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Experimental study of the flash point of flammable liquids under different altitudes in Tibet plateau

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ABSTRACT

To reveal the dependence the flash point of flammable liquids have on altitude, a series of field tests at different altitudes in Tibet plateau were carried out by aid of a portable flash point measuring apparatus. The five tested altitudes are 3650, 3950, 4250, 4500, and 4750 m in Tibet plateau, as well as a benchmark altitude of 58 m in Hefei (a sea-level city). The test results show the flash point has a nonlinear dependence on altitude for all the tested flammable liquids. The subsequent theoretical analysis indicates that the reciprocal of flash point depends linearly on the logarithmic of altitude, which in general agrees with the test results especially at relatively low altitudes. The study indicates that the fire hazard of flammable liquids increases as the altitude increases, which is an important consideration for the safety design of aircraft fuel tank as well as the fire safety management of oil production and transport in high-altitude plateau.

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1. INTRODUCTION

Flash point refers to the lowest temperature where the mixture of flammable liquid vapor and air can be ignited by a visible ignition source (or electric spark). Flash point is an important index to rate the fire hazard of a flammable liquid. The generally accepted definition of flash point in the American Society for Testing and Materials standard methods [1] is that in the predetermined experimental conditions, the flame caused by fire in the sample steam spread to the minimum temperature of the surface of the liquid, corrected to standard atmospheric pressure (101.3 KPa).

Determination of the flash point for flammable liquids is of vital importance for the storage and transportation of fuel oil and specifically for reducing the oil fire accidents related to airplanes and oil pipelines. Aviation oil explosion was considered to account for a large proportion of causes in air crashes [2]. In 1996, the American World Airlines flight TWA800 exploded at an altitude of 4194 m, for which the main cause was identified as an unknown source of ignition in the fuel tank. The world's rapidly increased demand on fuel results in a wide expansion of oil pipelines across the planet, especially some pass through high-altitude plateaus, such as the Golmud–Lhasa pipeline and the Southwest pipeline in China. To improve the fire safety related to flammable liquids in the upper air for airplanes and high-altitude plateaus for oil pipelines, it would be beneficial to determine the dependence of flash point on altitude and build a flash point database for typical flammable liquids.

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The low pressure at high altitudes increases the volatilization of flammable liquids and correspondingly reduces the minimum energy for ignition, that is, flash point. Shepherd *et al.* [3] based on and Chatelier [4] analyzed the effect of altitude on flash point from the influence factors of vapor pressure and mass transfer. Lee *et al.* [5] observed a linear relationship between the minimum ignition temperature and the flash point for aviation kerosene. Kong *et al.* [6] measured the flash point of dichloromethane under different oxygen concentrations, where the results showed that flash point depends little on oxygen concentration but largely on ignition source and ignition energy. Using a pressure vessel to simulate the low pressure environments corresponding to different high altitudes, Nestor *et al.* [7] and Tang *et al.* [8] observed that the flash point of RP5 Jet A decreases nonlinearly with the increase of altitude.

However, as probably the lack of high-altitude environments for field tests, the previous flash point studies focused mainly on relatively low altitudes, and flash point data for only a narrow selection of flammable liquids were reported. To comprehensively determine the relationship between altitude and flash point, more additional higher altitudes need to be explored for a variety of flammable liquids. An accurate description of the dependence of flash point on altitude would provide a more scientific insight into the reducing mechanism of the fire hazards related to fuel oil storage and transportation in cruising aircrafts and high-altitude plateaus.

In this study, by aid of the high-altitude environments in Tibet plateau, flash point at a series of altitudes was tested for a variety of flammable liquids, such as aviation kerosene, aviation diesel, and some hydrocarbon fuels. Influence analysis of the altitude on the vapor pressure was conducted to reveal the variation mechanism of flash point under different altitudes.

2. EXPERIMENTAL DESCRIPTION

A portable flash point measuring apparatus, Battery-Inverter-Flash Point Closed Bomb as shown in Figure 1, was designed according to the apparatus and methodology described in [9]. The inverter transforms direct current (DC) from the battery into pure sine wave alternative current (AC) and then outputs to the AC output ports. In each test, the Flash Point Bomb was powered by the DC–AC inverter, and initial barometric pressure and ambient temperature were recorded. A fixed volumetric amount of flammable liquid was added to a test pan, which was heated at a low temperature rise rate. During the heating process, a spark in an attempt to ignite the liquid was lit at fixed short intervals (3–5 s). Immediately after the flashover occurs, the current liquid temperature was recorded as the closest flash point under the testing conditions for the tested flammable liquids, meanwhile the electric heating system and high-voltage ignition system was switched off [10].

The portable flash point measuring apparatus was delivered by truck to different altitudes in Tibet plateau to conduct field flash point tests for different flammable liquids. As the highest plateau in the

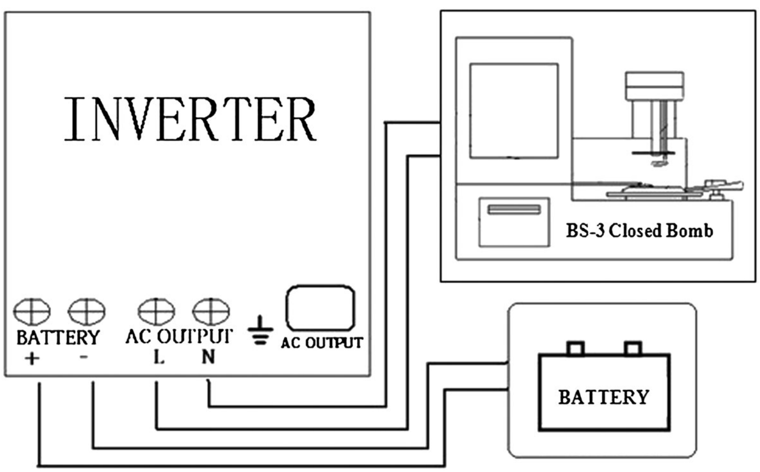

Figure 1. Apparatus of experiment setup and the connection.

world, Tibet plateau provides continuous altitudes for flash point measurements. The average altitude of Tibet plateau is 4500 m, and the highest altitude exceeds 5000 m. In Tibet, a series of five altitudes, that is, 3650, 3950, 4250, 4500, and 4750 m, were selected in the geographical line from Lhasa (altitude, 3650 m) via Damxung (altitude, 4250 m) to La ken la (altitude, 5190 m). For comparison, benchmark flash point tests at standard atmosphere (101 KPa) were conducted in the sea-level city Hefei (altitude, 58 m). Atmospheric pressure and ambient temperature were recorded for each test. The tested flammable liquids are RP-5 aviation kerosene, −10# diesel, *N*-decane, and *N,N*-dimethylacetamide.

3. THEORETICAL ANALYSIS ON THE ALTITUDE DEPENDENCE OF FLASH POINT

The flash point is observed corresponding [11, 12] to a fixed mass fuel/air ratio denoted as

$$f = \frac{N_f M_f}{N_{air} M_{air}} \tag{1}$$

where M_f is the molecular weight of the fuel, N_f is the moles of the fuel, M_{air} is the molecular weight of air, and N_{air} is the moles of air. According to Equation (1), the fuel–air ratio is only related to the composition of flammable liquids, that is, the fuel–air ratio is a constant when its temperature reaches flash point. Kuchta *et al.*[12] claimed that the flammable limits of flammable liquids always occur at a constant fuel–air ratio, especially for hydrocarbon fuels whose flammable limits are in the range of $0.038 < f_{LFL} < 0.041$. Shepherd *et al.* [11] obtained a fuel–air ratio of 0.038 for the explosive limits of flammable liquids.

In gas–liquid equilibrium, according to the Clausius–Clapeyron relation [13, 14], the partial pressure of the fuel vapor (P_f) above the liquid surface as a function of the liquid temperature T_f can be given as

$$P_f = P_1 \exp\left[\frac{h_{fg}}{R}\left(\frac{1}{T_1} - \frac{1}{T_f}\right)\right] \tag{2}$$

where P_1 is the known vapor pressure at a given temperature T_1. Then, the fuel–air ratio is related to the vapor pressure by

$$f = \frac{P_f}{P_0 - P_f}\frac{M_f}{M_{air}} \tag{3}$$

where P_0 is the ambient pressure.Rearrange Equations (2) and (3),

$$P = P_1\left(1 + \frac{1}{f}\frac{M_f}{M_{air}}\right)\exp\left[\frac{h_{fg}}{R}\left(\frac{1}{T_1} - \frac{1}{T_f}\right)\right] \tag{4}$$

where the second term in the parentheses is a constant because the fuel–air ratio is fixed for different flash points. Equation (4) presents the relationship between the ambient pressure and the flash point.

Within the atmosphere, the following equation (the barometric formula) relates atmospheric pressure P to altitude H_a [15]:

$$P = 101325\left(1 - 2.25577 \times 10^{-5} H_a\right)^{5.2558} \tag{5}$$

where a temperature lapse rate of 0.0065 K/m is assumed.

Substitute Equation (5) into Equation (4), the dependence of flash point on altitude can be expressed as

$$\frac{1}{T_f} = \frac{1}{T_1} - \frac{R}{h_{fg}} \ln\left[\left(1 + \frac{1}{f}\frac{M_f}{M_{air}}\right)^{-1} \frac{101325}{P_1}\left(1 - 2.25577 \times 10^{-5} H_a\right)^{5.25588}\right] \tag{6}$$

and simplified as

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$$\frac{1}{T_{\mathrm{f}}} = A \ln\left(1 - 2.25577 \times 10^{-5} H_{\mathrm{a}}\right) + C \tag{7}$$

where A and C are constant coefficients.

4. RESULTS AND DISCUSSION

The flash point measured at different altitudes for the four flammable liquids are listed in Table I. The study tested four flammable liquids: two pure substances, *N*,*N*-dimethylacetamide and *N*-decane, and two mixtures, -10# diesel and RP-5 aviation kerosene. Each test was repeated three times to ensure repeatability. The flash point at standard atmospheric pressure was measured to verify the test accuracy by comparing it with those given in literature.

The averaged flash point over three repeated measurements at each altitude is shown in Figure 2. Generally, the flash point decreases as the altitude increases for all the flammable liquids. And it is also worth noting that a lower flash point implies a material with more flammable fire hazards, because its ignition is more likely to occur.

Figure 3 presents the experimental measurements with the theoretical predictions, where the agreements are generally in reasonable accuracy. At an altitude of below 4250 m, the relationship of the reciprocal of flammable liquids' flash point with the logarithmic of altitude is linear, which can be approximated as $\frac{1}{T_{\mathrm{f}}} = A \ln\left(1 - 2.25577 \times 10^{-5} H_{\mathrm{a}}\right) + C$

The experimental results are in good agreement with the theoretical predictions, especially for those altitudes below 4250 m. As the altitude rises above 4250 m, a maximum 1.5% divergence between the measurements and the predictions was observed. This divergence can be probably due to the ignorance of water vapor in the fuel concentration evaluation, because the water vapor pressure and the liquid fuel vapor pressure can be comparable in the order of magnitude at altitudes high enough. The humidity is susceptible to the influence of season and climate changes. Environmental pressure measurement is susceptible to the influence of season factor and climatic changes, resulting in uncertainty in the fuel vapor evaluation.

5. CONCLUSION

In this study, a continuous measurement of flash point at five serial altitudes for four types of flammable liquids was conducted, with the aim of revealing the dependence of flash point on altitude. The main conclusions are as follows.(1) Through field tests, the flash point data for a variety of flammable liquids were obtained, where it is found that the flash point decreases significantly with the increasing of altitude, that is, the corresponding relationship between the flash point of flammable liquids and altitude is nonlinear. (2) Theoretical analysis on the vapor pressure shows that the relationship between the flash point of flammable liquids and altitude is nonlinear,

Table I. The flash point measured at serial altitudes for different flammable liquids.

		T_f (K)											
No.	Altitude (m)	*N*,*N*-dimethylacetamide			*N*-decane			Diesel			Aviation kerosene		
1	58	342	343	343	328	328	329	334	333	333	343	342	343
2	3650	308	307	308	302	303	303	305	305	306	318	318	319
3	3950	305	305	305	301	301	300	304	303	303	315	316	315
4	4250	301	303	302	300	299	298	299	300	301	310	310	311
5	4500	298	297	299	293	292	292	296	297	297	302	302	303
6	4750	290	291	290	284	284	283	286	287	288	293	292	293
7*	5000	277	279	278	–	–	–	–	–	–	–	–	–

*At an altitude of 5000 m, because of the low ambient temperature, the flash point for some of the flammable liquids cannot be obtained.

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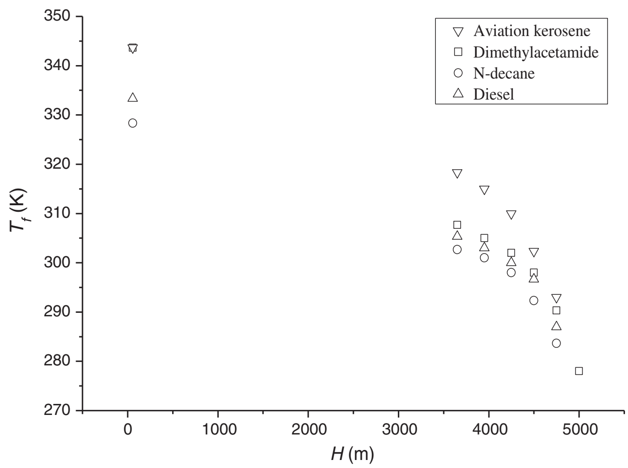

Figure 2. The flash point versus altitude for different flammable liquids.

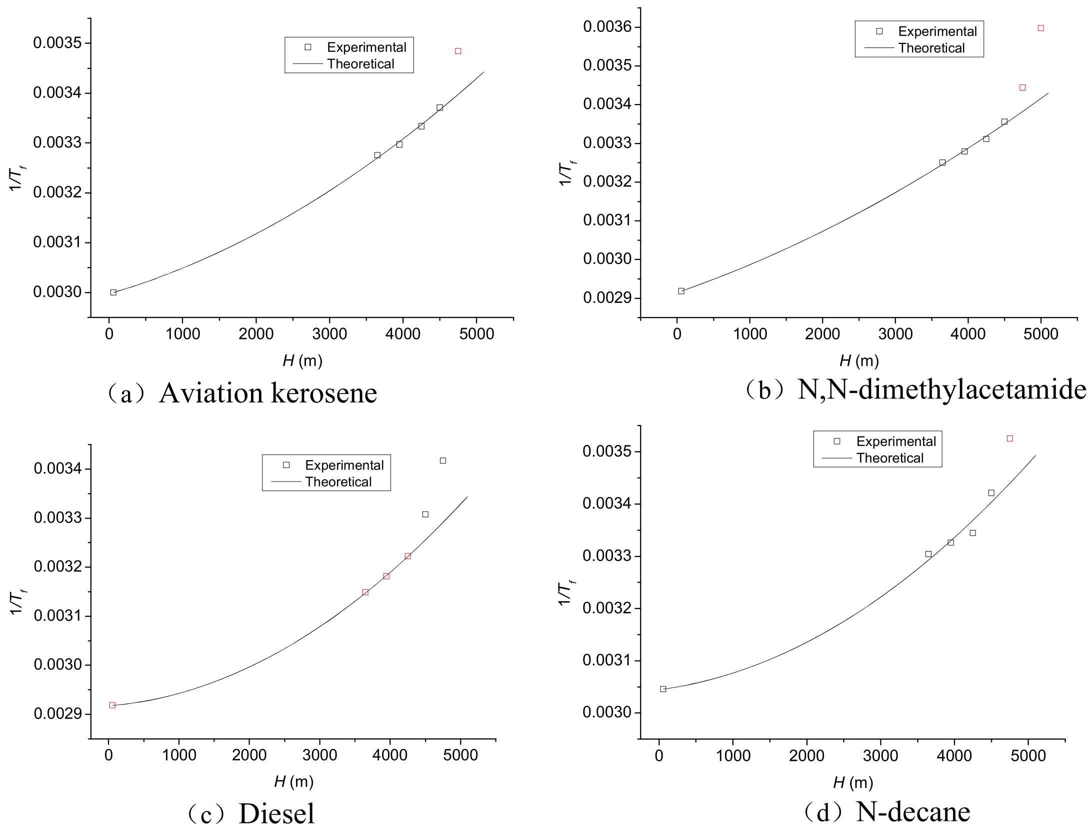

Figure 3. The reciprocal of flammable liquid flash point with the altitude curve: (a) aviation kerosene; (b) *N*, *N*-dimethylacetamide; (c) diesel; and (d) *N*-decane.

that is, the reciprocal of flash point is in proportion to the logarithmic of altitude, which is then validated by the experimental data.

Because the flash point of flammable liquids in high-altitude environments is significantly lower than in the normal environment, fire risk becomes increasingly severe at high altitudes. Therefore, it is necessary to re-evaluate the current fire safety status for high-altitude plateaus and airplanes in

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flight. For example, the safety protection of the fuel tank may become vulnerable when the airplanes in flight climb above a certain altitude. Moreover, the production, transportation, and storage of flammable liquids in the plateau environment should have new security emergency technologies, so as to keep away from the increased fire risks. Currently, the fire protection methods and techniques for the production, transportation, and storage of flammable liquids in the plateau environment are as the same as those adopted in sea-level cities. The field tests of flash point data in high-altitude plateaus are of significant meaning for high-altitude fire safety, which then provide foundation for the formulation of fire protection regulation in high-altitude regions.

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