New insights into the ignition characteristics of liquid fuels on

hot surfaces based on TG-FTIR

Jian Chen¹, Zhenghui Wang², Yanni Zhang¹, Yang Li³, Wai Cheong Tam⁴, Depeng Kong^{2,*} Jun Deng^{1,*}

¹College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China

²Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China), Qingdao 266580, China

³Forensic Science Institute, China People's Police University, Langfang, Hebei, 220 Xichang Road, 065000, China

⁴*Fire Research Division, National Institute of Standards and Technology, Gaithersburg, MD 20899, United States.*

Corresponding author: kongdepeng@upc.edu.cn (Prof. Kong); dengj518@xust.edu.cn (Prof. Deng)

Abstract

There are many potential hazards related with hot surface in industrial processes. Therefore, the ignition characteristics of liquid fuels on hot surfaces play an important role for fire safety engineering involved with energy utilization. In this study, thermogravimetric analysis and hot surface tests were systematically conducted for some typical liquid fuels. In the hot surface tests, ignition parameters were measured and investigated, including ignition probability and characteristic ignition temperature. It was found that the ignition of liquid fuel on the hot surface was probabilistic. The boil-over phenomenon was observed for transformer oil when the hot surface temperature was above 693 K, where the liquid fuel burned over the pan. For the three liquid fuel selected in our studies, the order of lowest ignition temperature was not consistent with the order of the kinetic parameter. Furthermore, the comparative analysis revealed that the lowest ignition temperatures with ignition probability of 5 % were observed to be within the temperature ranges of combustible gases generation, indicating that the ignition of the liquid fuels on the hot surface was significantly influenced by the combustible gas generated during the evaporation and thermal decomposition. Finally, the model describing the profiles for the concentration and temperature of combustible vapor was introduced to provide a detail explanation for the ignition mechanism of liquid fuels on hot surfaces. The established model could provide scientific basis to the fire risk assessment for liquid fuel fire caused by the hot surface, and further optimize the safe usage of liquid fuels.

Keywords: Hot surface, Liquid fuels, TG-FTIR analysis, Ignition probability

1. Introduction

Energy takes a leading role in the economic growth and industrial development. According to the World Energy Assessment Report, about 43% of the overall energy consumption around the world is provided by oil and the derived liquid fuels, which are essential in various fields in daily life and industrial production [1, 2]. Due to the widespread use of liquid fuels, the safety issues associated with them are currently attracting considerable critical attention, particularly in the energy and chemical industry. There are various potential risks associated with the production and consumption for liquid fuels, where the possibility of fire and explosion accidents is exceptionally high, which poses a significant threat to people's safety and also the surrounding environment [3, 4]. In order to identify and assess the hazards situations in energy utilization and production, the European Standard of EN 1127-1-2019 classifies 13 types of possible ignition sources, where hot surfaces are typical ignition sources that lead to fire and explosion. There are lots of hot surfaces existing in industrial processes. In the chemical industries, there are some severe operating conditions related with high temperature [5, 6]. These work conditions dictate the presence of installation equipment with hot surfaces, such as fluid catalytic cracking regenerator with 823 K, catalytic reforming reactor with 793 K and so on [7]. Once the liquid fuel encounters the obstacle with hot surfaces, it may lead to serious fire accidents. On the other hand, there are also many potential hazards related with hot surface in the energy transportation and utilization, such as overheated bearing, engines, turbochargers, etc. According to the statistics of vehicle fires in the United States, more than two-thirds of fire accidents occurs in the engine compartment, where hot surfaces are important ignition sources [8]. Therefore, the study involved with ignition characteristics for liquid fuels on hot surfaces could reduce the hazards of liquid fuel fire to ecological environment, and further enhance the safe usage of liquid fuels.

Auto-ignition temperature (AIT), defined as the lowest temperature at which the fuel can ignite in air at atmospheric pressure without the aid of external energy sources, is usually used in the fire risk assessment of liquid fuels [9, 10]. The measurement method for the auto-ignition temperature of liquid fuels is described in the standard of ASTM E-659. In the test, 100 μ L fluid is inserted into a uniformly heated glass flask that contains air at a predetermined temperature, and the liquid subsequently evaporates and mixes with the air. The ignition phenomenon is observed for approximately 10 minutes or until ignition occurs. Although the ASTM E-659 standard is widely used for evaluating the flammability characteristic of liquid fuels, it is not applicable for assessing the ignition characteristics of hot surfaces [11]. Therefore, many researchers have performed lots of hot surface tests, and measured the ignition characteristics for some common liquid fuels. According to the

previous numerous studies, it was found that ignition characteristics of liquid fuels on hot surfaces depend on many factors including physical properties of liquid fuels, surface properties and environmental factors [12]. The physical properties of liquid fuels, such as flash point, octane number and volatility, play a crucial role in its spreading, heat transfer, evaporation, boiling, and ignition behavior on the surface. Among the surface properties, the most important parameter is the roughness or texture, and previous studies [13-16] have shown that the ignition time of liquid oil droplets can be controlled by varying the roughness characteristics of the heated surface. In addition, external environmental conditions would have a significant influence on the ignition behavior, such as atmospheric pressure, ambient temperature, and velocity fields. Davis et al. [17, 18] conducted a series of hot surface test for various liquid fuel, and found that the ignition of liquid fuels was probabilistic, and the ignition temperature increased as octane number increased for standard gasoline blends. Moreover, the results obtained from Tang et al. [19] revealed that ignition possibility of liquid fuel on carbon steel was less than stainless steel and cast iron. Recently, Zhu et al. [20] described the flow field of fuel vapor on the hot surface with the effect of buoyancy, and indicated that the profiles of combustible vapor concentration and temperature produced were unstable.

As a pivotal ignition method, the hot surface ignition of liquid fuels has attracted substantial attention in the field of engine combustion. Tushar et al. [21] conducted a series of experiments on the hot surface ignition of fuel sprays in a combustion chamber, where experimental variables included chamber pressure, injection pressures, and surface temperature. The results revealed that the ignition delay time was strongly correlated with the wall surface temperature. To enhance the combustion characteristics of conventional

liquid fuels, the ignition properties of diesel-based nanofuels were studied through hot surface experiments [22-24]. It was discovered that metal oxide nanoparticles significantly improved the hot surface ignition probability of diesel, and the ignition probability increased with the nanoparticles concentration. Glushkov et al. [25] conducted further research for composite fuel droplets consisting of coal, oil and water, found that the leidenfrost phenomenon obviously influences the ignition properties of composite materials. Valiullin et al. [26] used hot surface as a typical conductive ignition method to investigate the ignition properties of slurry fuel, and discovered that the ash encrust forming in the contact area would decrease the intensity of oxidation reactions. Yi et al. [27] conducted research on the vaporization and spontaneous ignition of individual lubricating oil droplets under the operating conditions of a natural gas engine, and found that the vaporization characteristics of lubricating oil droplets with lower volatility would play an important role in the ignition behaviour. C. K. Law et al. [28] investigated the ignition phenomena exhibited by dodecane droplets within a controlled pressure chamber. The findings revealed that, at surface temperatures ranging from 473 K to 563 K, the autoignition only occurred at specific pressures. It should be noted that these hot surface ignition tests were predominantly conducted within combustion chambers to simulate engine conditions. However, liquid fuel leakage fire scenarios typically occur in open spaces. Although the application of hot surface ignition differs significantly from fire incidents induced by the hot surface, these relevant studies have elucidated the ignition process of a multiphase flow of fuel spray and air with hot surface, which offer profound insights into a more comprehensive understanding for fire accident caused by hot surface.

The liquid fuel after impinging on hot surfaces involves the full complex of heat and mass transfer processes occurring under conditions of intense phase (combustible vapor generation) and thermochemical transformations (thermal decomposition reactions of liquid fuel). A great deal of previous research [29-32] into this problem has focused on coal-water fuel. Kuznetsov et al. [29] introduced a analytical model for coal water fuel ignition. This model accounts for basic physical processes occuring together before ignition, encompassing water evaporation, thermal decomposition, volatile ignition and etc. Based on the proposed mathematical model, several factors influencing the ignition process of coal-water fuel were assessed, including heat transfer conditions [32], particle morphology [31], and the degree of coal metamorphism [30]. These studies for coal-water fuel offer crucial insights into the ignition conditions of liquid fuel related with complex thermochemical transformations.

After the thermochemical transformations for liquid fuel over the hot surface, the generated combustible vapor would mix with surrounding air, reaching ignition conditions. Therefore, much of the current literature on ignition mechanisms of liquid fuel pays particular attention to the numerical models related with ignition processes. Li et al. [33] utilized the Fire Dynamics Simulator to simulate turbulent plume flow of combustible vapor, where the large eddy simulation was applied. The results were analyzed to delineate the airborne ignition phenomenon and identify the significant role of boiling heat transfer in the ignition process. Then, Boussouf et al. [34] simulated the release of lubricating oil onto the hot surface, where the details information about temperature and concentration field were obtained to describe the ignition process and postion. Wang et al. [35] developed a three-dimensional numerical model for leaked fuel ignited by hot surface within ship

engine compartments, investigating the impact of ventilation and wettability on the ignition process.

To clearly describe the scientific reasons, the innovation and flowchart of current study are given in Fig. 1. In the previous studies related with the ignition characteristic of liquid fuels on hot surfaces, the most researchers investigated the ignition characteristic through probability statistics and qualitative descriptions as shown in the right half of Fig. 1, where characteristic parameters included ignition probability and ignition delay time [36]. However, there is relatively limited research on the ignition mechanism of liquid fuels on hot surfaces, apart from flow characteristics of combustible vapor through CFD method described in a few literature. With the effect of high temperatures, evaporation and thermal decomposition reactions would occur for liquid fuel after impinging on hot surfaces, therefore the chemical nature of liquid fuel would play important role in revealing the ignition mechanism of hot surface, especially for liquid fuels with a relatively complex composition [37]. Recently, Li et al. [38] combined thermogravimetric analysis and hot surface test for the ignition coal dust on the hot surface, and established the comprehensive assessment method to characterize the spontaneous ignition tendency of the coal dust on the hot surface. Antonov et al. [39] employed the high-speed cameras to study the microexplosive behavior of oil-water droplets containing coal particles, and found that the average radius of child droplets generated during the micro-explosion process decreased with the increase in temperature. Furthermore, the presence of coal particles also led to a significant reduction in these radii. Through experimental observation and numerical analysis, Glushkov et al. [40, 41] established a mathematical model for the coal dust ignited by hot particles, where the heat and mass transfer as well as chemical reactions were included. The introduced model could accurately predict ignition conditions during the interaction between hot metal particles and coal dust layers. Dhiman et al. [42] obtained the volatilization properties of biomass feedstock dusts by thermogravimetric analysis for estimating the hot surface ignition temperature. However, the comprehensive study of thermogravimetric analysis and hot surface ignition characteristics is currently limited to some typical solid fuels or coal water fuel. For liquid fuels, the relationship between the hot surface ignition characteristics and thermal behavior based on thermogravimetric analysis remains unknown. Therefore, it is necessary to further investigate the ignition mechanism of liquid fuels based on the thermogravimetric analysis.



Fig. 1. The innovation and flowchart of current study

Therefore, the chemical nature and hot surface ignition characteristics of liquid fuels were investigated thoroughly by comprehensive experiment, including thermogravimetric analyzer coupled with a Fourier transform infrared spectrometer (TG-FTIR) and hot surface ignition experiments. In the thermogravimetric analysis, the evolution of gaseous products for liquid fuels during high temperature was analyzed, and the kinetic parameters for some typical liquid fuel were calculated and compared. In the hot surface ignition experiments, the ignition characteristics were measured and investigated, including ignition probability and characteristic ignition temperature. Then, the relationship between ignition probabilities and the variations of the absorbance of combustible gases was revealed, and the model considering the auto-ignition temperature of combustible vapor was introduced to explain the ignition of liquid fuels on hot surfaces. The established model could promote the understanding for the ignition mechanism of flammable liquid fuels on hot surfaces. This work could provide scientific basis and technical support to the fire risk assessment for liquid fuel fire caused by the hot surface, and further optimize the safe usage of liquid fuels.

2. Experiments and methods

2.1 TG-FTIR experiments and kinetic analysis

The TG-FTIR test was performed using a thermogravimetric analyzer coupled with simultaneous FTIR spectrometer to investigate the composition of gaseous products generated during the thermogravimetric analysis. Thermogravimetric experiment was conducted on the thermogravimetric analyzer (TGA 8000) produced by PerkinElmer, USA. In the atmosphere with an air flow rate of 50 mL/min, the sample of ~ 10 mg was heated from 303 K to 1173 K at the heating rate of 10 K/min. The FTIR spectrometer (TL-9000, PerkinElmer, USA) was coupled with the TG analyzer to track the evolution of gaseous products of liquid fuel samples. The gaseous products from the thermogravimetric analyzer entered the FTIR spectrometer through a transmission line. Prior to experiments, the transfer line was heated to 523 K to prevent the condensation of the gaseous products. The

FTIR spectra of the gaseous products were recorded with the range of $4000-450 \text{ cm}^{-1}$, and the time interval for data collection was 11s.

The results of thermogravimetric experiments were used to estimate kinetic parameters, including apparent activation energy (E_a) and pre-exponential factor (A). The oxidation reaction rate of thermogravimetric experiments can be described as follows:

$$\frac{d\alpha}{dt} = \beta \frac{d\alpha}{dT} = k(T) f(\alpha) = Aexp\left(-\frac{E_a}{RT}\right) f(\alpha)$$
(1)

where β is heating rate, k(T) represented the constant of the reaction rate, T is the absolute temperature (K), R refers to the universal gas constant (8.314 J·mol⁻¹ ·K⁻¹), $f(\alpha)$ is the kinetic model. α is the degree of conversion, which can be calculated from Eq. (2):

$$\alpha = \frac{m_0 - m_t}{m_0 - m_f} \tag{2}$$

where m_0 , m_t , and m_f are the initial mass, instantaneous mass and final mass of the samples, respectively. The range of α is from 0 % to 100 %, representing the degree of pyrolytic conversion. Under linear heating conditions, Eq. (1) can be expressed as follows:

$$\frac{d\alpha}{dT} = \frac{A}{\beta} exp\left(-\frac{E_a}{RT}\right) f(\alpha)$$
(3)

The integral kinetic model $g(\alpha)$ is the integral form of $f(\alpha)$, which can be written as:

$$g(\alpha) = \int_0^\alpha \frac{d\alpha}{f(\alpha)} = \frac{A}{\beta} \int_{T_0}^T exp\left(-\frac{E_a}{RT}\right) dT$$
(4)

Eq. (4) can be used to determine the kinetic parameters, i.e. E_a and A. Through kinetic analysis, the thermal characteristics of liquid fuel samples could be quantified [43].



Fig. 2. Schematic of the ignition experiment setup for liquid fuel samples on the hot surface

The experiment setup of hot surface test was shown in Fig. 2, which was composed of the heating system and measurement system. The heating system included an electric heating plate (DB-XWJ, Lichen Technology, China) and a steel pan with an inner diameter of 8 cm and an inner depth of 2 cm. The pan thickness was 0.1 cm \pm 0.01 cm. The steel pan placed on the center of the heating plate was used as the hot surface to heat the liquid fuel samples. The steel pan was heated by the heating plate and its temperature could be increased from ambient temperature to 873 K by proportional integral derivative (PID) control. The temperature at different locations on the surface of the steel pan was measured by thermocouples to ensure uniform temperature distribution, where the surface temperature was controlled and stabilized within \pm 5 K. Then the liquid fuel of the 3 mL \pm 0.1mL was pumped onto the hot surface at a flow rate of 1 mL/s.

The ignition parameter measurement system was used to characterize the ignition characteristics. The mass loss rate with time was obtained by an electronic balance (UW6200H, Shimadzu, Japan), which was positioned directly under the heating plate. As shown in Fig. 2, some K type thermocouples with the diameter of 1 mm was placed above the hot surface to obtain the temperature field of combustible vapor and burning flame. The temperature sampling frequency is 1Hz. A digital camera (Canon 500D, Canon, Japan) with a frame rate of 50 fps was employed to record the entire ignition and burning process of liquid fuels on the hot surface. The camera was placed about 50 cm vertically away from the hot surface and 150 cm horizontally away from the center of the steel pan. The recorded video was analyzed by an in-house code written in MATLAB to extract the frame-by-frame information of the vapor and flame plume. In the present study, ignition was determined once small flame was observed, while it was considered as not ignited if ignition of the liquid fuel samples did not occur within a given heating time.

Fuel	Density (kg/m ³)	Heat of combustion (J/g)	Kinematic viscosity (mm ² /s)	Dynamic viscosity (mpa·s)
Light crude oil	860.62	43701	15.729	13.537
Transformer oil	838.62	38967	15.921	13.352
Corn oil	918.88	45743	59.336	54.523

Table 1 Thermophysical parameters of liquid fuel

In the real fire scenario caused by the liquid fuel on hot surfaces, such as in chemical plants, vehicle incidents, and kitchens, the liquid fuels involved include light crude oil, gasoline, diesel, transformer oil, and corn oil. Previous research [62] has been conducted on gasoline, diesel and aviation kerosene. Meanwhile considering the temperature limitation of electric heating plate, light crude oil, corn oil and transformer oil were chosen as liquid fuel samples in current study. It is noteworthy that more liquid fuels would be tested in the our future study, including battery electrolytes and biomass fuels.

Table 1 summarizes the thermophysical parameters of liquid fuel, including density, heat of combustion, kinematic viscosity and dynamic viscosity. Here, the heat of combustion was measured base on the Determination of calorific value of petroleum products (GB 384-1981). The viscosity was measured at 298 K based on the Standard test method for dynamic viscosity and density of liquids by Stabinger viscometer (NB/SH/T 0870-2013). According to the information provided by the manufacturer, the composition of light crude oil and lubricating oil includes hydrocarbons such as alkanes, aromatics, as well as non-hydrocarbon compounds like asphaltenes. Corn oil is mainly composed of unsaturated fatty acids. In addition, prior to the experiments, the liquid fuel samples were kept in air-tight containers to minimize oxidation.

3. Results and discussion

3.1. TG-FTIR analysis

3.1.1 TG analysis

Fig. 3 demonstrates the TG (thermogravimetry) and DTG (derivative thermogravimetry) curves of liquid fuel samples at the heating rate of 10 K/min, including light crude oil, corn oil and transformer oil. From the TG curves, it was found that the weights of the three liquid fuels decreased monotonically with the temperature increasing, indicating there was no significant oxygen absorption in the heating process. According to the DTG curves, the thermal process of light crude oil and corn oil could be divided into three stages, while the result of transformer oil showed only one stage with a noticeable single peak. As shown in Fig. 3, the total weight loss of light crude oil, transformer oil and corn oil were 98.09 %, 99.12 % and 99.10 %, respectively, which was caused by the

distillation, evaporation and oxidation reactions during the heating process [44]. The light crude oil had more residue remaining after oxidation reactions because it contained small amounts of heavy fractions, such as asphaltenes and resins [45].



Fig. 3. TG/DTG curves of liquid fuel samples in air atmosphere at the heating rate of 10 K/min.(a) light crude oil, (b) corn oil, (c) transformer oil.

Based on the TG-DTG curves, some different reaction stages are divided and summarized in Table 2. As shown in Table 2, the first oxidation reaction stage of light crude oil occurring in the temperature range of 303-654 K was generally referred as the low-temperature oxidation (LTO). As light crude oil was mainly composed of light components such as saturated hydrocarbons and aromatics, the mass loss of light crude oil in the low-temperature oxidation region was very large, about 84.29 %. In the initial phase with temperatures from 303 to 473 K, the mass loss of light crude oil was caused by the

evaporation and distillation of light components [46]. In addition, the low-temperature oxidation in the temperature range of 473-654 K consists of two main reactions, including aliphatic hydrocarbon form hydroperoxides through oxygen addition reactions, and isomerization and decomposition reactions of hydroperoxides [47]. Furthermore, the second reaction interval fell in the temperature range of 654-744 K, commonly known as the fuel deposition reaction (FD). The mass loss in this stage was about 5.58 %, which was mainly due to the occurrence of complex reactions, such as the cleavage of C-C and Cheteroatom bonds in alkyl side chains, alkanes attached to naphthenic rings or aromatic rings, as well as the dehydrogenation of naphthenic rings and aromatic structures [44]. In this stage, the oxidized products and some condensation compounds generated in the lowtemperature oxidation formed coke through the oxidative cracking reactions [46]. The coke formed in the fuel deposition reaction was the main material basis in the subsequent oxidation reaction, i.e. the high temperature oxidation (HTO). The high temperature oxidation occurred in the temperature interval of 744-873 K. In the high temperature oxidation, the mass loss for light crude oil was about 8.8 % due to the combustion of coke [48].

Liquid fuels	Reaction	Temperature range	Peak temperature	Mass loss
	Stage	(K)	(K)	(%)
Light crude oil	Ι	303-654	471	84.29
	II	654-744	710	5.58
	III	744-873	833	8.80
Corn oil	Ι	598-682	633	60.16
	II	682-737	694	15.51
	III	737-620	813	11.27
Transformer oil	Ι	438-520	494	85.24

 Table 2 Temperature range, peak temperature and mass loss for each reaction region obtained from

 TG-DTG curves of liquid fuel samples at the heating rate of 10 K/min.

As shown in Fig. 3(b), the thermal decomposition behavior of corn oil was similar to the light crude oil, with three main reaction intervals divided by the DTG curve. The first reaction stage took place from 598 K to 682 K, which was attributed to the evaporation of triglycerides and the decomposition of polyunsaturated fatty acids [49]. The mass loss in this stage was about 60.16 %. The second reaction stage, with the mass loss of 15.51 %, was mainly due to the thermal decomposition of monounsaturated fatty acids [50]. In this stage, the double bindings of monounsaturated fatty acids were broken, which lead to a saturation of the triglyceride molecules [51]. After the complete decomposition of unsaturated fatty acids, the remaining saturated fatty acids would continue to decompose in the temperature range of 737 K to 893 K. When compared with light crude oil and corn oil, the result of transformer oil showed a noticeable single peak. As shown in Table 2, the transformer oil decomposed in the stage at 438-520 K with a total mass loss of 85.24 %, which could be attributed to the evaporation and cracking of various hydrocarbons. The cracking process of the hydrocarbons included alkane bond cracking and dehydrogenation

reaction, would produce small molecular alkane, olefin and small amounts of hydrogen [52]. Besides, as the temperature rose above 520 K, the solid residue formed in the cracking reactions might be involved in the carbonation reaction [53]. Since the mass loss due to the carbonization of residues was negligible, one oxidation interval is found for transformer oil.

3.1.2 FTIR analysis of gaseous products



Fig. 4. 3D FTIR spectra of gaseous products of liquid fuel samples.(a) light crude oil, (b) transformer oil, (c) corn oil.

Using the TG-FTIR technique, the gases and functional groups in the evaporation, oxidation and thermal decomposition processes of liquid fuel could be identified, which could be used to further explain the ignition characteristics on the hot surface. Fig. 4 (a–c) showed the three-dimensional FTIR spectra results, in which the variation of absorbance with respect to wavenumber and time were represented. In order to present the FTIR spectra results in detail, Fig. 5 showed the gaseous products generated at different temperatures during the first stage of the thermal process, including onset temperatures, peak temperatures and ending temperatures of stage I. For three liquid fuel samples, the two significant absorption bands at around 2400-2200 cm⁻¹ and 700-650 cm⁻¹ observed in the FTIR spectra were attributed to the release of CO₂, which was the primary gas product of oxidation reactions, especially for corn oil [54]. The absorption band between 3100 and

2640 cm⁻¹ was indicated as the C-H stretch of hydrocarbons [55]. Hydrocarbon was the main combustible gas in the gaseous products of light crude oil and transformer oil. The wavenumber of 4000-3500 cm⁻¹ in the spectrum corresponded to O-H bond stretching vibration, which represented the formation of H₂O during the oxidation and thermal decomposition process [56]. For the FTIR spectra of corn oil, the significant absorption bands were detected at 1745-1700 cm⁻¹ and 1150-1100 cm⁻¹, indicating the C=O stretch of ketones and aldehydes, and the C-O-C stretch of esters, respectively [57]. It should be noted that the ketones and aldehydes are highly flammable and can be easily ignited in high-temperature environments [58].



Fig. 5. 2D spectra during the first stage of the thermal process at different temperatures of light crude oil, transformer oil and corn oil.

In addition to the composition of the gaseous products, the evolutionary characteristics of combustible vapor produced in the evaporation and oxidation reactions was also crucial to the ignition of liquid fuels on hot surfaces. For light crude oil, two distinct regions could be identified by the threshold temperature of 471 K based on the hydrocarbon absorption peaks in the three-dimensional FTIR spectra (see Fig. 4a). When the temperature was below 471 K, the release of hydrocarbons was caused by the evaporation of light fractions with a low boiling point in light crude oil [47]. With increasing temperature, the intensity of the hydrocarbon absorption peaks gradually decreased, which could be attributed to the gradual consumption of light fractions in light crude oil by evaporation [47]. The second region between 471 K and 654 K, produced CO₂, hydrocarbons and H₂O through complex oxidation reactions. For transformer oil, the intensity of the absorption peak of hydrocarbons was much higher than that of CO₂ and H₂O, which meant that the main gas produced was hydrocarbons. Since the boiling points of hydrocarbons in transformer oil were all higher than 438 K, no significant absorption bands of hydrocarbons were observed in the low temperature region of the FTIR spectra. When the temperature rose to 438 K, the transformer oil generated a large number of hydrocarbons due to the evaporation and cracking of various hydrocarbons. As the temperature reached 520 K, a noticeable decline in the intensity of hydrocarbon absorption peaks could be observed, which was due to the nearly complete exhaustion of transformer oil, as can be verified from Fig. 3(c). Compared to light crude oil and transformer oil, the highest onset temperature for gas production was observed as 473 K for corn oil. As shown in Fig. 4(c), the concentration of CO₂ was highest for all pyrolysis gases products and exhibited a decreasing trend in the temperature range of 598 K-682 K. With the increase in temperature, the release of gases such as hydrocarbons, ketones and aldehydes first gradually increased, and then gradually weakened due to the decreased of polyunsaturated fatty acids.

3.1.3 Kinetic analysis

During the thermal behavior based on thermogravimetric analysis, the activation energies for different oxidation stages will change significantly [59]. The kinetic parameters of low temperature oxidation prior to ignition is more important for ignition characteristics for liquid fuels on hot surfaces. Therefore, the results of thermogravimetric analysis and hot surface experiments were coupled to determine the kinetic parameters of the key reactions. The initial temperature of the first oxidation reaction stage in DTG curves was selected as the initial temperature for the kinetic analysis. The termination temperature is taken from the lowest ignition temperatures at hot surface, which was measured by the hot surface ignition experiment. The temperature intervals for the kinetic analysis of liquid fuels were summarized in Table 3. Considering the accuracy in the determination of the pyrolysis mechanisms for one single heating rate, Coats-Redfern method [60] was applied to analysis the thermodynamic characteristics of the liquid fuel samples:

$$\ln\left[\frac{g(\alpha)}{T^2}\right] = \ln\left[\frac{AR}{\beta E_a}\right] - \frac{E_a}{RT}$$
(5)

In which $g(\alpha)$ is the hypothetical models of reaction mechanisms in integral forms, and β is the heating rate. The kinetic parameters E_a and A can be calculated from the slope and intercept of a plot of $\ln(g(\alpha)/T^2)$ against 1/T. After comparing fitting results from different, the first order kinetic (n=1) is determined as the optimal model to explain the initial chemical reaction process of the liquid fuel samples, as expressed in Eq. (6):

$$\ln\left[\frac{-\ln\left(1-\alpha\right)}{T^{2}}\right] = \ln\left[\frac{AR}{\beta E_{a}}\left(1-\frac{2RT}{E_{a}}\right)\right] - \frac{E_{a}}{RT}$$
(6)

The relationship between $\ln\left[\frac{-\ln(1-\alpha)}{T^2}\right]$ and 1/T is shown in Fig. 6, where the

coefficients (R^2) are greater than 0.98 for three liquid fuels, indicating that the Coats-Redfern method could calculate kinetic parameters accurately. The calculated kinetic parameters for three liquid fuels within the selected temperature interval are summarized in Table 3, and the results obtained in this research are in good agreement with the previous studies [45, 61, 62]. The descending order of the apparent activation energy was the following: corn oil (103.04 kJ·mol⁻¹) > transformer oil (78.66 kJ·mol⁻¹)> light crude oil (10.44 kJ·mol⁻¹). The low activation energy of light crude oil was due to the unstable bonds in the LTO stage as described in section 3.1.1 [63]. Transformer oil, as a fractional distillation product of crude oil, removed light hydrocarbons during the fractional distillation process, which resulted in the higher activation energy for the first oxidation reaction stage [64]. The high activation energy of corn oil was related to the decomposition of polyunsaturated fatty acids, indicating that the oxidation reaction needed more energy to be activated [51]. In addition, activation energy could be related to the self-ignition risk of liquid fuels on hot surfaces, which will be explained further in the next section.



Fig. 6. The $\ln(-(\ln(1-\alpha))/T^2) - 1/T$ curves of obtained by Coats-Redfern model.

Fuel	Temperature range (K)	<i>R</i> ²	$A\left(\mathbf{s}^{\text{-1}}\right)$	E_a (kJ·mol ⁻¹)
Light crude oil	303-559	0.9882	8.17×10 ⁻³	10.44
Transformer oil	438-501	0.9813	2.24×10 ⁶	78.66
Corn oil	598-650	0.9930	8.09×10 ⁵	103.04

Table 3 Fitting results of kinetic models

3.2. Ignition characteristics of liquid fuels on hot surface

3.2.1 Ignition process



Fig. 7. Typical ignition process with T_s =753 K, (a) light crude oil, (b) transformer oil, (c) corn oil.

The ignition process of liquid fuels on the hot surface is a complex and multicriterial process. Fig. 7 presents the ignition process of the liquid fuel samples on the hot surface with 753 K. The time zero represented the moment that liquid fuels with 3 mL impinged on the hot surface. In order to obtain the ignition phenomena in details, the flow characteristics of vapor plume was observed through the scattering of particles induced by the laser sheet. For these liquid fuels, the fuel stream was flooring around the surface after dripping on the hot surface, while the fuel stream was rapidly heated by the hot surface. With the heat transfer from the hot surface to the liquid fuel, a large number of combustible gases were produced during the evaporation and thermal decomposition of liquid fuel,

which could be identified as the smoke flowed.



Fig. 8 The measured temperature for light crude oil on the hot surface with 753 K, where time=0 represented the moment when the fuel dropped onto the hot surface

(a) the change of temperature value with time; (b) temperature field above the hot

surface at some typical times

Fig. 8 presents the measured temperature for light crude oil on the hot surface with

753 K, including the temperature changing over time and temperature field at some typical times. Before the impinging of liquid fuel, the high-temperature zone mainly occurred within a 2 cm range above the hot surface. The temperature of the hot surface decreased sharply due to the cooling effect of the fuel flow, and then recovered to the set temperature within several seconds. The temperature increasing of the light crude oil lead to the continuous generation of combustible vapor. The concentration of combustible vapor increased within the 3.52 s after the impinging of the fuel stream on the hot surface, then decreased gradually until ignition occur. The combustible vapor flowed upward under buoyancy effect, and entrained surrounding air to formed the combustible gas mixtures, where the entrained vortex observed by laser irradiation are marked in Fig. 7. After heating for 33.44 s, the highest temperature above the hot surface reached around 600 K, and the hot sua yellow flame with small area was observed above the fuel burner. Then, the burning area spread rapidly through the combustible vapor, while ignited the remaining light crude oil on the hot surface. With the development of the pool fire above the hot surface, all measured temperature values reached maximum value.

When compared with light crude oil, there was less combustible vapor produced for the transformer oil and corn oil. As the liquid fuel temperature increased, a stable and clear plume could be observed in transformer oil. After the fuel stream impacted the surface, a white spherical ignition kernel suddenly appeared in the vapor plume. Interestingly, it was observed that the ignition kernel appeared in the air above the hot surface and its center was approximately 207 mm above the heated surface [33, 65]. Under the combined effect of heat transfer from the heating plate and heat feedback from the flame, boil-over phenomenon was observed where liquid fuel flowed and burnt over the pan sides, which was also found in the study related with kitchen fire [66]. It was inferred that the intense boiling would lead to the decrease of bulk density for the transformer oil, then the level of transformer oil in the pan increased until it flowed over the pan sides. It should be noted that boil-over phenomenon was only observed for transformer oil when the surface temperature was above 693 K.

During the heating process of corn oil on the hot surface, there was relatively little fuel vapor observed by laser irradiation. A small burning region was observed at the edge of the fuel burner at 6.76 s in Fig. 7(c), which was divided into the center orange flame region and the edge blue flame region. Subsequently, the orange flame merged with the blue flame and continued to spread, ignite the produced combustible vapor and corn oil, where the flame height and flame area were relatively small in the combustion process. It was observed that the ignition delay time varies with changes in hot surface temperature and fuel type, more discussion can be found in our previous study [67].

3.2.2 Hot surface ignition probability and characteristic ignition temperature

The experimental results indicated that the ignition of liquid fuels on hot surfaces was a probabilistic event, which has been confirmed in lots of previous studies [68]. In this section, the ignition probability was defined as the ratio of the number of ignitions to the total number of experiments for each experimental condition [69]. As shown in Fig. 5, the ignition probability increased from 0 to 100 % with an S-shaped distribution within a certain temperature range [70]. In order to quantitatively analyze the data, the ignition probability could be treated statistically using a logistic function [36]. The logistic regression expression is shown below:

$$P T = \frac{exp \ b_0 + b_1(T - 273)}{1 + exp \ b_0 + b_1(T - 273)}$$
(7)

where P(T) represents the ignition probability at the selected surface temperature, T(K) is the temperature of the surface, b_0 and $b_1(K^{-1})$ are the logistic regression coefficients.

Fuel	b_0	b_1 (K ⁻¹)	R ²
Light crude oil	-13.0843	273.0354	0.98
Transformer oil	-11.0354	273.0355	0.97
Corn oil	-55.0233	273.1381	0.99

 Table 4 Logistic Regression Coefficients and correlation coefficients (R²)

The ignition probability for the liquid fuel samples and the corresponding logistic curve fits as a function of temperature (K) are plotted in Fig. 9, including light crude oil, transformer oil, and corn oil. To further evaluate and interpret the data, the characteristic ignition temperatures can be characterized by using temperatures corresponding to a specific ignition probability. The surface temperatures with 5 %, 50 % and 95 % ignition probability were considered as the lowest ignition temperature, ignition temperature, and the highest non-ignition temperature, respectively [18]. Table 4 summarizes the results of the characteristic ignition temperatures in the present study. Among them, the characteristic ignition temperature of most concern in this paper was the lowest ignition temperature. The lowest ignition temperature represented the temperature threshold and safety boundary of the hot surface around the liquid fuels, and the surface temperature must be controlled below the lowest ignition temperature [71]. The lowest ignition temperature order with different liquid fuels was: corn oil (650 K) > light crude oil (560 K) > transformer oil (501 K). During transportation, storage and application of these flammable liquids, if there is the potential for touching the hot surfaces, the lowest ignition temperature would be more instructive than the auto-ignition temperature.



Fig. 9. Ignition probability as a function of surface temperature for different liquid fuels.

Based on the results of kinetic analysis, the apparent activation energy of lowtemperature oxidation of light crude oil was lower than that of transformer oil, while the lowest ignition temperature of light crude oil was higher than that of transformer oil. This suggested that apparent activation energy of liquid fuel would not represent the lowest ignition temperature on hot surfaces. Therefore, the comprehensive evaluation of apparent activation energy and the lowest ignition temperature is important in the risk assessment of liquid fuels on hot surfaces, which will be investigated in future studies.

3.3 Ignition mechanism of liquid fuels on hot surfaces based on TG-FTIR

In order to explore the ignition mechanism of liquid fuels on hot surfaces, it is necessary to investigate the relationship between ignition parameters and chemical nature based on TG-FTIR from a microscopic perspective. According to previous studies, the relative concentrations of the combustible gases can be represented by the absorbance of the typical functional group corresponding to these combustible gases [55]. Based on the

results of TG-FTIR analysis in section 3.1.2, the combustible gases were observed as hydrocarbons for light crude oil and transformer oil, while the combustible gases of corn oil included mainly ketones and aldehydes in addition to hydrocarbons. The variations of the absorbance of the typical functional groups corresponding to combustible gases with temperature are plotted in Fig. 10, where ignition probabilities as a function of the hot surface temperature are shown for comparative analysis. For the three liquid fuel samples, the lowest ignition temperatures with ignition probability of 5 % were observed to be within the temperature ranges of combustible gases generation, especially in the first stages of thermogravimetric analysis. Taking transformer oil as an example, combustible gases were generated in the temperature range of 461-529 K during thermal behavior based on thermogravimetric analysis, while the lowest ignition temperature measured in the ignition experiments was 501 K. This result indicated that the ignition of the liquid fuels on the hot surface was significantly influenced by the combustible gas generated during the evaporation and thermal decomposition, which provided a theoretical basis for investigating ignition mechanism of liquid fuels on hot surfaces based on TG-FTIR. Interestingly, the lowest ignition temperatures showed a good agreement with the temperature at which the concentration of combustible gases reached its peak, especially for transformer oil and corn oil. For light crude oil, the combustible gases generated at temperatures below 473 K would not lead to the occurrence of hot surface ignition due to the relatively high auto-ignition temperature of these light hydrocarbons [72].



Fig. 10. The variation of the FTIR absorbance for the main combustible gases and ignition probabilities with temperature.

(a) light crude oil, (b) transformer oil, (c) corn oil.

The ignition of liquid fuels on the hot surface is a complex progress, which is significantly influenced by surface spreading, heat transfer, evaporation, thermal decomposition, and ignition [12]. Based on the previous coupling analysis, Fig. 11 explains the ignition mechanism of liquid fuels on the hot surface. For liquid fuels with a wide distillation range and a relatively complex composition (e.g. crude oil), oxidation and thermal decomposition reactions might occur after impinging on the hot surface, while for liquid fuels with a relatively narrow distillation range (e.g. transformer oil), the combustible vapor was generated mainly from evaporation reaction [37]. The combustible vapor flowed upward under buoyancy effect, and entrained surrounding air to form the

combustible gas mixtures. When the combustible gas mixture reached its flammability limit and auto-ignition temperature (AIT), ignition would occur [73]. In order to quantify the influence of surface temperature on ignition, a hot surface ignition model considering flammability limit and auto-ignition temperature of combustible vapor can be used to describe the ignition process. In the model, it is assumed that the radial distribution of combustible vapor concentration and temperature are regarded as consistent. The concentration and temperature of combustible vapor decreases with vertical height, following as $z^{-5/3}$ based on the buoyancy plume model [12]. Fig. 11 illustrates the expected profiles of combustible vapor concentration and temperature in the vertical direction of the hot surface after liquid fuels imping on the hot surface. When the surface temperature is below auto-ignition temperature, combustible vapor will not reach the auto-ignition temperature during the upward flow due to the temperature gradient, and ignition cannot achieve (curve a). When the surface temperature exceeds auto-ignition temperature, the temperature of upward-flowing vapor may drop below the auto-ignition temperature before reaching its flammability limit, in which case the temperature and concentration conditions for ignition cannot be achieved simultaneously. As the surface temperature further increases, the concentration profiles of combustible vapor will shift to the right and likely cross the ignition zone (curve b), indicating that combustible vapor could simultaneously reach the flammability limit and auto-ignition temperature, resulting in ignition. It should be noted that the concentration and temperature of combustible vapor could change instantaneously due to turbulent flow of the vapor plume, which causes the probabilistic nature of ignition in hot surface test. As the surface temperature rises above the highest non-ignition temperature, the ignition probability is 1 (curve c). At this point, the combustible vapor will definitely reach both the concentration and temperature thresholds, and ignition will definitely occur. The comprehensive model considering the complex heat and mass transfer process should be built for liquid fuel with different chemical nature in the future investigations.



Fig. 11. Hot surface ignition mechanism of liquid fuel

4. Conclusions

In this study, thermogravimetric analysis and hot surface ignition experiments were systematically conducted to investigate the ignition characteristics of liquid fuels on hot surfaces based on TG-FTIR analysis, where typical liquid fuel included light crude oil, transformer oil, and corn oil. The main conclusions are:

(1) The thermogravimetric results of liquid fuel samples obtained through TG-FTIR showed significant differences in the thermal characteristics during the heating process. For light crude oil and corn oil, the thermal behavior based on thermogravimetric analysis could be divided into three stages, while the result of transformer oil shows only one stage.

As a key element for the ignition progress, the combustible gases were observed as hydrocarbons for light crude oil and transformer oil, while the combustible gases of corn oil included mainly ketones, and aldehydes in addition to hydrocarbons. Besides, the kinetic parameter E_a in the low temperature oxidation stage of liquid fuel samples was determined using the Coats-Redfern method and was 10.44, 78.66 and 103.04 kJ·mol⁻¹.

(2) In the hot surface tests, smoke flow composed of evaporation and thermal decomposition products was first observed above the surface, and then the ignition occurs for liquid fuel samples after a period of time. It should be noted that the ignition kernel appears in the air above the hot surface for transformer oil. When the surface temperature was above 693 K, boil-over phenomenon was observed where transformer oil flows and burn over the pan sides.

(3) The results of the hot surface ignition experiments demonstrated that ignition of liquid fuel samples was probabilistic. As the surface temperature increased, the ignition probability increases from 0 to 100 % with an S-shaped distribution within a certain temperature range, where the order of lowest ignition temperature with different liquid fuels was: corn oil (650 K) > light crude oil (560 K) > transformer oil (501 K). For the three liquid fuel samples, the order of lowest ignition temperature was not consistent with the order of the kinetic parameter E_{a} . It could be inferred that apparent activation energy of liquid fuel would not represent the lowest ignition temperature on hot surfaces, which could be further verified in the future researches.

(4) The comparative analysis of ignition probabilities and the variations of the absorbance of combustible gases revealed that the ignition of the liquid fuels on the hot surface was significantly influenced by the combustible gas generated during the evaporation and thermal decomposition processes. Finally, the model considering the autoignition temperature of combustible vapor was introduced to explain the ignition of liquid fuels on hot surfaces. The proposed model provided a detail explanation for the ignition mechanism of liquid fuels on hot surfaces, where the profiles for the concentration and temperature of combustible vapor were described, and the critical condition for ignition was given.

Acknowledgements

This work, excepted Wai Cheong Tam, is financially supported by the National Natural Science Foundation of China (No. 52304256, No. 51874344), the Shandong Provincial Natural Science Foundation (No. ZR2022QE144), the Opening Fund of the State KeyLaboratory of Fire Science (No. HZ2023-KF04), the Shaanxi Science Fund for Distinguished Young Scholars (No. 2023-JC-JQ-46) and the Postdoctoral Research Project of Shaanxi Province (No. 2023BSHEDZZ287).

References

[1] Forsberg C. What is the long-term demand for liquid hydrocarbon fuels and feedstocks? Appl Energy. 2023;341:121104.

[2] Bramstoft R, Pizarro-Alonso A, Jensen IG, Ravn H, Münster M. Modelling of renewable gas and renewable liquid fuels in future integrated energy systems. Appl Energy. 2020;268:114869.

[3] Li M, Li R, Wang C. Characteristics of flame velocity and burning rate of large-scale continuous leakage spilling fire of n-butanol fuel. Fuel. 2023;332:126148.

[4] Li M, Xu Z, Luo Q, Wang C. Investigation of bicubic flame radiation model of continuously opposed spilling fire over n-butanol fuel. Energy. 2023;272:127144.

[5] Arunraj NS, Maiti J. Risk-based maintenance—Techniques and applications. J Hazard Mater. 2007;142:653-61.

[6] Zhou X, Sun Z, Yan H, Feng X, Zhao H, Liu Y, et al. Produce petrochemicals directly from crude oil catalytic cracking, a techno-economic analysis and life cycle society-environment assessment. J Clean Prod. 2021;308:127283.

[7] Robinson PR. Petroleum processing overview. Practical advances in petroleum processing: Springer; 2006. p. 1-78.

[8] Zhang DL, Xiao LY, Wang Y, Huang GZ. Study on vehicle fire safety: Statistic, investigation methods and experimental analysis. Saf Sci. 2019;117:194-204.

[9] Menon SK, Boettcher PA, Ventura B, Blanquart G. Hot surface ignition of n-hexane in air. Combust Flame. 2016;163:42-53.

[10] Kumar D, Das T, Giri BS, Verma B. Optimization of biodiesel synthesis from nonedible oil using immobilized bio-support catalysts in jacketed packed bed bioreactor by response surface methodology. J Clean Prod. 2020;244:118700.

[11] Redd ME, Bloxham JC, Giles NF, Knotts Iv TA, Wilding WV. A study of unexpected autoignition temperature trends for pure n-alkanes.Fuel. 2021;306:121710.

[12] Michael Bennett J. Ignition of combustible fluids by heated surfaces. Process Saf Prog. 2001;20:29-36.

[13] Feoktistov DV, Glushkov DO, Nigay AG, Nikitin DS, Orlova EG, Shanenkov II. The effect of ceramic surface structure modification method on the ignition and combustion behavior of non-metallized and metallized gel fuel particles exposed to conductive heating. Fuel. 2022;330:125576. [14] Orlova E, Glushkov D, Abedtazehabadi A, Belyaev S, Feoktistov D. Influence of the Texture Configuration of Heating Surfaces Created by Laser Irradiation on the Ignition and Combustion Characteristics of Liquid Fuels. Applied Sciences. 2022;13:95.

[15] Pan J, Wei H, Shu G, Pan M, Feng D, Li N. LES analysis for autoignition induced abnormal combustion based on a downsized SI engine. Appl Energy. 2017;191:183-92.

[16] Chen L, Zhang R, Pan J, Wei H. Effects of partitioned fuel distribution on auto-ignition and knocking under spark assisted compression ignition conditions. Appl Energy. 2020;260:114269.

[17] Davis S, Chavez D, Kytomaa H. Hot Surface Ignition of Flammable and Combustible Liquids2006.

[18] Davis S, Kelly S, Somandepalli V. Hot Surface Ignition of Performance Fuels. Fire Technol. 2010;46:363-74.

[19] Tang W, Bahrami D, Yuan L, Thomas R, Soles J. Hot Surface Ignition of Liquid Fuels Under Ventilation. Mining, metallurgy & exploration. 2022;39:961-8.

[20] Zhu N, Wang X, Wei X, Ding C, Wang J. Experimental study on the ignition characteristics of leaking RP-3 aviation kerosene on a horizontal hot wall. EDP Sciences.

[21] Gupta T, Khan ME. Effect of Varying Hot Surface Temperature on Ignition Delay Characteristics for Different Fuel Sprays. International Journal of Recent Technology and Engineering (IJRTE). 2019;8.

[22] Shams Z, Moghiman M. An experimental investigation of ignition probability of diesel fuel droplets with metal oxide nanoparticles. Thermochimica Acta. 2017;657:79-85.

[23] Tanvir S, Qiao L. Effect of Addition of Energetic Nanoparticles on

Droplet-Burning Rate of Liquid Fuels. Journal of Propulsion and Power. 2014;31:408-15.

[24] Tyagi H, Phelan PE, Prasher R, Peck R, Lee T, Pacheco JR, et al. Increased Hot-Plate Ignition Probability for Nanoparticle-Laden Diesel Fuel. Nano Letters. 2008;8:1410-6.

[25] Glushkov DO, Strizhak PA, Vershinina KY. Hot Surface Ignition of A Composite Fuel Droplet. MATEC Web of Conferences. 2015;23.

[26] Valiullin T, Vershinina K, Strizhak P. Ignition of Slurry Fuel Droplets with Different Heating Conditions. Energies2019.

[27] Yi P, Long W, Feng L, Chen L, Cui J, Gong W. Investigation of evaporation and auto-ignition of isolated lubricating oil droplets in natural gas engine in-cylinder conditions. Fuel. 2019;235:1172-83.

[28] Zhang H, Law CK. Effects of temporally varying liquid-phase mass diffusivity in multicomponent droplet gasification. Combustion and Flame. 2008;153:593-602.

[29] Kuznetsov G, Salomatov V, Syrodoy S. Numerical simulation of ignition of particles of a coal–water fuel. Combustion, Explosion, and Shock Waves. 2015;51:409-15.

[30] Salomatov V, Kuznetsov G, Syrodoy S. Influence of the degree of coal metamorphism on characteristics and conditions of ignition of coalwater fuel drops. Thermophysics and Aeromechanics. 2018;25:773-88.

[31] Syrodoi S, Kuznetsov G, Salomatov V. Effect of the shape of particles on the characteristics of the ignition of coal–water fuel. Solid Fuel Chemistry. 2015;49:365-71.

[32] Syrodoy S, Kuznetsov G, Salomatov V. The influence of heat transfer conditions on the parameters characterizing the ignition of coal-water fuel particles. Thermal Engineering. 2015;62:703-7.

[33] Li Y-L, Wang Y-H, Lu S-X. Ignition of the leaked diesel on a heated horizontal surface. Fire safety journal. 2010;45:58-68.

[34] Boussouf A, Lecoustre VR, Li H, Sunderland PB. Autoignition of R32 and R410 refrigerant mixtures with lubricating oil. 2014.

[35] Wang K, Zhou Z, Ming Y, Qian X. Research on hot surface ignition characteristics of leaking fuel in ship engine room. Thermal Science. 2022:206-.

[36] Colwell JD, Reza A. Hot surface ignition of automotive and aviation fluids. Fire Technol. 2005;41:105-23.

[37] Šlančiauskas A, Kalpokaitė R. Behaviour of a heavy fuel oil droplet on a hot surface. Int J Heat Mass Transfer. 2006;49:1050-7.

[38] Li B, Liu G, Bi M-S, Li Z-B, Han B, Shu C-M. Self-ignition risk classification for coal dust layers of three coal types on a hot surface. Energy. 2021;216:119197.

[39] Antonov DV, Strizhak PA, Fedorenko RM, Nissar Z, Sazhin SS. Puffing/micro-explosion in rapeseed oil/water droplets: The effects of coal micro-particles in water. Fuel. 2021;289:119814.

[40] Glushkov DO, Kuznetsov GV, Strizhak PA. Experimental and numerical study of coal dust ignition by a hot particle. Applied Thermal Engineering. 2018;133:774-84.

[41] Glushkov DO, Kuznetsov GV, Strizhak PA, Taburchinov RI. Numerical simulation of gel fuel gas-phase ignition by a local source of limited heat content. Acta Astronautica. 2019;163:44-53.

[42] Dhiman J, Shrestha A, Fasina O, Adhikari S, Via B, Gallagher T.Physical, ignition, and volatilization properties of biomass feedstock dusts.Trans ASABE. 2015;58:1425-37.

[43] Ding Z, Chen X, Lu S, Wang Y. An investigation of flame tilt

transition inside the compartment with horizontal opening in cross wind. Proc Combust Inst. 2020.

[44] Chen H, Liu X, Sun L, Yang R, Yang S. Experimental study on dynamic characteristics of low temperature oxidation for Bohai offshore light oil under reservoir conditions. Fuel. 2021;283:119282.

[45] Wang Y, Ren S, Zhang L, Deng J, Peng X, Cheng H. New insights into the oxidation behaviors of crude oils and their exothermic characteristics: Experimental study via simultaneous TGA/DSC. Fuel. 2018;219:141-50.

[46] Zhao S, Pu W, Sun B, Gu F, Wang L. Comparative evaluation on the thermal behaviors and kinetics of combustion of heavy crude oil and its SARA fractions. Fuel. 2019;239:117-25.

[47] Yuan C, Emelianov DA, Varfolomeev MA. Oxidation behavior and kinetics of light, medium, and heavy crude oils characterized by thermogravimetry coupled with fourier transform infrared spectroscopy. Energy Fuels. 2018;32:5571-80.

[48] Zhao S, Pu W, Peng X, Zhang J, Ren H. Low-temperature oxidation of heavy crude oil characterized by TG, DSC, GC-MS, and negative ion ESI FT-ICR MS. Energy. 2021;214:119004.

[49] Jain S, Sharma MP. Thermal stability of biodiesel and its blends: A review. Renewable and Sustainable Energy Reviews. 2011;15:438-48.

[50] Górska A, Brzezińska R, Wirkowska-Wojdyła M, Bryś J, Domian E, Ostrowska-Ligęza E. Application of thermal methods to analyze the properties of coffee silverskin and oil extracted from the studied roasting by-product. Applied Sciences. 2020;10:8790.

[51] Santos JCO, Dos Santos IMG, De Souza AG, Prasad S, Dos Santos AV. Thermal stability and kinetic study on thermal decomposition of commercial edible oils by thermogravimetry. Journal of food science. 2002;67:1393-8.

[52] Du L, Wang W, Chen W, Wei C. Reaction mechanism of transformer oil pyrolysis based on TG-DSC and molecular simulation. IEEE.p. 1-4.

[53] Sun W, Lin W-C, You F, Shu C-M, Qin S-H. Prevention of green energy loss: Estimation of fire hazard potential in wind turbines. Renewable Energy. 2019;140:62-9.

[54] Tudorachi N, Mustata F. Thermal degradation and evolved gas analysis of some vegetable oils using TG/FT-IR/MS technique. Journal of Thermal Analysis and Calorimetry. 2015;119:1703-11.

[55] Hao J, Che Y, Tian Y, Li D, Zhang J, Qiao Y. Thermal cracking characteristics and kinetics of oil sand bitumen and its SARA fractions by TG–FTIR. Energy & Fuels. 2017;31:1295-309.

[56] Jameel AGA, Han Y, Brignoli O, Telalović S, Elbaz AM, Im HG, et al. Heavy fuel oil pyrolysis and combustion: Kinetics and evolved gases investigated by TGA-FTIR. Journal of analytical and applied pyrolysis. 2017;127:183-95.

[57] Li H, Niu S, Lu C, Wang Y. Comprehensive investigation of the thermal degradation characteristics of biodiesel and its feedstock oil through TGA–FTIR. Energy & Fuels. 2015;29:5145-53.

[58] Edo M, Budarin V, Aracil I, Persson P-E, Jansson S. The combined effect of plastics and food waste accelerates the thermal decomposition of refuse-derived fuels and fuel blends. Fuel. 2016;180:424-32.

[59] Elbaz AM, Gani A, Hourani N, Emwas A-H, Sarathy SM, Roberts WL. TG/DTG, FT-ICR mass spectrometry, and NMR spectroscopy study of heavy fuel oil. Energy & Fuels. 2015;29:7825-35.

[60] Mian I, Li X, Jian Y, Dacres OD, Zhong M, Liu J, et al. Kinetic study of biomass pellet pyrolysis by using distributed activation energy model and Coats Redfern methods and their comparison. Bioresource Technology. 2019;294:122099.

[61] Santos J, Santos I, Conceição M, Porto SL, Trindade M, Souza A, et al. Thermoanalytical, kinetic and rheological parameters of commercial edible vegetable oils. Journal of thermal analysis and calorimetry. 2004;75:419-28.

[62] An-Xin Z, Xiao-Jun T, Zhong-Hua Z, Jun-Hua L. The pyrolytic experiment and thermal dynamics analysis of insulating oil. IEEE. p. 89-92.

[63] Kapadia PR, Kallos MS, Gates ID. A review of pyrolysis, aquathermolysis, and oxidation of Athabasca bitumen. Fuel Processing Technology. 2015;131:270-89.

[64] Zhang J, Guo Y, Pau D, Li K, Xie K, Zou Y. Pyrolysis kinetics and determination of organic components and N-alkanes yields of Karamay transformer oil using TG, FTIR and Py-GC/MS analyses. Fuel. 2021;306:121691.

[65] Bennett J, Ballal D. Ignition of Combustible Fluids by HeatedSurfaces. 41st Aerospace Sciences Meeting and Exhibit2003. p. 148.

[66] Chen J, Hu Y, Wang Z, Lee KY, Kim SC, Bundy M, et al. Why are cooktop fires so hazardous? Fire Saf J. 2021;120:103070.

[67] Wang Z, Chen J, Yu Y, Kong D. Experimental study on the ignition and burning characteristics of liquid fuels on hot surfaces. Process Safety and Environmental Protection. 2023;176:725-33.

[68] Babrauskas V. Ignition of gases, vapors, and liquids by hot surfaces. Fire Technol. 2022;58:281-310.

[69] Goyal V, Benhidjeb-Carayon A, Simmons R, Meyer S, Gore J. Hot

Surface Ignition Temperatures of Hydrocarbon Fuels2017.

[70] Shaw A, Epling W, McKenna C, Weckman B. Evaluation of the ignition of diesel fuels on hot surfaces. Fire Technol. 2010;46:407-23.

[71] Mohaddes D, Ihme M. On the hot surface ignition of a wallstagnating spray flame. Combust Flame. 2022;240:111988.

[72] Huang L, Wang Y, Li Z, Zhang L, Yin Y, Chen C, et al. Experimental study on piloted ignition temperature and auto ignition temperature of heavy oils at high pressure. Energy. 2021;229:120644.

[73] Slippey A, Bender K, Tarau C, Rokkam S. Apparatus for characterizing hot surface ignition of aviation fuels. 2018 Joint Propulsion Conference2018. p. 4708.