Published in final edited form as:
Min Metall Explor. 2022 May 04; 39(3): 961–968. doi:10.1007/s42461-022-00609-w.

Hot Surface Ignition of Liquid Fuels Under Ventilation

Wei Tang[1], **Davood Bahrami**[1], **Liming Yuan**[1], **Richard Thomas**[1], **John Soles**[1]

[1]National Institute for Occupational Safety and Health (NIOSH), 626 Cochran Mill Road, Pittsburgh, PA 15236, USA

Abstract

Mine equipment fires remain as one of the most concerning safety issues in the mining industry, and most equipment fires were caused by hot surface ignitions. Detailed experimental investigations were conducted at the NIOSH Pittsburgh Mining Research Division on hot surface ignition of liquid fuels under ventilation in a mining environment. Three types of metal surface materials (stainless steel, cast iron, carbon steel), three types of liquids (diesel fuel, hydraulic fluid, engine oil), four air ventilation speeds (0, 0.5, 1.5, 3 m/s) were used to study the hot surface ignition probability under these conditions. Visual observation and thermocouples attached on the metal surface were used to indicate the hot surface ignition from the measured temperatures. Results show that the type of metal has a noticeable effect on the hot surface ignition, while ventilation speed has a mixed influence on ignition. Different types of liquid fuels also show different ranges of ignition temperatures. Results from this work can be used to help understand equipment mine fires and develop mitigation strategies.

Keywords

Hot surface ignition; Metal type; Liquid fuels; Ventilation; Logistic regression

1 Introduction

Hot surface ignition of flammable liquids and gases is a well-known problem in mechanical and industrial processes. In the mining industry, heavy-duty equipment underground provides favorable conditions for a hot surface ignition to occur. Between 2009 and 2018, 177 fires and 43 fire-related injuries were reported for metal and nonmetal mines in the USA. [1]. Most of the 177 fires reported were believed to be caused by hot surface ignitions involving combustible liquids as the fuel (diesel, engine oil, hydraulic fluid, anti-freeze, etc.) makes contacts or sprays within close proximity to the engine surface or exhaust component [2, 3]. While hot surface ignition of a liquid is a stochastic process that depends on three main factors—hot surface properties (material, geometry, roughness, etc.), liquid properties (liquid type, temperature, viscosity, flow rate, etc.), and ambient conditions (air

---

✉Wei Tang, wtang@cdc.gov.

Conflict of Interest The authors declare that there is no conflict of interest.

Disclaimer The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

temperature, humidity, airflow, etc.)—the occurrence of the phenomenon requires several other conditions as well. When flammable liquids impinge on a hot surface and evaporate or boil, a mixture of flammable gases with the surrounding air will be formed. If the flammable gas concentration of this mixture reaches certain level, and the temperature of the mixture is above its auto-ignition temperature (AIT), the mixture will ignite.

The minimum AIT of liquid fuels measured following ASTM E-659 [4] is a standardized method for hot surface ignition. However, numerous experiments have proved that the actual minimum hot surface ignition temperature of a liquid fuel is higher than the minimum AIT by ASTM [5], and the minimum hot surface ignition temperature are subject to changing environment significantly. Unlike minimum AIT measured by ASTM, the minimum hot surface ignition temperature is not a well-defined liquid property. In most cases of hot surface ignitions, fuel and the surface have a non-uniform contact and thus there exists a non-uniform heat transfer process. Hot surface ignition is triggered by the contact between the fuel vapor and the metal surface, thus external conditions including the air condition, metal surface condition, oxygen concentration, will affect the ignition process.

Shaw et al. [6] used infrared thermography to measure the hot surface temperatures and record the ignition processes for liquid fuels where they were applied as a single droplet onto the metal surface. Davis et al. [7] tested the ignition of performance fuels used in motorsports and engines on a hot surface. The results from the 900 ignition tests showed that the hot surface ignition of these liquid fuels is a probabilistic behavior and cannot be represented by a single ignition temperature. Li et al. [8] measured the minimum hot surface ignition temperature of the leaked diesel on a heated metal surface. Their study on the ignition process found that the heated surface has two-way effects on the ignition. More data and research are needed to better understand the mechanism governing hot surface ignitions to prevent such fires in a mining environment, where ventilation is present almost all the time, and airflow becomes another factor to the stochastic hot surface ignition process.

In this work, a series of experiments were designed to investigate the hot surface ignition of combustible liquids on a metal plate in an experimental tunnel. Several types of liquids (diesel, engine oil, hydraulic fluid) and metal plates (cast iron, stainless steel, carbon steel) were used to study their respective effects. The ignition probability for each type of liquid fuel and metal plate under different temperatures were also investigated. Results from this work will shed light on the ignition behavior of liquid fuels in a typical mining environment where hot surface and ventilation co-exist.

2 Experiments

Hot surface ignition experiments were conducted by researchers at the Pittsburgh Mining Research Division (PMRD). The experimental design of the testing is shown in Fig. 1. A fan was installed at one end of the tunnel to provide airflow for the ignition tests. Ventilation speed was measured using hot wire anemometers, which were positioned in front of the test section. Four airflow speeds were used in the tests: 0, 0.5 m/s, 1.5 m/s, and 3 m/s as they are in the range of required ventilation speed for diesel engine in mines [9]. Four electrical heaters were placed under a metal plate (22 cm by 22 cm) in a spatially uniform manner to heat the plate to the required temperatures. The electrical heaters have different power settings in order to reach different metal plate temperatures. The temperature of the metal plate temperature was monitored and kept constant for several minutes before testing. Thermal stresses within the hot plate can develop a slightly concave shape near the center, which tended to contain the liquid drops. Nine K-type thermocouples (0.8 mm in diameter) were attached to the surface of the metal plate to monitor the temperature of the plate. A small oil dispenser was positioned 25 cm above the metal plate, with a valve to control the liquid dripping rate. The liquid valve was set to drop to the hot metal surface at a rate of 2 drops per second, and the volume of each drop was about 0.045 ml. The fan was installed 5 m from the test section. Considering the ventilation might affect the trajectory of the liquid droplet, the fuel dispenser was positioned a little upstream from the plate center, and the liquid droplets fell on the plate central area where metal temperature was recorded. For each test, there were roughly 10 drops onto the metal surface or until ignition occurred. After each test, a minimum of a 30-s interval was allowed for the metal plate to regain thermal equilibrium. For each temperature setting, at least 10 tests were conducted, and the numbers of ignition and non-ignition tests were recorded. After each test, residue was removed from the metal surface to ensure a clear contact between the liquid and the hot surface. A K-type thermocouple was also placed in the oil dispenser to measure the oil temperature, which was around 20 °C. A camera was positioned in front of the setup to capture the ignition or non-ignition of the test. The test conditions are shown in Table 1. Every test was repeated at least twice to ensure repeatability. A total of about 3,000 tests were conducted.

Before the ignition tests, each metal plate was heated to check its uniformity at high temperatures. Figure 2 shows the temperature contour of the carbon steel at around 360 °C. The 9 red dots in the contour represent the location of thermocouples. It can be seen that the hottest area is in the middle of the plate onto which liquid oil will be dropped. The middle thermocouple data will also be recorded as the plate temperature for the tests. Figure 3 shows a sequence of photos of an ignition test with engine oil as the fuel and the stainless steel as the metal and under no ventilation.

3 Results and Discussion

As mentioned in the Introduction section, hot surface ignition is stochastic in nature. Given the same external conditions, some tests will lead to ignition and some will not. To study the ignition probability of liquid fuels under different test parameter settings, ignition and non-ignition tests were recorded during testing and denoted as 1 and 0, respectively. The logistic regression method was applied to the data to find the ignition probability under each testing scenario. Figure 3 shows the ignition test results of diesel on carbon steel with 3 m/s ventilation speed. It can be seen that there is a temperature below which ignition did not occur, and a temperature above which ignition occurred all the time. Between these two temperatures, there is an overlap (from about 440 °C to about 470 °C) for ignition and non-ignition tests. Several previous researchers [10–12] have noticed the same patterns, and the lowest temperature for ignition and the highest temperature for non-ignition were reported. Further data analysis with logistic regression reveals the ignition probability for each temperature setting, as shown in Fig. 3. Logistic regression formulas are written as Eqs. 1 and 2:

$$\ln\left(\frac{p}{1-p}\right) = a + bT \tag{1}$$

$$p = \frac{e^{(a + bT)}}{1 + e^{(a + bT)}} \tag{2}$$

The above equations will provide a logistic regression of the temperature data with the ignition probability (denoted as p in the equation), and a and b are coefficients. Logistic regression data fitting the results in an ignition probability equation versus temperature are shown in Fig. 3 for this case. A 95% confidence level was also presented as the two dashed lines in the figure. The same methods were applied to all the tests for each test setting. In the next sections, we will discuss the effect of hot surface metal type, ventilation speed on the ignition of diesel, hydraulic fluid, and engine oil with the help of the ignition probability curves in Fig. 4.

3.1 Effect of Fuel Type

Three fuel types—diesel fuel, engine oil, and hydraulic fluid—were chosen to study the effect of fuel type on the ignition probability. Table 2 lists their physical properties which include density, flash point, and auto-ignition temperature. Figure 5 shows two sets of examples of the comparison of the ignition probability curves. In the first set of examples, metal type is cast iron, and ventilation speed is 3.0 m/s. In the second set of examples, metal type is carbon steel, and ventilation speed is 1.5 m/s. In both examples, the ignition probability curve of diesel fuel was on the most left side of the graph, followed by engine oil, then hydraulic fluid. The same analysis procedure was also applied to other test conditions, and a similar trend was found. The indication from this comparison was that under the same circumstances, diesel is most likely to be ignited by a hot metal surface, followed by engine oil, and hydraulic fluid being least likely to be ignited. It is worth noting that in all the cases we tested, ignition temperature is higher than the auto-ignition temperatures listed in Table 2, indicating that hot surface ignition, which occurs in open space, requires a higher temperature for ignition. In designing fire prevention and fire suppression strategies in mines, consideration of the liquid fuel types present in mines is needed.

3.2 Effect of Metal Type

Metal type also has an impact on the hot surface ignition as different metal surfaces will provide different contact environments for the liquid fuel. Cast iron, carbon steel, and stainless steel were chosen for this study as they are potentially good candidate materials for engine boxes. During preliminary tests, we also tried aluminum and magnesium, but they were ruled out due to their bad performance in resisting heat. The properties of these hot surface metals are listed in Table 3. Figure 6 shows two sets of examples. In the first set, the fuel is diesel, and ventilation speed is 3.0 m/s. In the second set, the fuel is engine oil, and ventilation speed is 1.5 m/s. It can be seen from the figure that carbon steel requires a higher ignition temperature than the stainless steel and cast iron. Cast iron and stainless steel have a similar influence on the ignition temperature. One possible explanation for such different performances between the metals might be the metal properties and the features of their surfaces which are in direct contact with the liquid fuel, including the roughness, metal thickness, and specific heat of the metal. The indication from this study in regard to mine fire prevention and protection is that carbon steel might be a better choice compared to the other two metals for mining equipment that has the potential for a hot surface ignition. For the same external conditions, carbon steel will result in a higher ignition temperature for liquid fuel.

3.3 Effect of Ventilation Speed

Ventilation speed is another important factor in hot surface ignition of liquid fuels in a mining environment. The impact of ventilation on ignition is complicated. Ventilation airflow can help remove smoke product and cool the hot source to some extent, while ventilation airflow can enhance ignition as it provides oxygen to the fire. The ventilation for the tests was provided by an electrical fan, a 1-D anemometer was positioned 20 cm in front of the metal plate to avoid heat damage from the tests. The Round per Minute of the electrical fan was characterized and marked for each ventilation speed used in the tests. Each measurement of the ventilation speed by the electrical fan was repeated three times, and an averaged Round per Minute data was used for the corresponding tests. During the tests, the anemometer was also positioned in front the test plate to check the ventilation speed. It should be noted that for high wind speed cases, the oil dispenser was positioned a little further downstream so that the liquid fuel can fall onto the central area of the metal plate. The height from oil dispenser to the metal surface is kept at 25 cm so that there is minimum splash from the dropping. Figures 7 and 8 show two sets of examples. In the first set, the fuel is diesel, and the metal type is carbon steel. In the second set, the fuel is hydraulic fluid, and the metal type is cast iron. In both sets, no ventilation results in the highest ignition temperature, and 3.0 m/s ventilation speed has the lowest ignition temperature. The interception of the S curve on the X axis represents the lowest ignition temperature. For diesel fuel on carbon steel, the lowest temperature for ignition decreases with ventilation speed. It indicates that in those tests, the oxygen effect of ventilation to diesel fuel on carbon steel is more prominent than the cooling effect of ventilation. However, for hydraulic fluid on cast iron, the lowest temperature for ignition does not change much with ventilation, which indicate that in those tests the cooling and oxygen effect of ventilation might offset each other. Other test results also show that there is no clear trend or relation between the ignition probability and the ventilation speed given the test conditions in this study. The indication from this study in regard to mine fire prevention and protection is that ventilation does not necessarily help ignition or suppression. A more detailed experimental study is needed to find out the exact role of ventilation in hot surface ignition, suppression, and re-ignition in a mining environment.

3.4 Ignition Probability and Temperatures

Apart from the ignition probability curve of each of the test conditions reported above, there are other important data that can be helpful in mine fire suppression design, which include the 50% ignition probability temperature, highest temperature for non-ignition, and lowest temperature for ignition. Highest temperature for non-ignition and lowest temperature for ignition are the test data from the study. The 50% ignition probability temperature is retrieved from the ignition probability curves shown in Sects. 3.1 to 3.3. Table 4 shows the ignition temperatures at 50% probability for each test condition and the 95% confidence interval. Table 5 shows the highest temperatures for non-ignition and lowest temperatures for ignition. These two temperatures provide the overlap range of the ignition temperatures. The tables presented in this section could form a database for mine fire ignition conditions and provide guidelines for better fire protection designs.

This study was designed to investigate the hot surface ignition probability of different fuels used in underground mines under various external conditions such as ventilation. This is a first step toward a better fire suppression system for mine fires, further studies involving fire suppression designs will need data support from the current research. Codes and standards in MSHA regarding mine fire safety can also benefit from the current data. For example, it is indicated in the current study that diesel has the highest ignition probability under the same external conditions compared to other fuels. From the perspective of safety, MSHA will need to consider diesel as the worst-case scenario to design their fire prevention and suppression codes. One of the major contributions of the current study is to provide data for policy or rule makers to develop a better fire safety system in mines. Other than experimental research, numerical studies using CFD to study the ignition and suppression are still being investigated and will be reported.

4 Conclusion

A series of experiments were conducted to investigate the effects of fuel type, metal type, and ventilation speed on the ignition temperature and ignition probability of liquid fuel on the hot surfaces of mine equipment. Three types of metal (carbon steel, stainless steel, and cast iron), three types of liquid fuel (diesel, engine oil, hydraulic fluid), and four ventilation speeds (0, 0.5, 1.5, and 3.0 m/s) were chosen for the study. Logistic regression data analysis was applied to obtain the ignition probability curves and then compare the influence of each parameter on the ignition. Test results show that under the same circumstances, ignition probability of diesel fuel is higher than engine oil and hydraulic fluid. Ignition on carbon steel is less likely than stainless steel and cast iron, which makes it a better choice for mining equipment for the prevention of hot surface ignition. Ventilation speed has a mixed influence on the ignition of liquid fuels due to the competing mechanism between cooling and oxygen supplying. The experiment results demonstrate the probabilistic nature of hot surface ignition of common liquid fuels. Results from this work can help prevent mine fire ignitions and provide a dataset for better mine fire protection designs for mine equipment manufacturers.

Acknowledgements

Data from this manuscript had been presented at the 2022 SME Conference.

References

1. MSHA (2018) Accident data file downloads. United States Department of Labor, Mine Safety and Health Administration.https://arlweb.msha.gov/OpenGovernmentData/OGIMSHA.asp

2. DeRosa MI (2004) Analysis of mine fires for all U.S. metal/nonmetal mining categories, 1990–2001. Pittsburgh: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2005–105, Information Circular 9476; 1–52
3. Hansen R (2009). Literature survey–Fire and smoke spread in underground mines. Mälardalens Högskola, MdH SiST 2. Västerås
4. ASTM E-659 (2015) Standard test method for auto ignition temperature of chemicals. ASTM, West Conshohocken
5. NFPA 921 (2017) Guide for Fire and Explosion Investigations. National Fire Protection Association, Quincy
6. Shaw A, Epling W, McKenna C, Weckman B (2010) Evaluation of the ignition of diesel fuels on hot surfaces. Fire Technol 46:407–423
7. Davis S, Kelly S, Somandepalli V (2010) Hot surface ignition of performance fuels. Fire Technol 46:363–374
8. Li YL, Wang YH, Lu SX (2010) Ignition of the leaked diesel on a heated horizontal surface. Fire Saf J 45:56–68
9. MSHA (n.d.) Report on minimum ventilation requirement for mine diesel engines. https://lakegovprod3.msha.gov/ReportView.aspx?ReportCategory=EngineAppNumbers. Accessed Aug 2016
10. Foose JG (1983) F-16 Engine nacelle fire-prevention requirements study, general dynamics report no. 16, PR2771
11. Johnson AM, Roth AJ, Moussa NA (1988) Hot surface ignition tests of aircraft fluids, report no. AFWAL-TR-88–2101, Wright-Patterson Air Force Base, OH
12. Parts L (1979) Assessment of the flammability of aircraft hydraulic fluids, report no. AFAPL-TR-79–2055, Wright-Patterson Air Force Base, OH
13. Severy DM, Blaisdell DM, Kerkhoff JF (1974) Automotive collision fires. In: Proceedings of Eighteenth STAPP Car Crash Conference, Society of Automotive Engineers, Warrendale, PA, December 4–5, pp 113–199

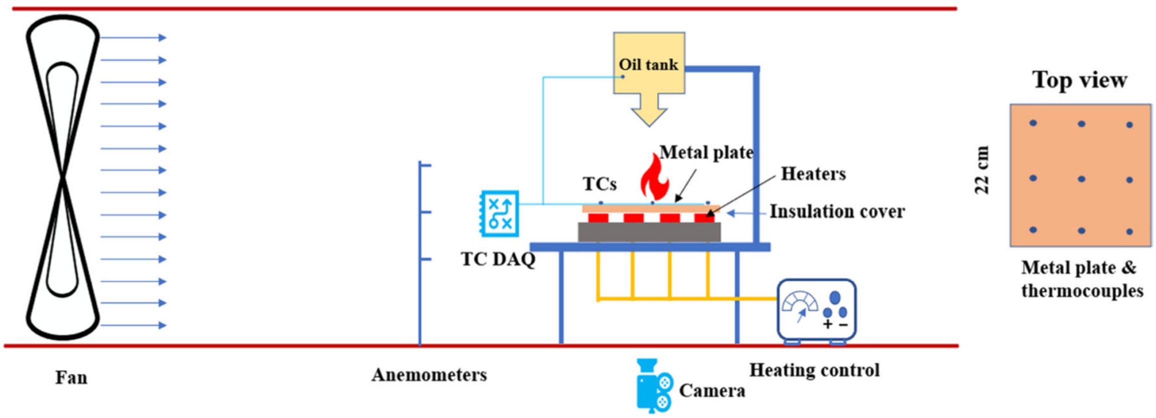

Fig. 1.
Hot surface ignition test setup

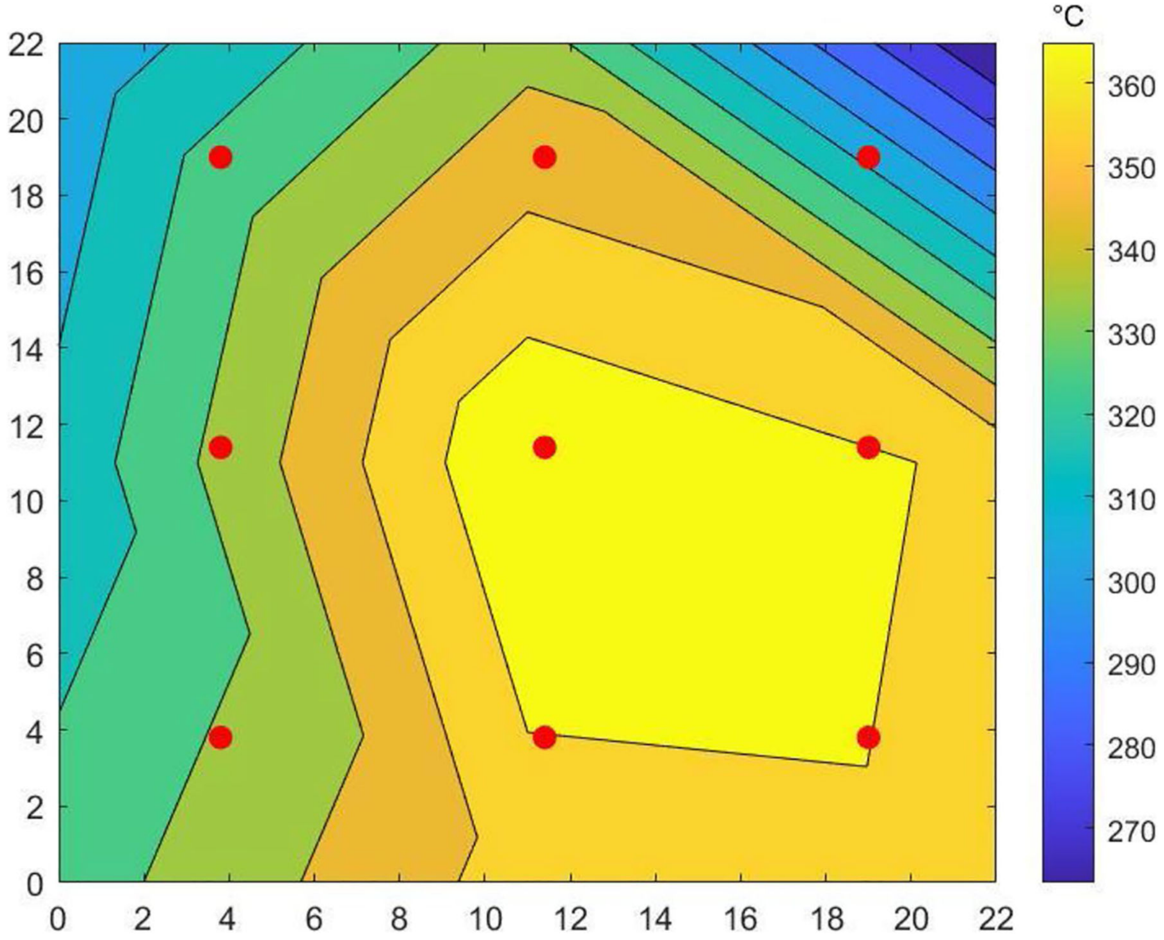

Fig. 2.

Carbon steel plate (22 cm by 22 cm) temperature mapping under high-temperature setting

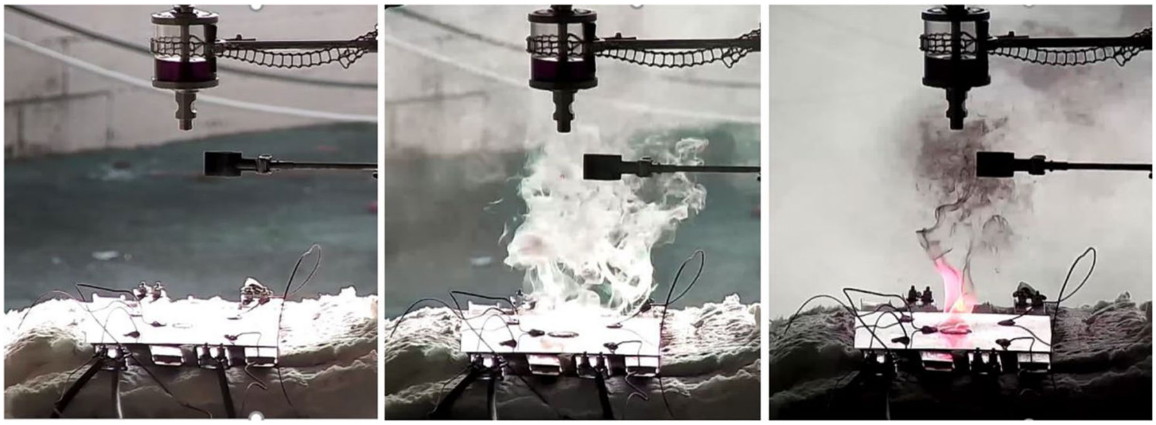

Fig. 3.

A sequence of ignition test of engine oil on stainless steel with no ventilation

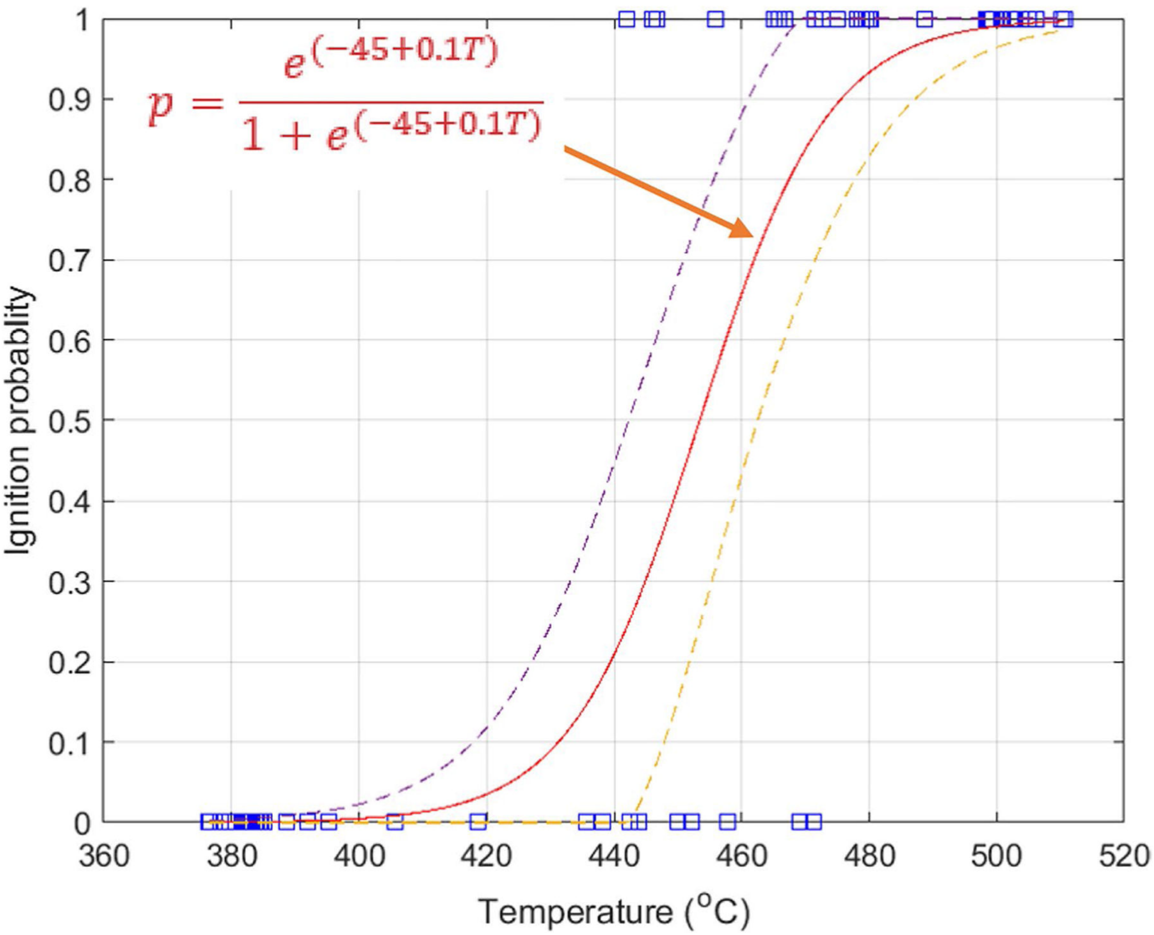

Fig. 4.

Ignition probability curve and 95% confidence level curves for diesel on carbon steel under 3 m/s ventilation

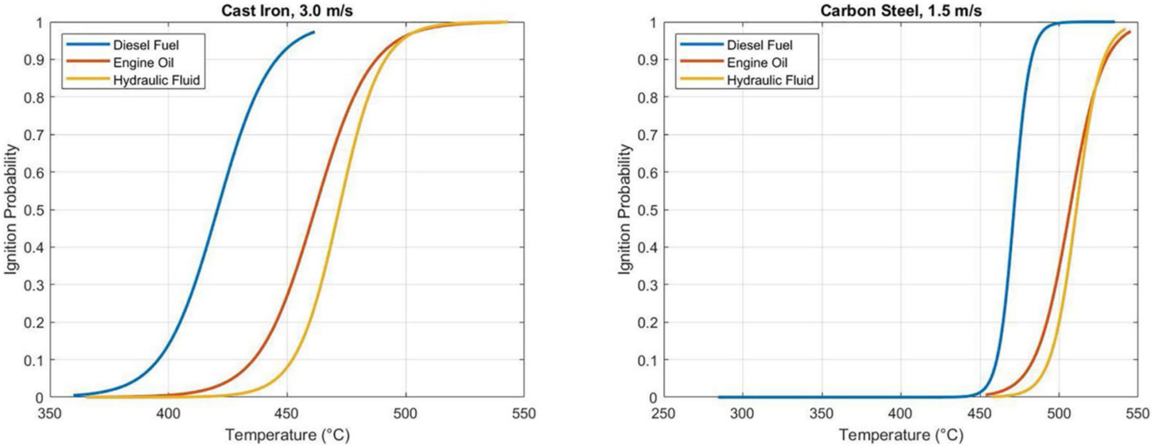

Fig. 5.

Effect of fuel type on the ignition probability

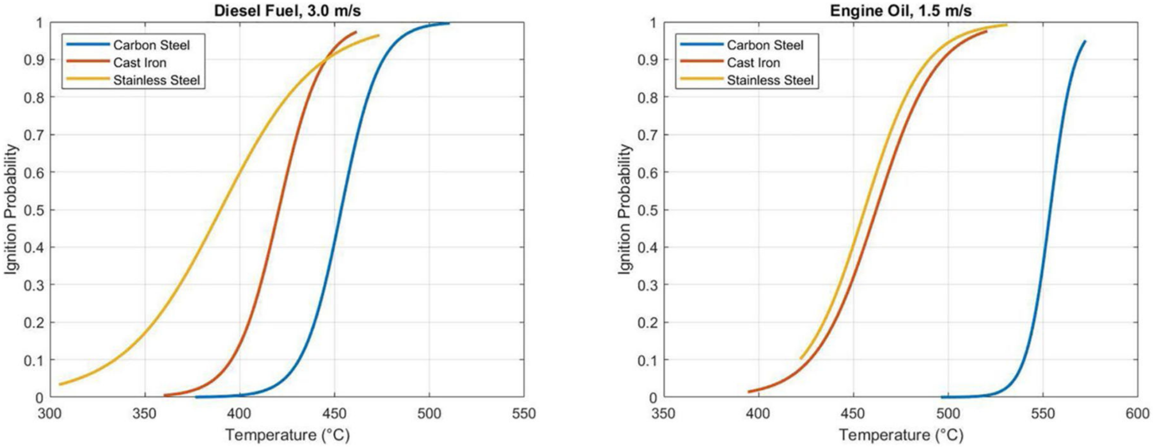

Fig. 6.

Effect of metal type on the ignition probability

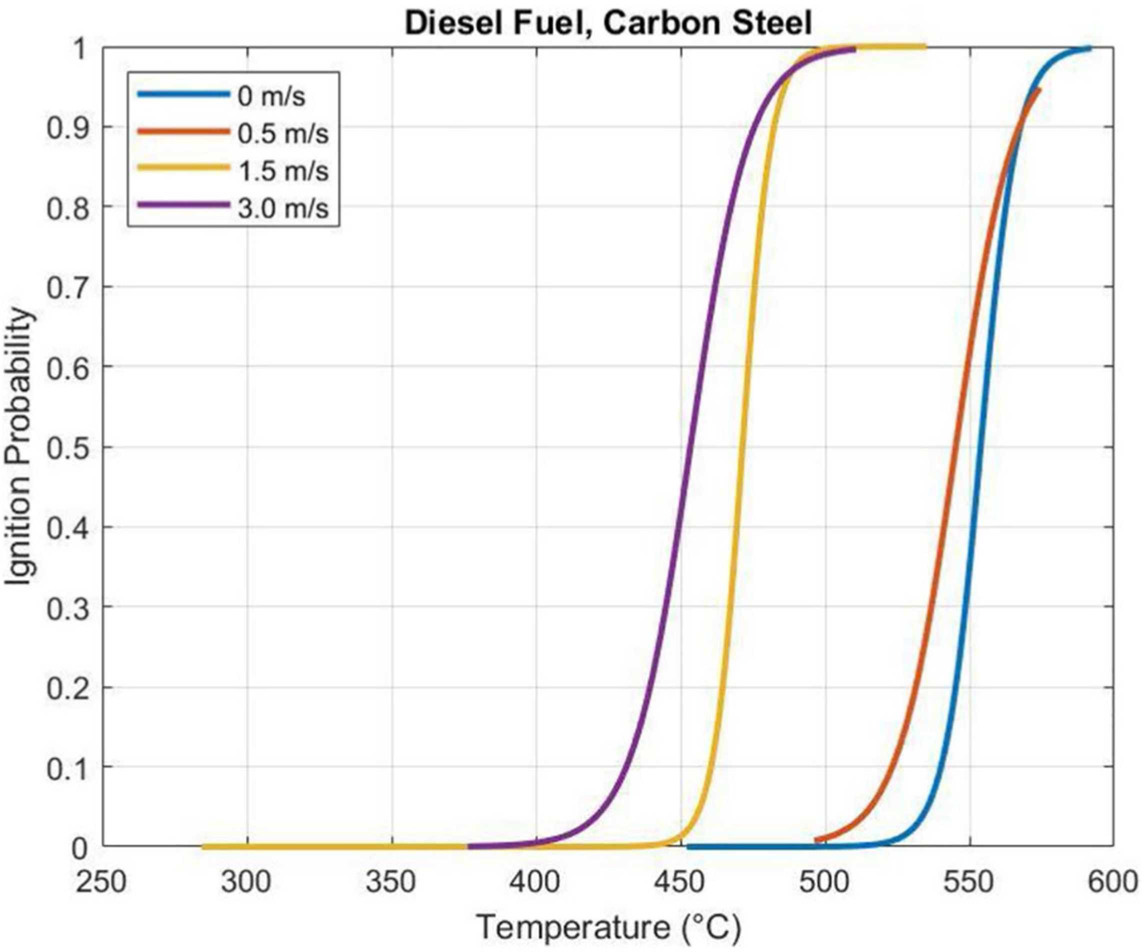

Fig. 7.

Effect of ventilation speed on the ignition probability for diesel fuel

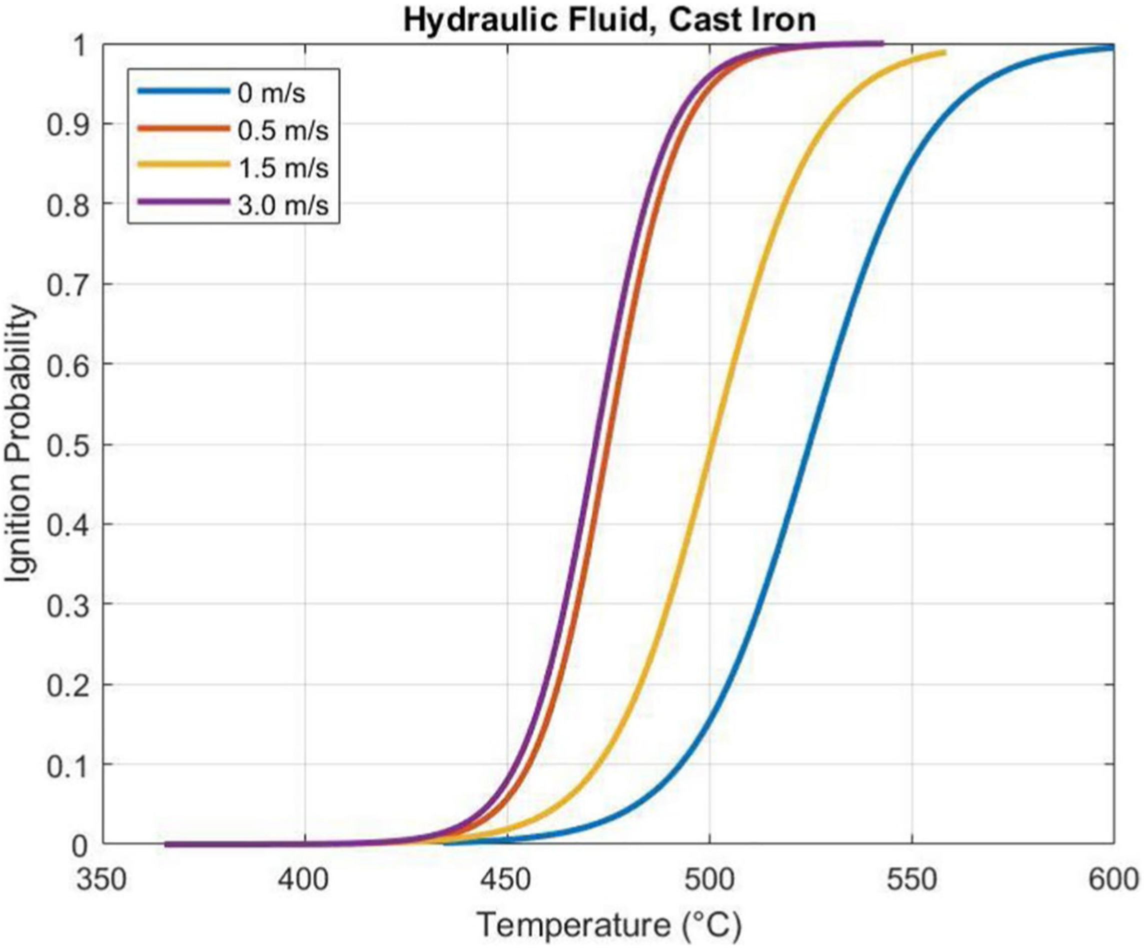

Fig. 8.

Effect of ventilation speed on the ignition probability for hydraulic fluid

Table 1

Test conditions

Fuel type	Metal plate type	Ventilation speed (m/s)
Diesel fuel	Cast iron/stainless steel/carbon steel	0, 0.5, 1.5, 3.0
Engine oil	Cast iron/stainless steel/carbon steel	0, 0.5, 1.5, 3.0
Hydraulic fluid	Cast iron/stainless steel/carbon steel	0, 0.5, 1.5, 3.0

Table 2

Liquid fuel properties

Liquid fuel type	Density (g/cm^3)	Flash point (°C)	Auto-ignition point (°C)
Engine oil	0.87	218	260–371 [5, 13]
Diesel fuel	0.85	52–96	257 [5, 13]
Hydraulic fluid	0.88	236	365 [11]

Diesel fuel: Diesel 2-D

Engine oil: SAE grade 10 W-30

Hydraulic fluid: SAE grade 30

Table 3

Hot surface metal properties

Metal type	Thickness (mm)	Roughness (mm)	Conductivity (W/(m·K))	Heat capacity (kJ/(kg K))
Carbon steel	2	0.02	45	0.49
Stainless steel	2	0.04	15	0.49
Cast iron	6	0.8	52	0.46

Table 4

Temperature for 50% ignition probability and 95% confidence interval

Fuel type	**Wind Speed (m/s)**	**Metal Type**								
		Cast iron			**Stainless steel**			**Carbon steel**		
		Temperature (°C)	**95% Confidence interval (°C)**		**Temperature (°C)**	**95% Confidence interval (°C)**		**Temperature (°C)**	**95% Confidence interval (°C)**	
Engine Oil	0	523	508	534	538	529	550	588	579	600
	0.5	462	452	474	456	447	464	554	547	558
	1.5	463	453	477	433	427	439	507	498	514
	3	462	452	475	427	401	458	471	464	478
Diesel Fuel	0	487	477	496	470	458	481	551	546	558
	0.5	462	450	479	450	440	458	545	536	552
	1.5	437	432	444	419	411	425	476	465	481
	3	421	412	432	390	372	403	454	442	463
Hydraulic Fluid	0	525	517	537	522	517	530	586	580	591
	0.5	475	468	486	481	473	487	555	552	558
	1.5	505	490	519	477	464	499	511	504	517
	3	483	461	502	456	442	478	482	473	490

Table 5

Highest temperature for non-ignition and lowest temperature for ignition

Fuel type	Wind Speed (m/s)	Metal Type					
		Cast iron		Stainless steel		Carbon steel	
		Lowest temp. for ignition (°C)	Highest temp. for non-ignition (°C)	Lowest temp. for ignition (°C)	Highest temp. for non-ignition (°C)	Lowest temp. for ignition (°C)	Highest temp. for non-ignition (°C)
Engine Oil	0	482	528	467	536	558	595
	0.5	426	467	438	505	550	562
	1.5	417	481	421	441	497	519
	3	447	476	344	459	461	482
Diesel Fuel	0	466	515	441	482	565	577
	0.5	418	466	435	477	528	564
	1.5	414	457	405	441	460	467
	3	379	422	391	446	442	471
Hydraulic Fluid	0	502	547	510	532	563	596
	0.5	449	478	466	500	550	556
	1.5	452	494	410	477	492	526
	3	454	466	402	453	465	498