Experimental study on the ignition characteristics of leaking RP-3 aviation kerosene on a horizontal hot wall

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Abstract. The accidental ignition of liquid fuels is an industrial safety concern due to the storage and transport of pressurized flammable liquids near components at elevated temperatures. In this work, the ignition process of leaked RP-3 aviation kerosene on the surface of the high temperature heat meter was studied experimentally and the critical temperature of the 50% ignition probability was obtained by the statistical method. The ignition process of fuel on horizontal hot wall was analysed by using the ignition video shot by high-speed camera, and the fuel steam plume model of the minimum hot surface ignition temperature for spilled fuel was established, which provided a theoretical basis for quantitative research on the ignition characteristics of leaking fuel on the hot surface. It shows that the temperature field and spatial concentration distribution produced by oil evaporation are time-varying and helpful for engine room fire protection. This study complements the related content of the fuel ignition mechanism on hot wall, at the same time, and provides fundamental understanding of the physical phenomena involved in the thermal ignition of impinging sprays in different regimes toward the goal of improved industrial safety.

Keywords: Aviation fuel, Hot surface, Thermal ignition, Fuel steam plume model.

1 Introduction

Accidental ignition is a critical safety concern for many industries[1-5]. In particular, the ignition of fuel sprays by hot surfaces is a hazard that is present in a wide range of industries and consumer applications that operate with flammable liquids[6, 7]. These include the automotive, aerospace, chemical, and petroleum industries[2, 8].If any leaked fuel is spayed over them accidentally, it would be evaporated. The resulting vapor can be heated by the hot surface and may ignite[9].

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Ignition by hot surfaces has been studied for both gaseous and liquid fuels in both premixed and non-premixed regimes[2]. Early theoretical work by Law[10] and Laurendeau[11] established the importance of surface temperature, pressure and flow velocity in the premixed context. However, they have not established a proper method to measure the MHSIT for the fuels with multiple components and have few researches on the mechanism of fuel fire in engine compartment. The convective plume of fuel vapor above a horizontal heated surface is very complex despite its simple geometry.

In this paper, the rule and the influence factors of the leaked aviation kerosene on horizontal hot wall were studied and analyzed through utilizing experiment to simulate the whole ignition process of the leaked aviation kerosene on horizontal hot surface[9, 12]. The present study seeks to build a three-dimensional model to describe the fuel vapor plume on a heated surface, and model and analyze the hot surface ignition behavior of an impinging RP -3 jet fuel at atmospheric pressure[2].

2 Experiment

The experimental set-up is shown in Fig.1[9].Temperature measuring device adopts imported K-type thermocouple, temperature measuring range can be (0~1370) ℃, installed at the bottom of the heating plate, measurement of high temperature hot surface temperature. The fuel leak simulator consists of an adjustable platform device and a glass dropper. The heat loss from the hot plate was mainly from the upward side to the surrounding area. Program control keeped hot plate temperature stable. The fuel flowed out from the leakage simulator, and the leakage port was 2 cm away from the hot plate to prevent the fuel from sputtering after contacting the hot plate. As the experiment began, the surface would be heated to a target temperature. The disk temperature was thought to be stable as the temperature changed by less than 5℃/min. Then a liquid fuel of the 5ml was pumped onto the heated surface by a funnel. A camera at 50 frames per second was applied to record the process of the evaporation and ignition above the heated surface. During the experiment, the ambient gas convection was controlled to reduce the influence of external gas flow.

The motion and ignition processes of the hot surface were recorded with a video camera (at 50 frames per second) from a front view. Because of the complexity and randomness in experimental conditions, at least 5-6 repeated runs were conducted for each set of experimental conditions to quantify the probability of each experimental outcome[1, 9].

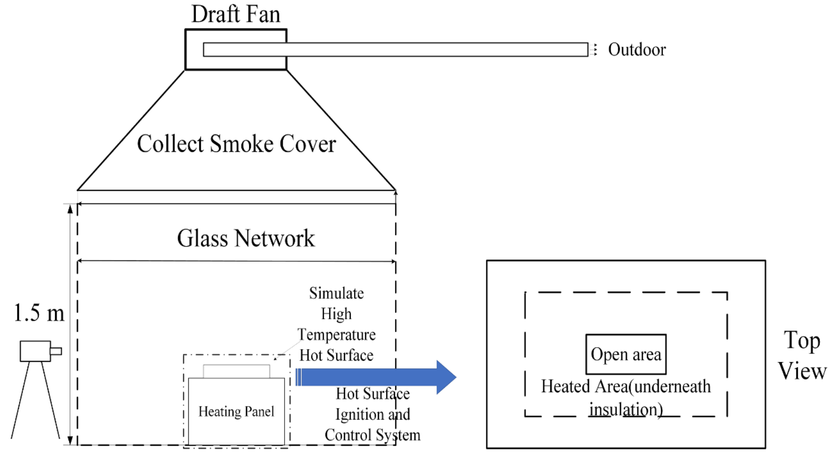

Fig. 1. Experimental setup for the hot wall ignition of leaking fuel.

3 Results and discussion

3.1 Ignition phenomenon

After the fuel flowed to the hot wall, due to that the hot wall temperature was higher than the boiling point of the fuel, the fuel would appear the boiling phenomenon (as shown in Fig.2)[12]. As the temperature of hot wall increased, the three boiling modes could be observed[7]. When the fuel oil on the hot surface began to boil, a lot of steam was produced. Unlike a pool fire, it can be observed that the fire reaches its maximum size immediately after the fuel oil leaks onto the hot surface, which does not have an initial growth stage.

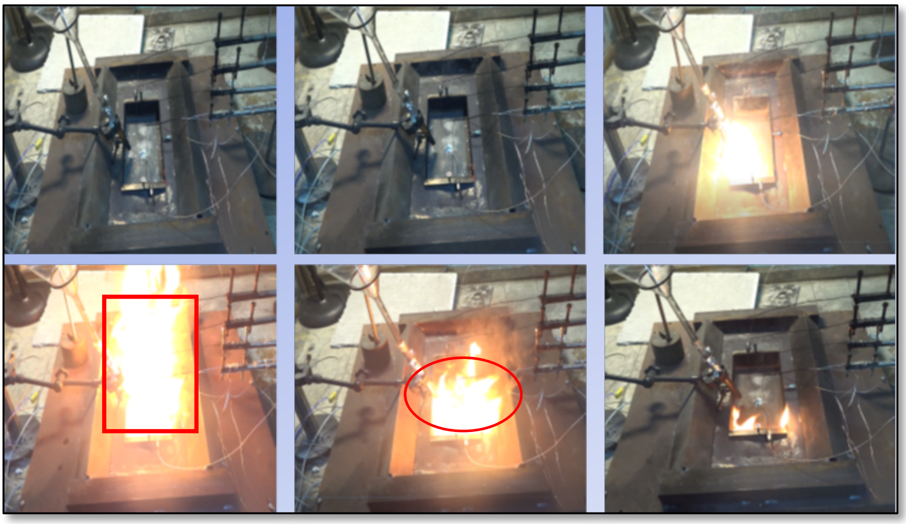

Fig. 2. Hot wall fire diagram of leaking fuel.

From Fig. 3 it can be seen that the fuel ignition process is captured by a high-speed camera. As the superheat increased, the number of active nucleation points and the frequency of bubble rise augmented. When there were too many active nucleation points on the wall surface, the bubbles began to gather and merge with each other, which were blown away from the hot wall. The formation, growth, jump and movement of a large number of bubbles constitute a strong convective heat transfer between the hot wall surface and the fluid.

Fig. 3. Ignition spread process of 5 mL jet coal at high temperature hot surface.

3.2 Ignition temperature

The movement of air around the horizontal hot plate under the action of convection and diffusion is very complicated, and the uncertainty of evaporation of continuous liquid flow on the hot plate surface and subsequent entrainment of steam and air makes the determination of the ignition conditions much more difficult. The ignition of fuel oscillates over a certain temperature range. In order to judge the ignition temperature accurately, Bruceton statistical processing method was used[9]. It was found that the measured minimum heated surface ignition temperature(MHSIT) changed over a wide range. In the experiment, the starting horizontal temperature h and the temperature interval d were determined. The first experiment was carried out at the horizontal temperature h. If there was fire, it was indicated by the symbol "√". Then the next experiment should be carried out at $h-d$ temperature. If "no fire", with the symbol "×", the next experiment should be conducted at $h+d$ temperature, and so on. The all "no fire" under the next experiment should increase the temperature, and the all "fire" under the experiment to reduce the temperature. The experimental results are shown in Table 1.

Table 1. Ignition results of aviation fuel on horizontal thermal wall.

Experimental condition (ignition √,no ignition ×)																			Ignition results	
Hot surface temperature/℃	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Ignition	No ignition
410	√																		1	0
400		√						√						√		√		√	5	0
390			√				×		√		√		×		×		×		3	4
380				√		×				×		×							1	3
370					×														0	1

The critical temperature at which the ignition probability is 50% can be provided based on the statistical results. It is calculated using[9]:

$$T_m = h + d(\frac{1}{N(0)}\sum in_0 + \frac{1}{2}) \tag{1}$$

where T_m is the critical temperature at which the ignition probability is 50%, h is the initial temperature , d is the temperature interval, $N(0)$ is the total number of ignition , i is the level number 1,2,3…, $n(0)$ is the number of ignition on each level.

By putting the experimental data into the statistical formula, the hot surface temperature T_m with 50% ignition probability is 402 ℃.

3.3 Empirical modeling of minimum hot surface ignition temperature for spilled fuel

In the experiment, it was found that a certain amount of fuel leaked to the hot surface of high temperature would generally evaporate as moving small liquid beads or a mass of oil film, as shown in Fig 2. Therefore, the ignition process of a certain amount of fuel on the hot surface under static conditions is studied.

As shown in Fig.4, the buoyancy plume model can be used to describe the movement and ignition of fuel vapor on the hot wall under buoyancy caused by the density difference between steam generated by fuel evaporation and air and to estimate the concentration distribution of fuel vapor at a certain height above the hot wall adopted by Bennett et al[13]. The concentration distribution of fuel steam can be expressed as:

$$B = \frac{\dot{m}_p\, g(\rho_\infty - \rho)}{\rho_\infty} \tag{4}$$

$$u = (\frac{5}{6}\alpha)(\frac{9aB}{10\pi})^{1/3} z^{-\frac{1}{3}} \tag{5}$$

$$\frac{\Delta\rho}{\rho^2_\infty} = (\frac{5B}{6\pi\alpha g})(\frac{9\alpha B}{10\pi})^{-\frac{1}{3}} z^{-\frac{5}{3}} \tag{6}$$

where B is the initial specific buoyant flux, $\dot{m}_p$ is the initial mass flow rate of fuel steam (it is assumed that it approximates the boiling evaporation rate of the oil film), ρ_∞ is the air density, ρ is the local plume density at a certain altitude z .

Fig. 5 depicts the process of boiling of the spilled fuel on the different temperature hot surfaces. As the evaporation proceeds, the fuel steam accumulates and fires occur. The temperature changes of 0.15m,0.20m and 0.25m above the hot surface were recorded by the thermocouples. It can be seen that when the hot surface temperature are 370℃ and 400℃ respectively, the temperature zones appear in the fuel vapor plumes. This is consistent with the plume model proposed by Bennett[13].

According to the ignition theory, it is assumed that the steam change trend is consistent at any point in the vertical direction of the oil pool or oil film. As the steam leaves the liquid surface, it moves upward, sucking in the surrounding air. As the temperature of the surrounding air is lower, the temperature of the mixture decreases as the steam is diluted by the air. Next, the vapor concentration drops to near zero and the temperature of the gas is the temperature of the air at infinity[14-18]. This trend is well described in Fig.4 and Fig.5.

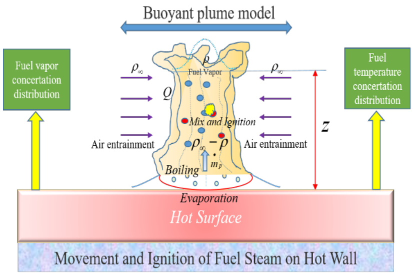

Fig. 4. Empirical modeling of minimum hot surface ignition temperature for spilled fuel.

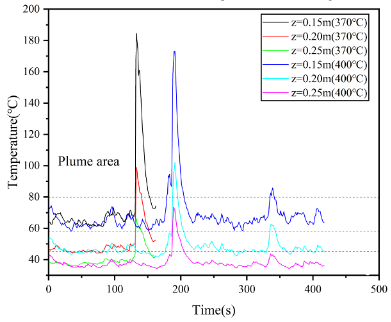

Fig. 5. Temperature distribution of the fuel vapor plumes at the different heights.

4 Conclusions

An impinging fuel spray was analyzed under conditions of hot surface ignition using the combination of experiment and theoretical methods, the conclusions are obtained as below:

(1) The critical temperature for the 50% ignition probability was calculated. By analyzing the boiling heat transfer of leaked oil on the hot surface, in the experiment, it was found that the temperature of the thermocouple controlled by temperature and the actual temperature were within this range.

(2) The buoyancy plume model can be used to describe the movement. The ignition of fuel vapor on the hot wall under buoyancy caused by the density difference between steam generated by fuel evaporation and air and to estimate the concentration distribution of fuel vapor at a certain height above the hot wall. It can be seen that when the hot surface temperature are 370℃ and 400℃ respectively, the temperature zones appear in the fuel vapor plumes. It shows that the temperature field and spatial concentration distribution produced by oil evaporation are time-varying.

Future research will focus on providing the suitable surface protection to weaken the boiling heat transfer from a heated surface in order to delay the ignition and lower the probability of fire. It requires the consideration of effects of the impingement angle, fuel mass flow rate and initially non-quiescent domains on the development of mixing structures and subsequent ignition.

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