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Experimental Study on the Protection of Cooking Oil Fires Using Dust Additives in Water Mist

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***Abstract*—Cooking oil fires represent one of the most hazardous types of fires occurring in domestic and commercial kitchens because of their high ignition temperature, rapid flame development, intense heat release, and strong tendency to re-ignite after suppression. Conventional extinguishing agents such as foam, carbon dioxide, and dry powders can suppress the flame but often fail to sufficiently cool the hot oil below its auto-ignition temperature. Water mist technology has emerged as an efficient and environmentally friendly fire protection method due to its strong cooling capacity, low water consumption, and ability to attenuate thermal radiation. However, the performance of water mist systems can be further enhanced through the use of suitable additives. The objective of this study is to investigate experimentally the effectiveness of a water mist system with dust additives for protecting cooking oil fires. A series of experiments were carried out using palm oil as the fuel in a steel container under open-air conditions. A high-pressure water mist system equipped with a nozzle and a pressure booster was used to generate a mist curtain. Flame temperature and thermal radiation were measured using an infrared radiometer in order to evaluate the cooling performance and radiation attenuation of the system. The results show that the addition of dust particles significantly improves the fire protection performance of the water mist system. The maximum heat flux decreased from about 126.52 W/m² without protection to 47.47 W/m² with pure water mist and to about 22.08 W/m² with dusty water mist. Similarly, flame temperature was considerably reduced when the mist curtain was activated. These findings demonstrate that dust additives enhance the cooling and radiation shielding effects of water mist systems and provide a promising and cost-effective solution for protecting against cooking oil fires in kitchen environments.**

***Keywords*—water mist, dust additive, cooking oil fires, fire protection efficiency**

I. INTRODUCTION

For millennia, cooking-oil fires have been a major cause of household fires. Statistics indicate that nearly 50% of all accidental fires in hotels, restaurants, and fast-food outlets originate in kitchens, with most of them involving liquid cooking oil or fat fires [1]. In the United States, data from 1999 to 2002 show that an average of 125,500 home fires per year started in kitchens, including confined cooking fires, resulting in approximately 460 deaths annually [2]. In recent years, the occurrence of kitchen cooking-oil fires has increased, and their combustion characteristics differ significantly from those of general hydrocarbon fires. These fires are difficult to extinguish and can easily lead to severe casualties and substantial property losses; therefore, they are classified separately as Class K fires [1, 3, 4]. Class K fires are characterized by a relatively high ignition temperature of cooking oil, typically between 350 and 380 °C [5–7], a rapid fire growth, with stable combustion reached within approximately 8 s accompanied by high combustion intensity, dense smoke production, and strong thermal radiation capable of igniting nearby combustibles, as well as a strong tendency for re-ignition.

To further improve the fire protection and extinguishing performance of water mist systems, various additives have been investigated. However, several of these additives present significant limitations in practical applications. For instance, inorganic additives may lead to corrosion problems in fire protection equipment [8]. Conventional extinguishing agents such as foam, dry powder, and carbon dioxide are capable of suppressing flames on the oil surface; however, they are generally unable to cool the hot oil below its auto-ignition temperature because of their limited cooling capacity, which may result in re-ignition. Wet chemical agents are widely used in commercial kitchen fire protection systems. Although these agents are effective in extinguishing cooking oil fires, the cooling process may require a relatively long time depending on the amount of agent applied [1]. In addition, wet chemical agents may cause skin and eye irritation and may also create cleaning difficulties after fire suppression. Chow and Ni [9] compared the performance of water mist and dry powders in suppressing cooking oil fires and reported that discharge pressure is a key parameter influencing the suppression efficiency. Moreover, the installation cost of wet chemical suppression systems is relatively high. In contrast, water mist systems represent a potentially cost-effective alternative for cooking oil fire

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protection. Water in the form of fine droplets acts as an efficient sensible heat removal medium and has been investigated for fire protection applications since the 1950s [10–13]. Water mist technology has also been considered as a promising alternative to halon-based systems because of several advantages, including low cost, non-toxicity, reduced water consumption, and the ability of small droplets to move around obstacles and behave similarly to flooding agents [14–16]. A water mist system is generally defined as a fixed or portable fire protection system that uses atomized water to control, suppress, or extinguish fires. According to the standard definition, water mist consists of droplets generated by a mist nozzle for which the volumetric diameter Dv0.90 is less than 1000 μm at the minimum operating pressure [16–18]. Water-based fire protection systems such as water mist can also reduce the fire spread rate by scattering and absorbing thermal radiation [19]. Numerous studies have demonstrated that water mist systems can effectively extinguish Class A, B, C, and K fires while providing efficient cooling, low toxicity, reduced water consumption, minimal water damage, and limited clean-up requirements [4, 20, 21]. Consequently, water mist systems are increasingly used in restaurants and hotels where kitchen fire risks are significant. Because of the specific characteristics of cooking oil fires, fire suppression agents used in such environments must be non-toxic, environmentally safe, and capable of preventing oil re-ignition. For this reason, conducting experimental investigations on extinguishment and cooling mechanisms for kitchen fire scenarios remains essential.

The objective of the present work was to develop a proposed additive (dust) in water mist system to effectively protect cooking oil fires. In order to achieve this goal, the mechanisms of water mist in protecting cooking oil fires were investigated. In addition, characteristics of the cooking oil and its fire in the heating and burning periods were examined. Planck's law was used to calculate thermal radiation and thermal transmissivity. Reductions in peak temperature and maximum heat flux while the protection system was operating were assessed. The results could provide several references in designing water mist fire protecting systems for places with potential cooking oil fire risks to decrease the number of firefighter casualties while extinguishing hot oil fires. The Fig. 1 illustrates the photo of experimental setup during the measurements with oil fire source. However, standards do not describe the design of water curtain in details.

Fig. 1. Photo of water curtain switched on during experiment.

II. MATERIALS AND EXPERIMENTAL SETUP

The experiment was conducted in open air. The experimental setup consisted of three parts: the combustion system, the fire protection system, and the data acquisition system, which is shown in Fig. 2. The distance between the water mist and the center of the container was 45 cm, and that between water mist and radiometer was 70 cm for the first measurement. All tests were conducted under open-air conditions, with natural air supply.

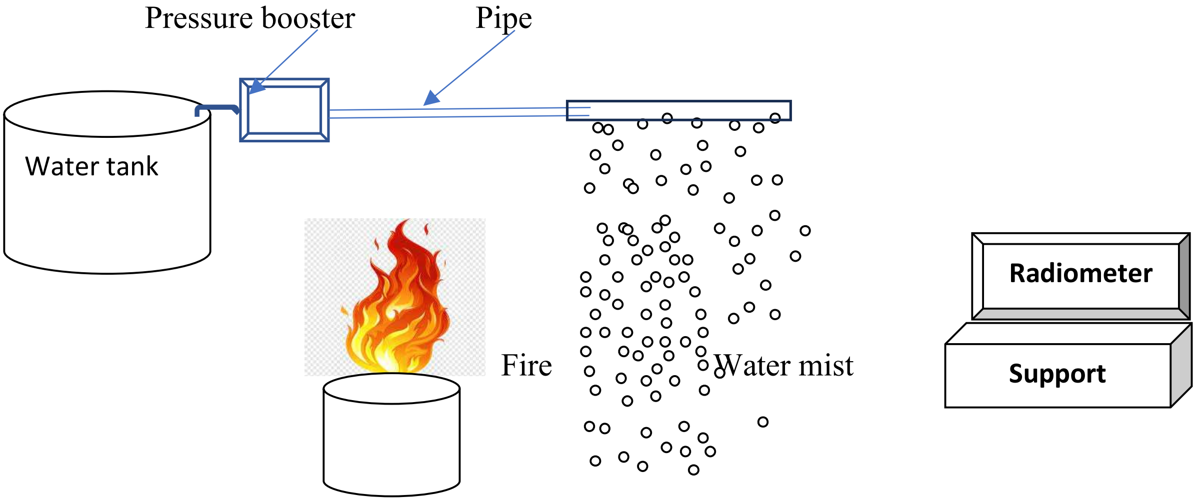

Fig. 2. Experimental setup for studying the radiation blockage effects by water mist.

A. Cooking Oil Fires

The tested cooking oil was palm oil. A total of 500 ml was placed in a 30.5 cm-diameter and 13 cm high steel container. Cooking oil was difficult to ignite because of its high flashpoint. A gas stove with a thermal power of 5 kW was used to heat the cooking oil to auto-ignition. Then, the gas stove was removed to allow the cooking oil to burn freely. The type of gas stove may affect the heating process; hence different ignition time of cooking oil was recorded. The specific heat capacity of cold processed palm oil was generally lower, ranging from 1.29-5.26 J/g°C while that of hot processed samples ranged from 1.80–6.24 J/g°C [22].

B. Water Curtain

The water mist fire protection system comprised a water storage tank, pressure booster through the pipe of 16 mm diameter. 2 types of water curtain were used: pure water and dust-laden water curtains. Water with dust additives was obtained by mixing dust in pure water. A plastic cylinder, containing 50 L of pressurized water, was then connected to the pipe. The water mist system, including the nozzle, pipe and cylinder, was connected to the high voltage secondary of the transformer, and the electric potential between the nozzle tip and the radiometer was maintained around 220 V during tests.

C. Water Pressure Booster

The high-pressure pump used in this work is a 2.2 KW KARCHER 595 with maximum pressure of 120 bars and flow rate 8.5 L/min. The advantage of this high-pressure system is that it creates a mist of smaller droplets, entraining more air around the flames. Evaporated water would absorb heat and lower the temperature. The water mist discharged from the high-pressure system, having a higher velocity and momentum is able to penetrate the fire plume to act at the flame. Therefore, the amount of heat absorbed per unit time will be considerably greater. We can conclude that, this high-pressure water mist system is more effective in protecting the fire.

D. Infrared Imager

Table 1. Key technical specification of infrared imager radiometer LH 129

Measuring range	**1-9999W/m^2**
Response spectrum	760-1700nm
Accuracy	10%
Specification	132×71×29mm

The entire process of cooking oil combustion is recorded in real time by the infrared imager's LH-video function. Table1 lists the key technical specifications of the infrared imager, RADIOMETER LH 129.

E. Testing Procedure

The measurements are recorded using a testing procedure described through 3 main steps:

(i) Ignite oil, switch on the video function of infrared radiometer and start collecting data (temperature over the time and thermal radiation over the time) without water curtain.

(ii) Test the performance on curtain fighting fire with pure and water with dust additives are used. Put pure water curtain, start collecting data (temperature over the time and thermal radiation over the time).

(iii) Substitute the pure water with water with dust additives and repeat "step (ii)''.

III. THEORETICAL BASIS

The infrared radiation is emitted from the oil fire and is received by the infrared imager. Temperature value is displayed on the infrared imager screen. Given that infrared radiation is attenuated by the water curtain, a difference is observed between the displayed temperature of the infrared imager when the water curtain is switched on and off. Based on the Planck's law, thermal radiation can be calculated by temperature data [23] as shown in Eq. (1):

$$E = \varepsilon\sigma T^4 \tag{1}$$

where σ is the Stefan–Boltzmann constant whose value is $5.67 \times 10^{-8} W.m^{-2}K^{-4}$, ε is the flame emissivity.

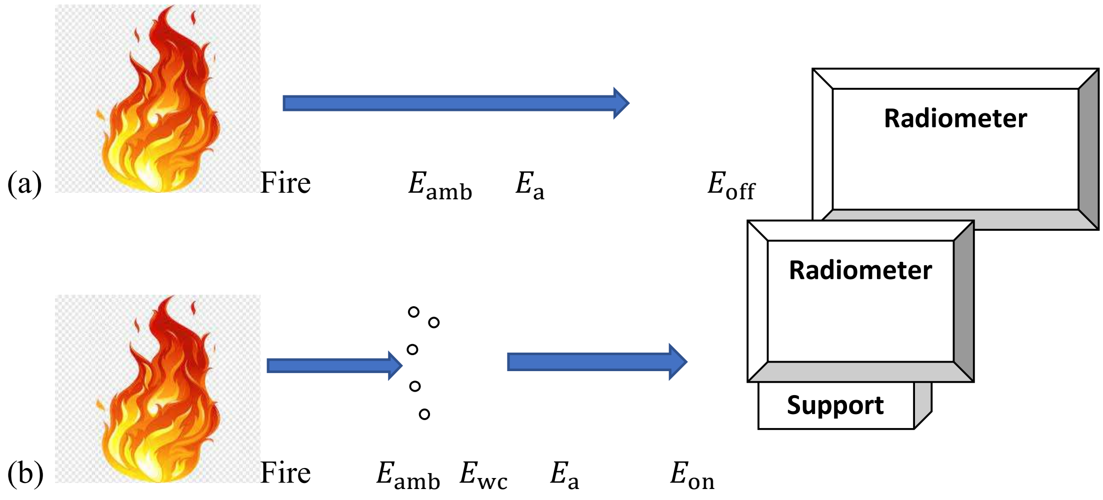

Fig. 3. Principle of infrared imager collecting data: (a) Water curtain switched off, (b) Water curtain turned on.

Fig. 3 shows the different thermal radiation levels when the water curtain is switched off and on. E_{a} is the thermal radiation attenuation due to atmospheric absorption, and E_{wc} is the thermal radiation attenuated by the water curtain and E_{amb} is the ambient heat flux without fire. In this experiment, E_{amb} was 3.01 W/m^2 and ambient temperature was 20 °C The relationship can be written as in the following Eq. (2):

$$E_{\mathrm{fire}} = E_{\mathrm{off}} + E_{\mathrm{a}} - E_{\mathrm{amb}} \tag{2}$$

$$E_{\mathrm{fire}} = E_{\mathrm{on}} + E_{\mathrm{a}} + E_{\mathrm{wc}} - E_{\mathrm{amb}} \tag{3}$$

Based on Eq. (2) and Eq. (3), for a temperature value which displayed on infrared imager screen, the transmissivity through curtain can be calculated as shown in Eq. (4) [24, 25].

$$T_{\mathrm{r},i} = \frac{E_{\mathrm{fire}} - E_{\mathrm{a}} - E_{\mathrm{wc}} + E_{\mathrm{amb}}}{E_{\mathrm{fire}} - E_{\mathrm{a}} + E_{\mathrm{amb}}} = \frac{E_{\mathrm{on},i}}{E_{\mathrm{off}}} \qquad i = 1,2,3,4 \tag{4}$$

where E_{off} is the heat flux without water curtain (with empty container) while $E_{\mathrm{on},1}$ and $E_{\mathrm{on},2}$ are the heat fluxes when the water curtain is made respectively of pure and water with dust additives.

IV. RESULTS AND DISCUSSION

A. Fluctuation of the Flame During Combustion

According to the actual testing situation, the ambient temperature was 20 °C, ambient heat flux without fire was 0.508 W/m^2. According to the size of container, the value of flame emissivity of burning oil is 0.95 [22, 26].

Fig. 4 gives the typical photographs of tests during experiments. It was shown that the oil fire has bright flames and produces a large heat flux. As shown in Figs. 4(a–c), are recorded when the water curtain was switched off, while Figs. 4(d–g) are recorded when the water mists were switched on. Pure water curtain was switched on at 250 s and water with dust additives at 500 s. The burning lasted about 1500 s. Flame fluctuations are caused by ambient air disturbances. The flame height varies significantly over time, by contrast, the flame width exhibits a smaller variation.


(a) (b) (c) (d) (e) (f) (g)

Fig. 4. Periodic infrared images of turbulent fluctuating flame. (a) 30 s. (b) 80 s. (c) 120 s. (d) 250 s. (e) 300 s. (f) 450 s. (g) 140 s.

B. Effect of Water Mist Additives on Cooking Oil Cooling

In order to investigate the effects of the new dust additive on fire protection and to determine the optimization value of the additive, a series of experiments were conducted wherein the additive concentration varied from 12.20% to 50% as shown in Table 2 and Table 3. These additives play an important role in extinguishing and protecting fire by suffocating the flame and forms an effective thermal barrier between the radiative source and the target to be protected by absorption and diffusion of thermal radiation which are physical mechanisms of water droplets. It was observed that increasing the mineral texture (percentage) by 100% would result in the reduction of the transmission time by approximately 26%. These additives can improve the efficiency of water mist in protecting cooking oil fires.

Table 2. Mineral texture

Mineral texture	Percentage (%)
Sand	25
Total silt	50
Clay	25

Table 3. Organic texture

Organic texture	Percentage (%)
Organic carbon	12.20
Organic material	21.02

C. Fireproofing Performance of Water Curtain with Different Types of Water

Three tests were carried out in the same testing environment. The tests used the same testing platform, only the water mist curtains were changed.

At the 250th second, the pure water was turned on. Testing was conducted under the operation condition of 120 bars pressure and 8.5 L/min flow rate.

D. Comparative Analysis of Temperature Above the Fire Source with Different Curtains

Table 4 and Table 5 compare different values of temperature during oil cooking combustion without and with water mist curtains. As shown in these tables, the flame temperature changed continuously over both time and space. While the temperature of the flame root remained stable, the temperature of other areas constantly changed. A temperature comparison is displayed in the infrared imager when pure and water with dust additives mist curtains were switched on and off. An obvious difference is observed in the maximum temperature value displayed on the thermal infrared radiometer. As shown in Table 4 and Table 5, it can be seen that the temperature rises rapidly after the combustion starts with 58.0 °C as maximum value. When respectively the pure and dirty high-pressure water mist curtain fire-protection condition were adopted in the space, it can be seen that the peak temperature of the fire was significantly reduced, fluctuating between 46.6 °C and 32.7 °C both in time and space. The temperature in space was effectively control with water with dust additives. Qualitatively and quantitatively the water mist curtain with dust additives has a strong cooling effect and can lower flame temperature.

Table 4. Temperature of oil cooking flame over the time

t (s)	T_{off} (°C)	$T_{on,1}$ (°C)	$T_{on,2}$ (°C)
40	51.1	46	32.3
80	49.9	44.8	32.7
120	50.7	46.6	31.1
160	56.3	42.5	29
200	57.9	43.9	27.8
240	58.0	42	27.5

Table 5. Temperature of oil cooking flame over the space

d (cm)	T_{off} (°C)	$T_{on,1}$ (°C)	$T_{on,2}$ (°C)
70	50.9	42.6	29.1
80	49.1	41.9	28.8
90	47.1	39.1	28.9
100	48.6	36.9	25.7
110	44.8	33.6	24.1
120	41.4	29.4	22.7

E. Comparative Analysis of Thermal Radiation Above the Fire Source with Different Curtains

Table 6 and Table 7 show different thermal radiation levels over time and horizontal variation whatever the water mist curtain is switched off or on, their arithmetic average values can be calculated. The transmissivity of water mist curtain can be determined by a ratio of the average radiation value when water mist curtain on over the case water curtain off. The peak heat flux was 126.52 W/m^2 in the case of no water discharge,47.47 W/m^2 and 22.08 W/m^2 respectively in the case of pure water and dust-laden water curtains operating both in time and space. As expected, water with dust additives provides the highest attenuation of heat flux than pure water. Qualitatively, the water with dust additives mist curtain can quickly attenuate thermal radiation of fire.

Table 6. Different level of thermal radiation over the time

t (s)	E_{off} (W/m^2)	$E_{on,1}$ (W/m^2)	$E_{on,2}$ (W/m^2)
40	112.98	44.12	21.02
80	100.21	39.25	20.14
120	102.38	45.19	21.56
160	126.52	42.17	17.24
200	119.35	38.61	14.92
240	120.34	34.64	13.32

Table 7. Different level of thermal radiation over the space

d (cm)	E_{off} (W/m^2)	$E_{on,1}$ (W/m^2)	$E_{on,2}$ (W/m^2)
70	123.18	47.47	22.08
80	117.12	42.11	22.1
90	115.72	40.01	19.09
100	94.62	38.98	20.35
110	91.12	39.12	10.01
120	82.53	36.43	9.34

F. Comparative Analysis of Thermal Transmissivity Above the Fire Source with Different Curtains

Table 8. Real-time transmissivity variation of water mist curtains

T (s)	$T_{r,1}$	$T_{r,2}$
40	0.39	0.18
80	0.39	0.2
120	0.44	0.21
160	0.33	0.13
200	0.32	0.12
240	0.28	0.11
Mean	0.358	0.158

Table 9. Transmissivity of water mist curtains over the space

d (cm)	$T_{r,1}$	$T_{r,2}$
70	0.38	0.17
80	0.35	0.18
90	0.34	0.16
100	0.41	0.21
110	0.42	0.10
120	0.44	0.11
Mean	0.390	0.155

The results of transmissivity obtained from the experimentations with water mist curtains operating are summarized in Table 8 and Table 9. Considering the results obtained, the average values are 0.358 and 0.158 over the time, 0.39 and 0.155 over space respectively with pure and water with dust additives mist curtain. At a given time, the transmissivity is defined as the ratio of radiation with the water mist curtain switched on over the case when water curtain is switched off. After water curtain switched on. The oscillation of transmissivity is due to the fluctuation of flame during combustion. For the testing of pure water mist curtains over time and space, the maximum transmissivity is about 0.44 while the minimum is approximately 0.28 but for the testing of water with dust additives mist curtain, the maximum transmissivity is approximately 0.21 while the minimum is about 0.10. Furthermore, a comprehensive analysis of Table 8 and Table 9 shows that the transmissivity of water mist curtains fluctuated around the average value and the fluctuation range is less than 10%. In these tables, one can see how dust added to pure water increases attenuation of thermal radiation.

V. CONCLUSION

A series of cooking fire experiments were conducted to examine the hazard associated with cooking oil fires. The results showed that:

Cooking oil fires are more difficult to extinguish than other types of liquid fuel fires because they burn at high temperatures and re-ignite easily. Fires that were ignited by 500 ml of cooking oil in a 25 cm-diameter pan induced the maximum radiative heat flux of about 126.52 W/m^2 and minimum thermal transmissivity of about 0.10. The flame temperature could be as high as 58.0 °C, and the burning could last for about 1500 s.

Compared with pure water mist, water with dust additives mist showed higher efficiency with the proposed additive. The proposed additive for water mist developed in this work is a composite material, and each component can affect the fire protection mechanism of water mist curtain. The total silt, sand and clay in the dust additive can enhance the physical effects (scattering and absorption) fire protection. These physical effects explain the reason that dust as additive in water mist improves fire protection efficiency.

The proposed method can provide guidance for the development and design of water-based fire protection systems.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

GHP, FK, RK conducted the research; FK, RK, PEO analyzed the data; FK, RK, GLY wrote the paper; GNJB, RT supervised the work; all authors had approved the final version.

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