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EXPERIMENTAL STUDY ON WATER CURTAIN FIGHTING FIRE BASED ON INFRARED TECHNIQUE

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ABSTRACT

Infrared radiation is a type of electromagnetic radiation and invisible to human eyes. It is used widely in industrial, scientific, and medical applications. Pool fire is an emergent accident, which emits intense thermal radiation. In order to quantify the performance of water curtain fighting fire, a testing platform is built and experimental studies are carried out. An infrared imager is used to acquire real-time experimental data and respond to the variations of flame in time and space dimensions. Experimental principles and operating procedures are described in detail. The transmissivity is used to quantify the performance of water curtain fighting fire. Experimental results show that the flame presents obvious fluctuations during combustion. Analysis on the average value of transmissivity over time show that a water curtain with cone-shaped nozzles achieved higher performance of fighting fire than a water curtain with fan-shaped nozzles. The proposed method can be used to provide guidance on the development and design of water curtain fighting fire.

Keywords: *Water Curtain, Infrared Imager, Radiation Attenuation, Transmissivity*

1. INTRODUCTION

Infrared radiation is a kind of invisible heat radiation emitted from hot bodies or objects, and infrared technique is used widely in national defense, military, safety and chemical engineering etc. (Glowacz et al., 2015; Park and Zhang, 2013). Pool fire is a common accident in the petrochemical industry. With the exception of active fire-fighting facilities, responding to fire accidents requires passive protection measures that can slow down fire spread and gain more time for rescue. Due to the ability of thermal radiation attenuation, water curtain is listed as one of fire preventive facilities in the standard of the NFPA (2015). API regulations require the consideration of water curtain as a means of fighting fire in petroleum chemical risk assessment (2014). As industry standards of China stipulated (2010), it is mandatory that water curtain systems shall be installed in oil and gas terminals (Fig. 1). However, standards do not describe the design of water curtain in details.

Studies on experiment and numerical simulation have been reported. The fourier transform spectrometer (FTS) was used to simulate radiation source, the finite volume method and the discrete ordinates method were discussed from the perspective of quantitative spectral radiation (Boulet et al., 2007; Collin et al., 2010; Parent et al., 2006). Based on the Mie theory, it has been proved that large droplets show extremely weak spectral characteristics (Sudiarta and Chylek, 2001). Researches on pool fire showed that the flame combustion is an unstable process (Santoni et al., 2002; Sudheer and Prabhu, 2013; Zhu et al., 2015). However, there are few studies focusing on effect of flame variations over time on water curtain fighting fire.

In the present paper, an outdoor testing platform is built. An infrared imager is used to acquire data in real time, and experiments for three kinds of water curtain nozzles are carried out in the same testing environment. Experimental principles and operating procedures are described in detail. The presented method can be used to provide guidance on the development and design of water curtain fighting fire.

Fig. 1 Photo of water curtain switched on in an oil and gas terminal

2. EXPERIMENTAL SETUP

2.1 Experimental platform

Figure 2 shows the outdoor experimental platform. For diesel combustion, the steel container size is 1 m × 1 m × 0.1 m. The distance between the water curtain and the center of the container is 3.5 m, and that between the water curtain and the infrared imager is 3.2 m. The

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water supply pipe diameter is 12.7 mm. The water curtain contains four nozzles, each spaced 0.5 m apart. The whole test process is recorded in real time by an infrared imager in the form of video data.

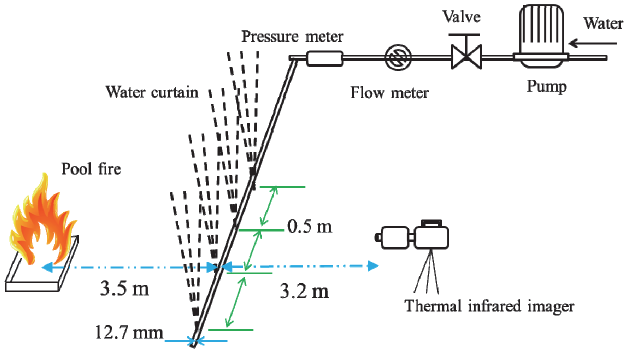

Fig. 2 Schematic of the experimental platform

2.2 Water curtain nozzles

Three types of nozzles are used in the experiment: (1) Cone-shaped [Fig. 3(a)]. The cone-shaped nozzle produces a solid cone shaped spray pattern with a round impact area, this type of nozzle ensures a precise uniformed distribution of liquids throughout the entire circular impact area. (2) Vertical ejection fan-shaped [Fig. 3(b)]. The vertical ejection fan-shaped nozzle produces a flat fan spray pattern with an even and uniform distribution across the spray width. In the present testing experiment, vertical ejection fan-shaped nozzles are used with an initial spray angle of 90°. (3) Lateral ejection fan-shaped [Fig. 3(c)]. The lateral ejection fan-shaped nozzle is similar to the one with vertical ejection, but the spray is deflected 90° from inlet of orifice. The statistics of droplets diameter of each nozzle obeys a logarithmic normal distribution, more details are show in table 1.

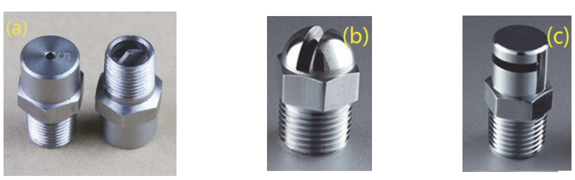

Fig. 3 Water curtain nozzles: (a) Cone-shaped, (b) Vertical ejection fan-shaped, (c) Lateral ejection fan-shaped

Table 1 Information of nozzles and droplets diameter distribution

Nozzle	Spray angle	Mean value (mm)	Standard deviation (mm)
cone-shaped	75°	2.011	0.478
vertical ejection fan-shaped	180°	2.856	0.469
lateral ejection fan-shaped	180°	2.963	0.456

2.3 Infrared imager

The entire process of diesel combustion is recorded in real time by the infrared imager's IR-video function. Table 2 lists the key technical specifications of the infrared imager FLIR SC660 (FLIR, 2010).

Table 2 Key technical specifications of the infrared imager FLIR SC660

Spectrum range (μm)	7.5–13
Measurement range (°C)	-40 °C–+1500
Accuracy	±1% from measured value
Thermal sensitivity (mK)	< 0.03
Spatial resolution	640×480

2.4 Testing procedure

I. Turn on infrared imager, enter the initial parameters based on the environment, and check the status of equipment.
II. Ignite diesel, switch to the video function of the infrared imager, and start collecting data.
III. When the pool fire is close to extinguishment, turn off the infrared imager.
IV. Test the performance on water curtain fighting fire, which cone-shaped nozzles are used. Switch on the water curtain, check pressure meter and flow meter then record the values, and switch off the water curtain. Ignite diesel, turn on the video function of the infrared imager, and start collecting data. When diesel combustion stabilizes, switch on the water curtain. About 2 min later, switch off the water curtain and turn off the infrared imager.
V. Substitute the vertical ejection fan-shaped nozzles for the cone-shaped nozzles, and repeat "Step IV".
VI. Substitute the lateral ejection fan-shaped nozzles for the vertical ejection fan-shaped nozzles, and repeat "Step IV".

3. THEORETICAL BASIS

The infrared radiation is emitted from the pool 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 (Siegel and Howell, 1992):

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

Where σ is the Stefan–Boltzmann constant whose value is 5.67×10^{-8} W•m^{-2}•K^{-4}, ε is the flame emissivity. Based on Eq. (1), for a temperature value which displayed on infrared imager screen, the thermal radiation emitted from fire can be calculated.

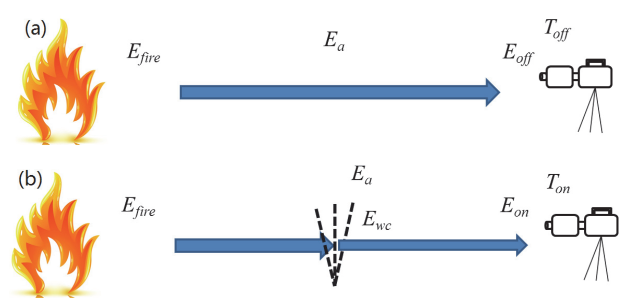

Fig. 4 Principle of infrared imager collecting data: (a) Water curtain switched off, (b) Water curtain switched on

Figure 4 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. The relationship can be written as follows:

$$E_{fire} = E_{off} + E_a \tag{2}$$

$$E_{fire} = E_{on} + E_a + E_{wc} \tag{3}$$

Based on Eqs. (2) and (3), the transmissivity can be defined as

$$Tr = \frac{E_{fire} - E_a - E_{wc}}{E_{fire} - E_a} = \frac{E_{on}}{E_{off}} \tag{4}$$

4. EXPERIMENTAL DATA PROCESSING

Experimental data were processed by FLIR ResearchIR Software which is a professional IR camera control and analysis software for research

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and science applications.

The FLIR ResearchIR Software is based on Digital Image Analysis. Spatial resolution of the infrared imager FLIR SC660 is 640×480, it means that an infrared image is segmented into 640×480 micro-scale regions which represent thermal properties of objects in the infrared image (FLIR, 2011). Figure 5 shows that there are 640 pixels in horizontal dimension and 480 pixels in vertical dimension. The outermost contour of flame can be identified by software and only the data of fire is analyzed, and the background information can be excluded. The flame is a part of image, so micro-scale regions corresponding to flame is less than 640×480.

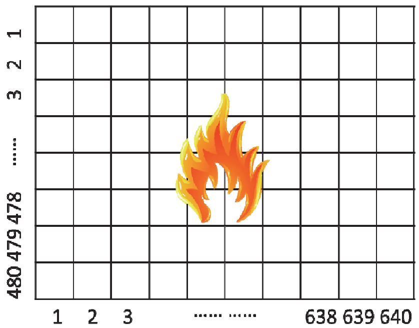

Fig. 5 An image has been segmented into 640×480 micro-scale regions

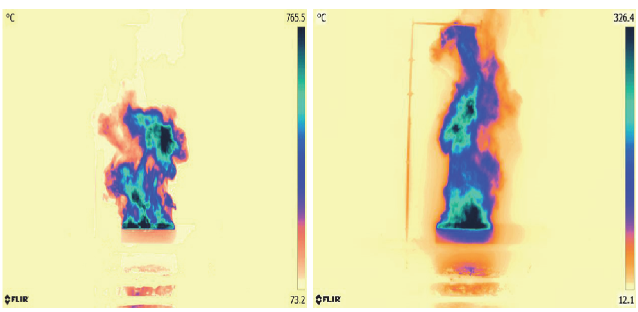

Fig. 6 Infrared images when the water curtain is switched off (left) and on (right)

For a given time, Fig. 6 shows infrared images obtained when the water curtain was switched off and on. The flame height varies significantly over time, by contrast, the flame width exhibits a smaller variation. Based on the FLIR ResearchIR Software, data for temperature and thermal radiation variations are shown in Fig. 7 and Fig. 8, respectively. The horizontal coordinates is, for the horizontal projection of flame, a total number of micro-scale regions away from the left-most of flame. In Fig. 7, the vertical coordinates is an average datum corresponding to micro-scale regions which sum vertical micro-scale regions for a certain horizontal micro-scale region of the flame.

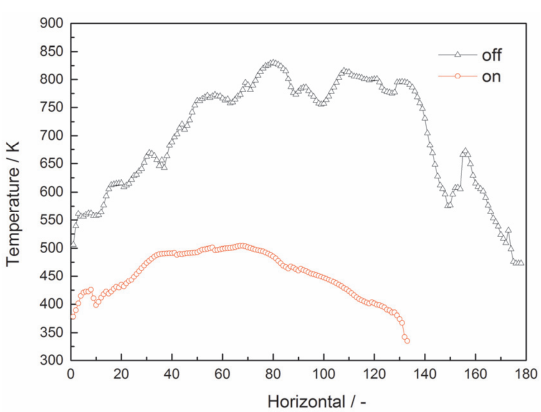

Fig. 7 Temperature of pool fire

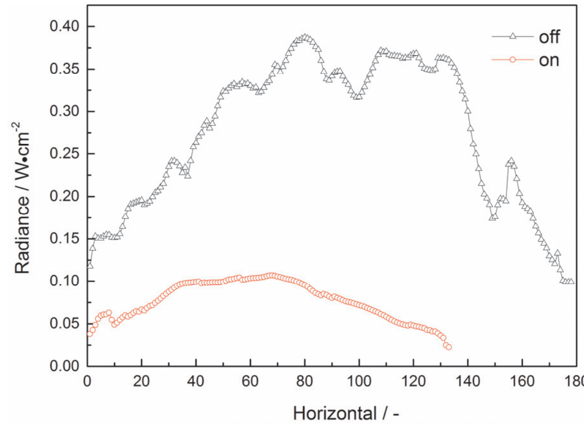

Fig. 8 Thermal radiation emitted from pool fire

Figure 8 shows different thermal radiation levels over horizontal variation whatever the water curtain is switched off or on, their arithmetic average values can be calculated. The transmissivity of water curtain can be determined by a ratio of the average radiation value when water curtain on over the case water curtain off.

5. RESULTS AND DISCUSSIONS

According to the actual testing situation, values of atmospheric temperature, atmospheric humidity, and testing distance are inputted in the infrared imager. According to the size of container, the value of flame emissivity of burning diesel is 0.8 (Kamimoto and Murayama, 2011; Zhang et al., 2009).

5.1 Fluctuation of flame during combustion

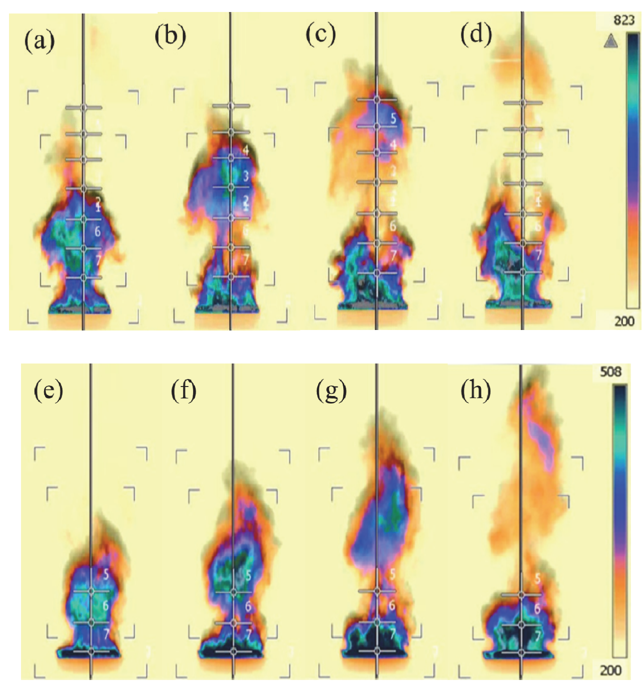

Fig. 9 Periodic infrared images of turbulent fluctuating flame. (a), (b), (c), and (d) are captured when the water curtain was switched off, (e), (f), (g), and (h) are captured when the water curtain was switched on.

Figure 9 contains a group of periodic infrared images of flame turbulent fluctuations during combustion. As shown in Fig. 9 (a), (b), (c), and (d) are recorded when the water curtain was switched off, while (e), (f), (g), and (h) are recorded when the water curtain was switched on. 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 the water curtain was switched on and off. An obvious difference is observed in the maximum temperature value displayed on the thermal infrared imager. When the water curtain was switched on, the maximum displayed temperature is about 850 °C (1023 K), and the temperature is around 500 °C (773 K) when water curtain was switched off. Qualitatively, the water curtain can attenuate thermal radiation of fire.

As shown in Fig. 9, the flame temperature changed continuously over both time and space, it is a rational way to quantitatively characterize the thermal radiation attenuation of water curtain that by using the average radiation value. At a given time, the transmissivity is defined as the ratio of radiation with the water curtain switched on over the case when water curtain is switched off. After water curtain switched on, the value of transmissivity updated every 5 seconds.

5.2 Fireproofing performance of water curtain with different nozzle types

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

(1) Cone-shaped nozzle

At the 50th second, the pump was turned on. Testing was conducted under the operation condition of 0.13 MPa pressure and 51 L/min flow rate.

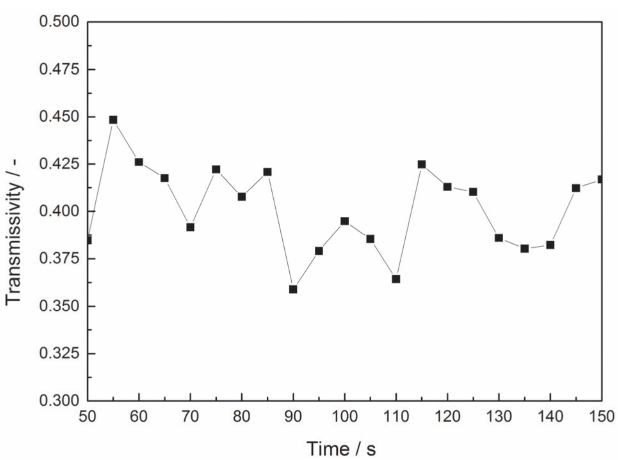

Fig. 10 Real-time transmissivity of water curtain with cone-shaped nozzles

Figure 10 shows the transmissivity variation over time, and the average value is 0.417. The oscillation of transmissivity is due to the fluctuation of flame during combustion. For the testing of cone-shaped nozzle, the maximum transmissivity is about 0.45 while the minimum is approximately 0.35.

(2) Vertical ejection fan-shaped nozzle

At the 70th second, the pump was turned on. Testing was conducted with 0.05 MPa pressure and 54 L/min flow rate.

Figure 11 shows that the average value of transmissivity is 0.611, the minimum transmissivity is approximately 0.55 while the maximum is about 0.65 with an exceptional datum which more than 0.7. The abnormal datum reflects that an abnormal intense radiation is collected by infrared imager, which means that the flame combusts more intense suddenly. According to the situation of testing, this phenomenon probably because, on one hand, a sudden lateral wind which intensifies the combustion of fire, on the other hand, water droplets mingled with flame, which makes the boiling overflow and splash of pool fire.

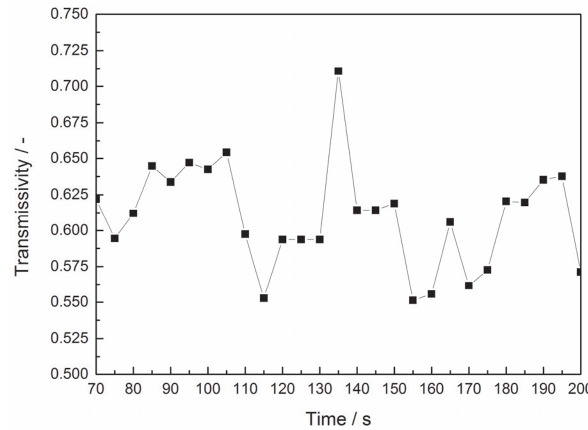

Fig. 11 Real-time transmissivity of water curtain with vertical ejection fan-shaped nozzles

(3) Lateral ejection fan-shaped nozzle

At the 40th second, the pump was turned on. The testing involved a pressure of 0.04 MPa and a flow rate of 59 L/min.

Figure 12 shows that the average value of transmissivity is 0.701, the minimum transmissivity is approximately 0.65 while the maximum is about 0.75. Furthermore, a comprehensive analysis of Figs. 10-12 shows that the transmissivity of water curtain fluctuated around the average value and the fluctuation range is less than 10%.

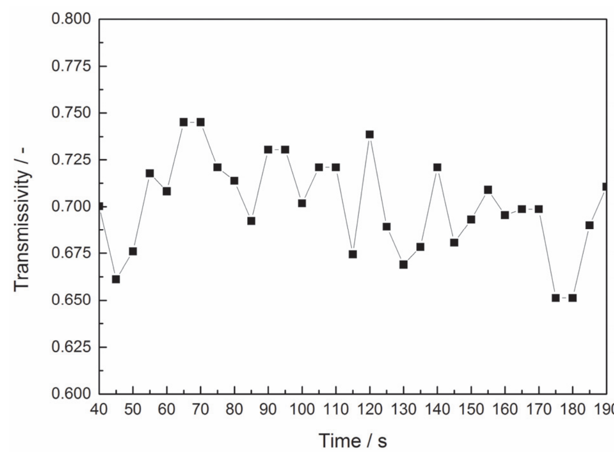

Fig. 12 Real-time transmissivity of water curtain with lateral injection fan nozzles

6. CONCLUSIONS

An experimental method based on infrared technique was developed to quantify the performance on water curtain fighting fire.

1) A flame of pool fire showed obvious turbulent fluctuation during combustion. An infrared imager could make a real-time response to dynamic temperature and thermal radiation fluctuations of the flame, regardless of whether the water curtain was switched on or not.

2) To deal with the fluctuation of flame, the transmissivity of water curtain can be defined by a ratio of an average radiation value when water curtain on over the case water curtain off, and be determined by the average value over time finally.

3) For tests used the same testing platform, only the water curtain nozzles were changed. Average values of transmissivity for water curtain with cone-shaped nozzles, vertical ejection fan-shaped nozzles and lateral ejection fan-shaped nozzles were 0.417, 0.611 and 0.701 respectively, and the fluctuation range was less than 10%.

4) The proposed method can be used to provide guidance on the development and design of water curtain fighting fire in fields such as national defense, military, safety and chemical engineering.

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