These new components were produced due to the hydroperoxidation of the double bonds in the cooking oil. In the 1720 cm^{-1} to 1600 cm^{-1} spectral region (see Figure 6b), a shoulder appeared at wavenumber 1689 cm^{-1} in the oil sampled at 350°C. This represents a typical carbonyl double bond of saturated aldehydes, such as hexanal generated by degradation of hydroperoxides [19]. In the trans region, 1050 to 900 cm^{-1} (see Figure 6c), there was a bimodal band/double peak at 997 cm^{-1} and 972 cm^{-1} that is a characteristic of trans double bonds generated by the collapse of hydroperoxides.

Experimental results also showed that the spectra/composition of the oil was changed when the fire was extinguished using water mist. As shown in Figure 6a, the hydroperoxide peak disappeared but a low intensity broad band appeared at 3330 cm^{-1} . This spectral feature can be attributed to a “flash” hydrolysis of glyceride ester bonds of the oil due to water mist discharge, leading to the formation of di- and mono- glycerides and free glycerol. In addition, with water mist discharge, a well defined peak at 1712 cm^{-1} of typical unsaturated aldehyde appeared in the carbonyl stretching region (see Figure 6b). The discharge of water mist also resulted in a much better defined peak at 968 cm^{-1} in the trans region (Figure 6c). These features may result from the presence of β -unsaturated aldehydes in the degraded fatty acid chains that are still bound to glycerol.

Figure 6c Spectra of the oil sampled at different oil temperatures

Most of the new components produced in the oil during heating period, such as short-chain alcohols, aldehydes and acids, have relatively low boiling points and low auto-ignition temperatures, compared with the parent triglycerides [19, 20]. New components, such as glycerol and mono- and di-glycerides, produced by hydrolytic degradation due to the discharge of water mist into overheated oil could accumulate in the oil because of their relatively high boiling points [19, 20]. These components can undergo further hydrolysis in the hot oil to produce acrolein that has a low boiling point and a low auto-ignition temperature [19-23]. Therefore, after undergoing a certain period of heating and suppression, the cooking oil has a strong propensity for re-ignition due to the change in oil compositions. In order to extinguish a

cooking oil fire, the suppression agent must not only extinguish the flame over the oil surface but also cool the oil from its high burning temperature to below its new auto-ignition temperature.

Effectiveness of Water Mist against Cooking Oil Fires

Water mist extinguishes fires mainly by physical means: cooling the flame, wetting/cooling the fuel, displacing the oxygen and fuel vapour available for combustion and radiant heat attenuation. When cooking oil burns in a deep fat fryer, heat is transferred to the oil from flame by convection and radiation. With water mist application, heat is lost from the oil by the evaporation of water droplets and by heat transfer through the fryer. The fire can be extinguished by water mist mainly by cooling the fuel surface, as the rate of supply of fuel vapour or burning rate is reduced sufficiently enough not to support the flame. The energy balance of the fuel surface at the fire point is [24]:

$$S = (f_c \Delta H_c - L_{fv}) \dot{m}_f + \dot{Q}_E - \dot{Q}_L \quad (1)$$

where f_c is fraction of the heat of combustion of the fuel (ΔH_c) that is transferred from the flame to the fuel, $\dot{m}_f$ is the oil burning rate, L_{fv} is latent heat of evaporation of the fuel (kJ/mol), $\dot{Q}_E$ is the external heating flux transferred to the fuel, $\dot{Q}_L$ is the heat loss from the fuel surface and include heat loss to open space, to the depth of the fuel, and to the water:

$$\dot{Q}_L = \epsilon \sigma T_{fs}^4 + K_f \frac{(T_{fs} - T_{fo})}{\delta} + \dot{m}_w (C_{pw}(T_{fs} - T_w) + L_{vw}) \quad (2)$$

where T_{fs} and T_{fo} are the flame temperature at the fuel surface, and fuel temperature inside the fuel, respectively, δ is the thickness of the heating layer below the fuel surface, and K_f is the heat conductivity of the fuel, $\dot{m}_w$ is the water mist discharge rate (kg/s) that reaches the oil, L_{vw} is latent heat of evaporation of water (2500 J/kg).

The energy balance at the oil surface can be rewritten as:

$$S = (f_c \Delta H_c - L_{fv}) \dot{m}_f + \dot{Q}_E - (\epsilon \sigma T_{fs}^4 + K_f \frac{(T_{fs} - T_{fo})}{\delta} + \dot{m}_w (L_{vw} + C_{pw}(T_{fs} - T_w))) \quad (3)$$

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. In order to extinguish a cooking oil fire, the fire size must be reduced to minimise heat transfer from the flame to the oil, and at the same time, the oil must be cooled down by the water to reduce the fuel vapour available for combustion. The energy balance equation (3) also explains one of reasons why the cooking oil fire is difficult to extinguish. Unlike other types of fire, oil temperature, T_{fo} , below oil surface is higher than oil temperature, T_{fs} , at oil surface during fire suppression. The oil

itself was not an energy sink but an energy supply to maintain the flame at oil surface. The heat supplied to oil surface from the oil is determined by heat retaining capability of the fryer and the amount of cooking oil in the fryer. The more the cooking oil quantity in the fryer and the more heat retained by the fryer, the more difficult to extinguish the fire.

Spray coverage, water flow rate and spray momentum are considered as three most important factors to extinguish a cooking oil fire. Firstly, water mist coverage must be large enough to cover the entire oil surface and to extinguish the whole flames over the oil surface at once, otherwise the flames that are not attacked by the 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. Secondly, the amount of discharged water must be sufficient enough to extinguish the flame and remove sufficient heat from the flame, and to cool the oil below its ignition temperature. Thirdly, water mist must have sufficient momentum to penetrate the fire plume and reach the fuel surface. Water mist with low momentum will be carried away by the fire plume. To avoid having the water mist carried away by the fire plume, the water mist momentum must be at least equal in magnitude, and opposite in direction, to the fire plume momentum:

$$\vec{M}_{wy} \geq \vec{M}_{fy} \quad (4)$$

where $\vec{M}_{wy}$ and $\vec{M}_{fy}$ are the 'y' components of the water droplets and fire plume momentum, respectively. The water spray momentum, $\vec{M}_w$, includes not only discharged water mass but also water vapour and air entrained by the water mist. The fire plume momentum, $\vec{M}_f$, also should include the mass of combustion products, as well as the mass of fire gases and air entrained by the fire plume. They can be expressed as follows [16]:

$$\vec{M}_w = (m_{wl} + m_{wv} + m_{wa}) \times \vec{V}_w \quad (5)$$

$$\vec{M}_f = (m_{fp} + m_{fg} + m_{fa}) \times \vec{V}_f \quad (6)$$

where m_{wl} , m_{wv} and m_{wa} are the mass of water, water vapour and air entrained by the water mist, respectively, $\vec{V}_w$ is the velocity vector of the water mist, m_{fp} , m_{fg} and m_{fa} are the mass of combustion products, fire gases and air entrained by the fire plume, respectively, and $\vec{V}_f$ is the velocity vector of the fire plume.

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 the intermittent flame [25]:

$$u_{f \max} = 1.9 \dot{Q}_c^{0.2} \quad (7)$$

where $\dot{Q}_c$ is heat release rate of the flame.

For an individual water drop, its momentum is mainly determined by drop size and velocity and can be expressed by:

$$\vec{M}_d = \left(\frac{1}{6}\pi D^3 \rho\right)\vec{V} \quad (8)$$

$$V \propto P^{0.5} \quad (9)$$

where D is the diameter of the drop, ρ is the water density, V is the drop velocity and P is the discharge pressure. For individual water drop, the drop momentum is more sensitive to the change in drop size than in discharge pressure. For water spray, as indicated in Equation (5), its momentum is determined by many factors, including droplet size and velocity, discharge pressure, water flow rate and cone angle. For example, the spray momentum increases as the amount of air entrained by the water spray increases with spray cone angle and spray velocity.

The full-scale testing results were consistent with the extinguishing mechanisms of water mist as discussed above. The water mist system #1 produced finer water droplets, compared to the other systems. However, as shown in Figure 7 (Test K-3), the fine water droplets could not penetrate into the fire plume due to their low spray momentum, when nozzle #1 was located 1.1 m away from the oil surface and with a discharge pressure of 27 bar. The cooking oil fire was not extinguished and the fire size was increased during water mist application. When the discharge pressure was gradually increased from 27 bar to 48 bar, the spray momentum increased and water droplets were able to penetrate the fire plume and to control the fire. However, the hollow spray cone produced by using nozzle #1 did not allow the water mist

Figure 7. A cooking oil fire suppressed by the water mist system #1

covering the entire oil surface. A portion of the fire on the oil surface was extinguished but other

portions of the fire that were not hit by water mist could not be extinguished and still remained on the oil surface during the 40 s discharge period.

The relatively large water droplets produced by water mist system #2 had sufficient momentum to penetrate the fire plume and reach the fuel surface. The spray angle produced by water mist system #2 was 60 degrees. This spray angle was not changed by the increase in discharge pressure and the water spray was able to cover the entire fuel surface. In addition, the water mist system #2 had relatively high flow rates. At a discharge pressure of 13 bar, the water flow rate was 10.5 L/min.

Figure 8 shows the flame and oil temperatures during Test K-4 with nozzle #2 located 1.1 m from the oil surface and with a discharge pressure of 13 bar. During fire suppression, the flame temperature near the fuel surface (thermocouple #3) was reduced slowly, while the oil temperature did not show substantial reduction. It took 15 s for the water mist system to extinguish the fire. After the fire was extinguished, a further 20 s water mist discharge was applied to cool the oil temperature to below 300°C. No re-ignition of the oil was observed in the experiment.

Figure 8 The variation of oil and fire temperatures with time (Nozzle #2, 13 bar)

The water mist system #3 had similar spray characteristics as the system #2, but it had a larger spray angle (90 degrees) and a higher water flow rate (20.4 L/min at a discharge pressure of 13 bar). Its spray angle was also reduced with discharge pressure. Figure 9 shows the amount of water collected in the fryer with nozzles #2 and #3 during non-fire experiments. Under low discharge pressures, the amount of water collected in the fryer with the two nozzles was

comparable, even though the flow rate of nozzle #3 was much higher. This was because much of water droplets discharged from nozzle #3 was outside of the fryer due to its large spray angle. Under high discharge pressure, the amount of collected water was increased.

Figure 9 The variation of amount of water collected in the fryer with change in discharge pressure and nozzle (1.1 m from fuel surface)

As shown in Figure 10, the percentage of water collected in the fryer with nozzle #2 was much higher than with nozzle #3 at low discharge pressures. However, at higher discharge pressures, the spray angle of nozzle #3 became narrower and the percentage of collected water increased linearly. As a result, the amount of water collected by the fryer with water mist system #3, at high discharge pressures, was more than that with system #2.

Figure 11 shows the changes in oil and flame temperatures using nozzle #3 in Test K-6 (nozzle location 1.1 m above oil surface and 13 bar discharge pressure). Since both nozzles #2 and #3 had similar mist characteristics and discharged almost the same amount of water onto the fryer at low discharge pressures, it took the same time (15 s) to extinguish the cooking oil fire as the water mist system with nozzle #2. For nozzle #3, 13 bar was the lowest discharge pressure required for extinguishing cooking oil fires as observed in Test K-5, when the nozzle was located 1.1 m away from the oil surface. When the discharge pressure was increased beyond this value, the extinguishing times were significantly reduced (see Figure 12) due to the increased water flow rate and spray momentum. The time required to cool the oil to below its auto-re-ignition temperature of 300°C was also reduced substantially. At a discharge pressure of 28.5 bar, the cooking oil fire was extinguished in approximately 1 s.

Figure 10 The variation of rate of water collected in the fryer to total amount of discharged water with changes in discharge pressure and nozzle (1.1 m from fuel surface)

When the distance of the nozzle to the fuel surface was reduced, the amount of collected water by the fryer increased, as shown in Figure 13. Also, with the reduction in the nozzle distance, the loss of spray momentum in the fire plume was reduced and more water droplets were able to reach the oil. As a result, as shown in Figure 14, the extinguishing time as well as the time required to cool the oil below its auto-re-ignition temperature decreased linearly with the reduction of the nozzle distance. At a nozzle distance of 0.86 m, the cooking oil fire was extinguished in 2 s after activation of the system under a discharge pressure of 13 bar. To achieve the same extinguishing time at a nozzle distance of 1.1 m, the required discharge pressure was 26 bar, as shown in Figure 12.

In Test K-12, only one cylinder containing water and compressed air was used to investigate the effect of descending discharge pressure on water mist performance. Nozzle #3 with its location of 1.1 m from the oil surface was used in the test. The discharge pressure started from 17.2 bar and then quickly decreased to 11.5 bar during the 45 s discharge. The fire was extinguished at 2 s after the discharge and no re-ignition was observed. Testing results suggested that descending discharge pressure during suppression had less impact on water mist performance against cooking oil fires and the size of water mist systems designed for the protection of cooking areas could be reduced as only one cylinder containing both water and compressed air was used.

Figure 11 The variation of oil and fire temperatures with time (Nozzle #3, 13 bar)

The full-scale tests also showed that activation of the water mist system produced a momentary flare-up of the fire during the initial suppression stage (see Figure 14). This was partly because air entrained by the water mist discharge, as indicated in the Equation (5), increased the burning rate of the flame, and partly because the flame separated from the oil surface quickly expanded in the air. The size of the fire flare-up was dependent on the discharge pressure, flow rate, and nozzle location. With a large spray coverage and a high water flow rate, the fire was quickly extinguished and the fire flare-up was small and well controlled. However, the fire substantially enlarged under water mist application if the fire could not be quickly controlled and extinguished, as observed in the test using nozzle #1. The potential impact of the fire flare-up on personal safety should be taken into account in the design of a water mist system for use in extinguishing cooking oil fires.

Figure 13 The variation of amount of water collected in the fryer and percentage to total discharged water with change in nozzle distance to fuel surface. (nozzle #3, discharge pressure: 13 bar)

Figure 14 The variation of extinguishing time and cooling time from oil burning temperature to its auto-ignition temperature with change in nozzle distance (nozzle #3, 13 bar discharge pressure)

(nozzle #3)

Water Mist Splash Tests

The possible splashing of hot oils caused by the water mist discharge is one of the safety concerns with the use of a water mist system to extinguish cooking oil fires. The tendency for oil splashing depends on the properties of the water droplets, such as droplet size and velocity, as well as the properties of oil and its depth [26-30]. Table 3 shows the physical properties of water, gasoline, diesel fuel and some cooking oils [6, 31, 32]. Compared to other types of liquids, the viscosity of the cooking oils is very high, indicating that it is difficult to produce splashing over the cooking oil.

Table 3. Physical Properties of the Liquids [6, 31, 32]

Liquid	Density (kg/m³)	Viscosity (kg/m.s)	Surface Tension (N/m)
Water (25°C)	996	8.67×10^{-4}	0.0717
Gasoline (15°C)	738	6.03×10^{-4}	0.0195
Diesel #1 (15°C)	874	1.98×10^{-3}	0.025
Canola oil (20°C)	915	7.15×10^{-2}	
Corn oil (25°C)	918	2.83×10^{-2} (40°C)	0.0348
Peanut oil (21°C)	915	6.45×10^{-2}	0.0356
Soybean oil (25°C)	917	4.67×10^{-2}	

Seven splashing experiments were conducted under non-fire conditions. The water mist was discharged onto the cooling oil at the cooking temperature of 190°C. Test parameters included different discharge pressures (13 bar to 34.5 bar) and different nozzle distances from the fuel surface (0.86 m to 1.1 m) with the three types of nozzles. As observed in all seven experiments, the oil surface was not disturbed by the water mist discharge, and the fine water droplets disappeared quickly into the oil. No oil droplets were splashed outside the fryer during the 5 s discharge period. After water mist discharge stopped, the water in the hot oil quickly evaporated and a large amount of steam was produced.

Figure 16 shows the changes in the oil temperature and air temperatures above the oil during the splash experiment with nozzle #3 and a 17.2 bar discharge pressure. The nozzle was located 0.86 m away from the oil surface. During the 5 s discharge period, the oil temperature quickly dropped to 170°C. The air temperature above the oil surface also dropped during the discharge period. However, the air temperature increased sharply when the water mist discharge was stopped, because a large amount of hot steam was produced as the water evaporated in the hot oil.

Figure 15. Cooking oil fire extinguished by the water mist system #3 (13 bar, 1.1 m from oil surface)

In the 12 full-scale fire experiments, no burning droplets of the cooking oil were splashed outside the fryer with the application of water mist. As shown in Figures 8 and 11, the oil temperature did not show any substantial reduction during fire suppression until the fire was extinguished. It indicated that fine water droplets did not have sufficient momentum to hit the oil surface and to splash the burning cooking oil outside the fryer, and most of the water droplets were evaporated in the fire plume.

After fire extinguishment, water mist was able to reach the oil surface, resulting in the reduction in cooking oil temperature. It was observed that when the water mist discharge stopped, a large amount of water vapour was produced as water quickly evaporated in the oil. At high discharge pressures and short penetration distances (e.g., 28.5 bar at nozzle distance of 0.86 m) with nozzle #3, many water droplets reached the oil surface and did not evaporate completely in the hot oil. When the water mist discharge stopped, the water in the hot oil was boiling and some oil droplets were splashed outside the fryer as the water bubbles collapsed. At low discharge pressures (e.g., 13 bar at nozzle distance of 0.86 m), less water droplets reached the oil surface, and the water quickly evaporated in the hot oil, resulting in less water remaining in the oil. Oil splashing outside the fryer was not observed after the water mist discharge was stopped.

Figure 16 The variation of oil and air temperatures with time during splash test (17.2 bar, 0.85 m from oil surface)

CONCLUSIONS

Cooking oil fires, compared to other types of liquid fuel fires, are difficult to extinguish, because they burn at high temperature and re-ignite easily. During the 2 min of free burn, the cooking oil fire was fully developed and the oil was further heated to a higher temperature. The highest oil temperature measured in the tests was 403°C, which was 38°C above the auto-ignition temperature. Also, the change in oil composition during the free burn and fire suppression periods reduced the auto-ignition temperature of the oil below its original auto-ignition temperature. The lowest auto-re-ignition temperature measured in the experiments was approximately 65°C below the original auto-ignition temperature.

Full-scale fire experiments demonstrated that the water mist fire suppression systems developed in the present work were capable of extinguishing cooking oil fires and preventing their re-ignition. The predominant extinguishing mechanism was the cooling of the fire plume and the wetting/cooling of the oil.

Extinguishing cooking oil fires requires flame extinction over the entire surface at once and rapid cooling of oil below its auto-re-ignition temperature to prevent re-ignition. The full-scale testing results indicated that spray momentum, spray coverage area and flow rate are the three most important factors that determine the effectiveness of a water mist system for extinguishing cooking oil fires. The discharge of water mist does not cause oil to splash outside the fryer.

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