

HOT SURFACE IGNITION OF LIQUID FUELS UNDER VENTILATION

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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 temperature. Results from this work can be used to help understand equipment mine fires and develop mitigation strategies.

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 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 U.S. [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, antifreeze, 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 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/boil, a mixture of flammable gases with the surrounding air will be formed. If the flammable gas concentration of this mixture is between the lower flammable limit and the upper flammable limit of the fuel, and the temperature of the mixture is above its auto-ignition temperature (AIT), the mixture will ignite.

While the minimum AIT measured using ASTM E-659 [4] has been used to prevent such hot surface ignition accidents, it was experimentally found that the actual minimum hot surface ignition temperature of fuels is much greater than the minimum AIT and significantly affected by many factors [5]. Unlike the flash point and the minimum AIT, which are well-defined properties of liquid fuels and can be measured with ASTM standards, the temperature at which hot surface ignition occurs is not an intrinsic fluid property but is strongly coupled with numerous external conditions. Hot surface ignition is further complicated because liquid fuel is often dispensed directly onto the hot surface, which makes a non-uniform contact in most cases. Since a portion of the fuel must be evaporated and come into contact with the hot surface such that sufficient heat transfer can occur, ignition is directly coupled with these complex phenomena. Auto-ignition of a

fuel depends on the property of the material being ignited, its tendency to ignite at a given temperature, the temperature of the surface in question, and other environmental factors. Environmental factors include airflow, surface condition, and availability of oxygen. Both airflow and surface conditions may influence the potential for ignition on surfaces of the same temperature. Airflow may affect the air/fuel mixture and the time period for heat transfer. Finally, a rough or scaly surface may provide pockets that can increase the time that fuel remains in the presence of heat (residence time).

Shaw et al. [6] measured surface temperatures and recorded the evaporation and ignition events using infrared thermography for gasoline, diesel, and biodiesel fuels applied as single droplets to heated surfaces. Davis et al. [7] evaluated the propensity of performance fuels used in motorsports and high-performance engines to ignite on a hot surface. The results of 900 ignition tests show that hot surface ignition is probabilistic in nature and cannot be defined by a single ignition temperature. Li et al. [8] measured the minimum hot surface ignition temperature of the leaked diesel on a heated horizontal surface using a bracketing method. Their study on the ignition process found that the heated surface has two-way effects on the ignition delay and ignition location. 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.

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 Figure 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. 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. For each test, there were roughly 10 drops onto the metal surface or until ignition occurred. After each test, a minimum of a 30-second 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.

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

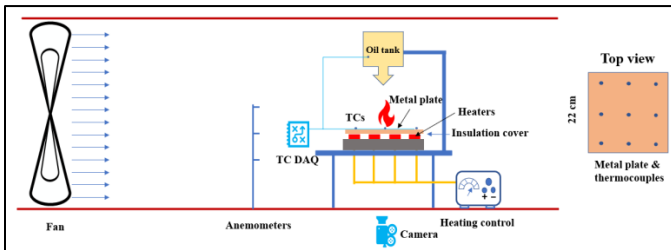


Figure 1. Hot surface ignition test setup.

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.

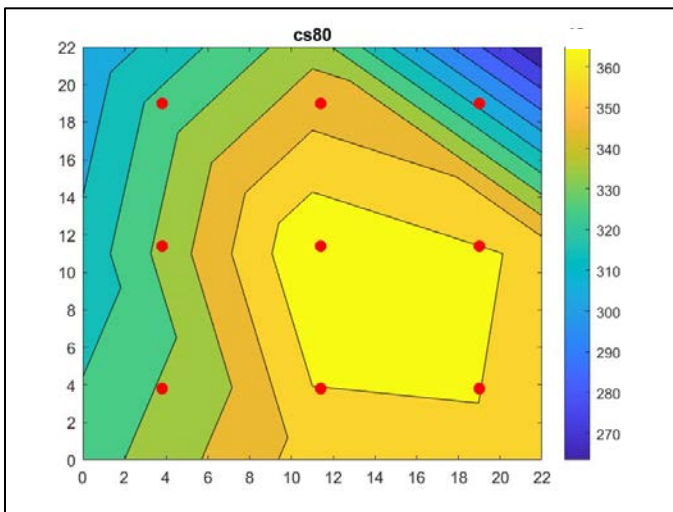


Figure 2. Carbon steel plate (22 cm by 22 cm) temperature mapping under high temperature setting.

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. Many previous researchers [9, 10, 11] 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 Figure 3. Logistic regression formulas are written as Equations 1 and 2:

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



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

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 Figure 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 Figure 3.

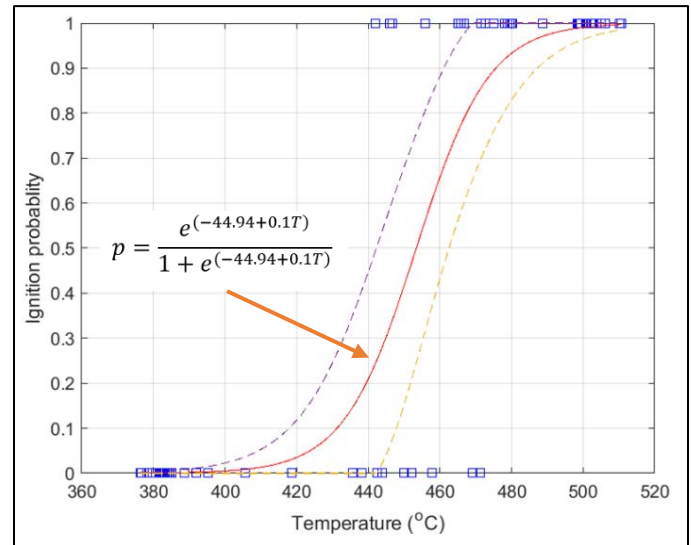


Figure 3. Ignition probability curve and 95% confidence level curves for diesel on carbon steel under 3 m/s ventilation.

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 4 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.

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, 12]
Diesel fuel	0.85	52–96	257 [5, 12]
Hydraulic fluid	0.88	236	365 [10]

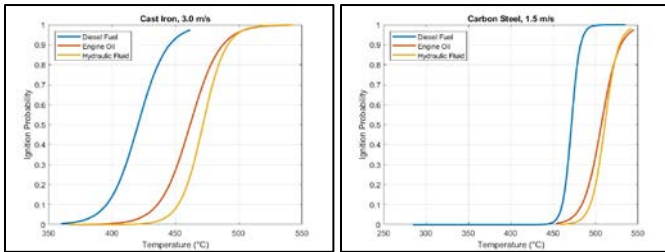


Figure 4. Effect of fuel type on the ignition probability.

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. The properties of these hot surface metals are listed in Table 3. Figure 5 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.

Table 3. Hot surface metal properties.

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

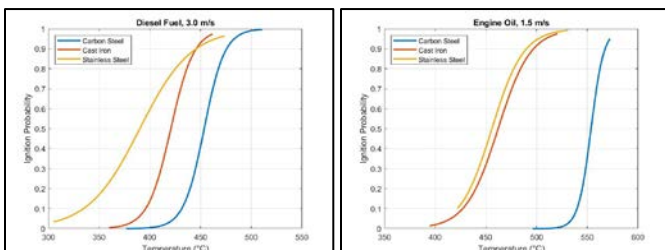


Figure 5. Effect of metal type on the ignition probability.

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 very 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. Figure 6 shows 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. However, for hydraulic fluid on cast iron, the lowest temperature for ignition does not change much with ventilation. 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.

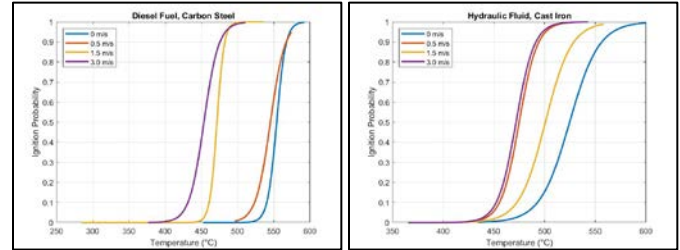


Figure 6. Effect of ventilation speed on the ignition probability.

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 sections 3.1 to 3.3. Table 4 (see APPENDIX) shows the ignition temperatures at 50% probability for each test condition and the 95% confidence interval. Table 5 (see APPENDIX) 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.

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. With the help of logistic regression, the relationship between surface temperature and ignition probability can be revealed. Results from this work can help prevent mine fire ignitions and provide a dataset for better mine fire protection designs for mine equipment manufacturers.

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.

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APPENDIX

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	523.4	508.2	533.6	537.5	528.7	550.0	588.3	578.7	600.2
	0.5	462.0	452.2	474.3	455.8	446.7	463.9	553.7	547.3	557.9
	1.5	462.7	452.7	476.9	433.1	427.1	438.6	506.8	497.7	514.1
	3	461.7	452.1	474.5	427.3	400.7	457.7	470.5	463.5	478.1
Diesel Fuel	0	486.6	476.9	495.8	470.3	458.4	481.0	550.6	545.6	558.0
	0.5	462.3	449.7	478.6	450.4	439.8	458.3	545.2	535.5	551.7
	1.5	437.0	432.2	444.0	419.0	411.3	425.0	475.7	464.9	481.3
	3	420.6	412.2	431.7	389.8	372.4	402.9	453.5	442.3	462.7
Hydraulic Fluid	0	524.6	516.5	537.3	522.3	516.7	529.5	586.0	579.8	591.1
	0.5	474.8	467.9	485.8	480.5	472.8	486.8	555.0	552.4	557.8
	1.5	504.9	489.7	519.0	477.0	463.9	499.2	511.2	504.2	517.2
	3	483.3	461.2	502.1	455.5	441.7	478.3	481.6	473.0	489.5

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	482.46	527.66	467.21	536.30	558.39	594.67
	0.5	426.21	467.21	437.76	504.60	549.70	562.32
	1.5	416.99	481.36	420.58	440.55	497.47	518.97
	3	447.24	476.43	343.82	458.68	461.27	482.31
Diesel Fuel	0	465.99	514.72	440.77	481.83	564.73	576.65
	0.5	418.06	466.30	434.93	477.08	528.18	563.91
	1.5	414.06	456.73	404.76	440.98	459.99	466.50
	3	379.47	422.35	390.84	446.14	441.99	471.32
Hydraulic Fluid	0	501.53	547.30	509.85	531.60	562.82	596.42
	0.5	449.23	477.63	466.04	500.11	550.23	555.69
	1.5	451.75	494.40	409.69	477.01	491.96	525.93
	3	453.92	465.90	402.14	453.48	465.25	498.39