Ignition of hydraulic fluid sprays by open flames and hot surfaces

Liming Yuan*
Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, P.O. Box 18070, Cochrans Mill Road, Pittsburgh, PA 15236, USA

Abstract

A study of the ignition of non-fire-resistant hydraulic fluid sprays was conducted by the National Institute for Occupational Safety and Health. Both an open flame and a hot steel surface were used as the external heat sources. With the open flame as the heat source, the minimum oil temperature and minimum spray nozzle pressure that resulted in an ignition were measured. The effects of the distance between the open flame and the nozzle and the nozzle orifice diameter on the ignitability of the hydraulic fluid sprays were examined. With the hot surface as the heat source, the minimum surface ignition temperature was determined. The degree of oil atomization and the relative direction of oil injection with respect to the hot surface are discussed. The ignition of oil sprays from the impingement of oil jets onto a vertical surface was also investigated. Finally, the results are compared with those obtained for fire-resistant hydraulic fluids.

Keywords: Ignition; hot surface; open flame; hydraulic fluid

1. Introduction

Hydraulic fluids are widely utilized in many industries, such as mining and construction, for power transmission. Most hydraulic fluids are combustible and are used under high pressure to transmit power or motion. Pressurized oil in hydraulic systems presents a considerable fire hazard, particularly where ignition sources are present. When hydraulic oil is released under pressure, it often results in an atomized spray or mist of oil droplets that may extend as far as 10 m from the break (Bowen & Shirvill, 1994). The oil spray can be ignited readily by hot surfaces, such as heated or molten metal, electric heaters, open flames or welding arcs. The resulting fire usually is torch-like, with a very high heat release rate, and can cause significant property damage, even loss of human lives. The frequency of fires involving hydraulic fluids has prompted the introduction of fire-resistant fluids in hydraulic systems.

Fire-resistant hydraulic fluids can be divided into four groups: high-water containing fluids (HFA), invert emulsions (HFB), water glycols (HFC), and water-free fluids, including synthetics (HFD). Almost all fire-resistant hydraulic fluids can still burn under certain conditions. HFB and HFA fluids will

* Tel: +1 412 386 4961; fax: +1 412 386 6595. E-mail address: lcy6@cdc.gov.

burn if a certain amount of water evaporates. Most HFD fluids will ignite, but self-extinguish and do not propagate the fire. Only HFA fluids can really be considered noncombustible. Several test methods have been established to determine the fire resistance of hydraulic fluids (Roberts & Brookes, 1981; Holmstedt & Persson, 1985; Little, Pande, Romans & Matuszko, 1991; Yule & Moodie, 1992; Khan, 1996). One of the most common tests is the one used by FM Global (Khan, 1996). The FM test method simulates a high-pressure leak with an ignition source present. A value called the spray flammability parameter is calculated (SFP). Fire-resistant fluids are grouped into three categories based on their SFP values. In the US mining industry, the U.S. Mine Safety and Health Administration (MSHA) has established a set of testing methods for determining fire-resistant hydraulic fluids (Code of Federal Regulation, 2001). The MSHA testing methods include an autoignition temperature test, a temperature-pressure spray ignition test and a test to determine the effect of evaporation on flammability. A hydraulic fluid is designated as fire-resistant if it passes all three tests.

Although fire-resistant hydraulic fluids have been available for many years, non-fire-resistant hydraulic fluids are still primarily used in most industries. There are two likely reasons for this: First, fire-resistant hydraulic fluids generally do not have exactly the same physical and chemical properties as the most commonly used mineral oils. For existing systems, the change from mineral hydraulic oil to fire-resistant hydraulic fluid usually requires a retrofit of the system (Castleton, 1998). If care is not exercised in the selection of components, system design, compatibility, and suitability of fluids, then the hydraulic system may become unreliable. Secondly, most fire-resistant hydraulic fluids cost more than mineral oils. In the U.S. coal mining sector, MSHA regulations require that fire-resistant hydraulic fluids be used in certain underground mining equipment. In the metal/nonmetal mining sector, however, there is no mandatory requirement for using fire-resistant hydraulic fluids. Approximately 89 mobile equipment fires at US metal/nonmetal mines were caused by hydraulic fluids/fuel from 1990 to 2001 with 46 injuries and 3 fatalities (De Rosa, 2004). In order to reduce the fire hazards caused by non-fire-resistant hydraulic fluids, it is necessary to further investigate the ignition of hydraulic fluids under various fire scenarios.

The spray ignition and combustion of liquid fuels has long been an important topic in combustion research. Aggarwal reviewed theoretical and experimental studies dealing with the spray ignition phenomena covering both the external-source ignition of liquid fuel sprays and the spontaneous spray ignition (Aggarwal, 1998). A successful ignition event is thought to begin with an "ignition kernel", a localized region of high reactivity and heat release, followed by the establishment of a flame. This depends upon a number of parameters, such as the structure of the local flow field, the mixture composition, and the mode of depositing ignition energy. For liquid fuel-air mixtures, additional parameters are the spatial distribution of droplets in the vicinity of the "ignition kernel", the droplet size distribution, and the fraction of fuel in the vapor and liquid phase. A majority of experimental investigations on external-source ignition have employed spark ignition to examine the ignition characteristics of monodisperse and polydisperse sprays, nearly-quiescent and flowing sprays, and single-component and multicomponent fuel sprays. Some experimental studies have also examined spray ignition in the thermal boundary of a heated wall. Sommer conducted an experimental study to identify the importance of transport mechanisms on fuel droplet ignition by an electrically heated flat plate positioned in front of a vertical stream of decane droplets (Sommer, 1986). The ignition event was found to depend on the temperature of the hot surface, the geometry of the arrangement, the physical properties of the fuel, the residence time of the droplets in the thermal boundary layer and the fuel vapor concentration of the carrier gas at room temperature. Graves et al. investigated the ignition of Jet-A fuel sprays by an isothermal hot surface in a vertical axisymmetric duct (Graves, Tang & Skifstad, 1986). The surface temperature necessary for ignition increased with increasing freestream velocity, and wide ranges of droplet sizes had little effect on fuel ignition. The thermal effect of vaporization of the fuel in the boundary layer was found to be a significant factor in the ignition of a fuel spray, apart from the role of vaporization in merely establishing a combustible fuel/air spray. Parts developed an apparatus for measurement of ignitability characteristics of fluids at high temperatures and studied ignitability, flame propagation properties, and heats of combustion of a number of aircraft fluids (Parts, 1979). Myronuk investigated the dynamic surface ignition characteristics of aircraft fuels and hydraulic fluids on heated stainless steel and titanium surfaces (Myronuk, 1980). It was found that higher local surface air speeds necessitated higher surface temperatures for ignition of an applied fluid. Rao and Lefebvre investigated the ignition of kerosene fuel sprays in a flowing air stream (Rao and Lefebvre, 1973). Von Pidoll studied the ignition behavior of combustible clouds of sprays, powders and fibers (Von Pidoll, 1997; Von Pidoll, 2001). In the aircraft industry, much work has also been done on the ignition of aircraft fluids on high temperature engine surface (Goodall & Ingle, 1966, Westfield, 1971; Snyder & Krawetz, 1981).

An objective of the NIOSH fire prevention and fire fighting program is to reduce the number of fires and fire injuries due to equipment fires in the mining industry. To help meet this objective, research was undertaken to investigate the ignitability of several non-fire-resistant hydraulic fluids commonly used in the mining industry under different fire scenarios using either an open flame or a hot surface as the external heat sources. The kinematic viscosity and flash point for these non-fire-resistant hydraulic fluids are shown in Table 1. The effects of oil temperature, pressure, orifice size and spray properties on the ignitability were examined. The results were compared with those from some fire-resistant hydraulic fluids. The ignitability of jets of hydraulic fluid impinging on a vertical surface was also investigated. The experimental results are of importance to understand the ignition mechanism of hydraulic fluid sprays and to help minimize the risk of hydraulic fluid fires.

2. Experimental

An experimental system was developed to test the ignitability of hydraulic fluids using different spray nozzles and heat sources. The experimental setup is shown in Figure 1. A 5-liter tank was used to hold the hydraulic fluid, and the fluid was heated using an electric heating and control system. The oil tank was pressurized by nitrogen from a cylinder. Different nozzles were connected to the bottom of the tank by metal tubing to generate the desired oil sprays or jets. An open flame or a hot surface was used as the external heat sources. The open flame was a 14-cm long, line methane diffusion flame and was placed perpendicular to the centerline of the oil spray. The heat release rate for the flame was about 6 kW. The hot surface was built with electric strip heaters connected to a heating control unit. The hot surface was made of stainless steel with a size of 50 cm × 30 cm × 0.1 cm. The hot surface temperature was measured with a 0.5-mm-diameter wire K type, inconel shielded, grounded thermocouple fastened to the center of the surface. With the center temperature at 700ºC, the edge temperatures were about 50ºC lower than the center temperature. In this study, the center temperature was used as the hot surface temperature. The oil temperatures at the top and bottom of the oil tank were also measured using K type thermocouples. The oil temperature at the top was slightly higher than that at the bottom, and the bottom oil temperature was used as the bulk oil temperature. No radiation correction was made for the temperature measurements. Nozzles used for the spray tests were impingement-type pressure nozzles with different orifice diameters. These nozzles generate a fine cone-shaped spray with a spray angle of 90º. Eight non-fire-resistant hydraulic fluids and four fire-resistant hydraulic fluids were tested in the study. Diesel fuel was also tested for comparison.

During each test, the oil was first heated to the desired temperature and pressurized to the desired pressure. The typical hydraulic system pressure used in mining equipment is between 1000 to 5000 psig. The droplet size of a hydraulic fluid spray resulted from a rupture of hydraulic system pipelines can be in a wide range, depending on the size of the hole and the temperature of the fluid. In this study, the impingement-type pressure nozzle was used to generate the oil spray with a droplet size ranging from 30 to 150 μm, representing the typical droplet size range from a rupture of hydraulic system pipelines at high pressure in real situations. If the open flame was used as the heat source, the methane flame was ignited and placed at a preselected position. With the hot surface as the heat source, the spray nozzle was located 23 cm above and 23 cm from the edge of the hot surface, with its centerline parallel to that of the hot surface. The surface was first heated to about 300ºC and stabilized for 5 minutes. Then the oil spray was sprayed on to the surface for about 10 seconds. If there was no ignition, the oil spray was turned off. The hot surface was then heated to 310ºC and stabilized for 5 minutes. Then the oil spray was turned on again. If there was still no ignition, the hot surface temperature was increased by another 10ºC, and the spray test was repeated until the oil spray was ignited. Because ignition is a very sensitive event, each test sequence was repeated three times.

3. Results and discussion

3.1. Ignition of hydraulic fluids using the open flame as the heat source

An oil spray from the release of pressurized hydraulic fluid may be ignited by an external heat source such as an electric spark, a hot surface, or an open flame. The open flame is the strongest ignition source and may represent the worst oil spray ignition scenario. The ignition of a hydraulic fluid spray by an open flame is defined as the sustaining of the spray flame when the heat source is removed. The ignitability of an oil spray is dependent on the spray properties, ignition source power and location, and local flow conditions. The minimum ignition energy for oil sprays is usually higher by one or more orders of magnitude than for gas/air mixtures because the combustion of the spray requires additional energy for evaporating the droplets. Von Pidoll found that, for pure hydrocarbon mixtures sprayed with coarse nozzles, the spray could be ignited with a minimum electric spark energy as low as 0.5 J (Von Pidoll, 2001). The heat release rate of the open flame used in this study is about 6 kW, so strength of the heat source is not a concern.

(1) Effect of the distance from the open flame to the nozzle

The effect of the distance from the open flame to the nozzle on the ignitability of the hydraulic fluid sprays was studied by placing the open flame at 20 cm, 45 cm and 70 cm from the nozzle. With the 0.5 mm orifice-diameter nozzle, the AW 32 oil at 16ºC and 100 psig, and the open flame located at 70 cm from the nozzle, there was nearly no burning. At the 45 cm location, some separated oil droplets above the open flame were burning, exhibiting a droplet ignition mode (Chiu & Liu, 1977). At the 20 cm location, the oil spray above the open flame was burning, but the oil flame would not propagate towards the nozzle and the burning was not sustained when the open flame was removed, exhibiting a cloud ignition mode. At the nozzle orifice, the spray flame still could not be sustained with the open flame removed. When the oil pressure was increased to 120 psig, at the 70 cm location, separated oil droplets were burning. At the 45 cm location, the spray was burning but the flame was not sustained. At the 20 cm location, the spray was ignited and the flame propagated to the nozzle orifice, exhibiting a spray ignition mode. When the oil pressure was further increased to 140 psig and up, even at the 70 cm location, the oil spray was ignited and the flame propagated to the nozzle and burned after the removal of the open flame. In order to ignite an oil spray and have sustained flame propagation, the oil droplet density must reach a certain value to ensure that the heat released from droplet burning is larger than the heat lost to the surrounding air. The net heat gain, if sufficient, can ignite the nearby oil droplets. Because of the conical shape of the oil spray, with the increase of the distance from the nozzle, the oil density inside the spray will decrease. Thus, a maximum ignition distance exists beyond which the oil droplet density is not high enough to support a flame. With the increase of the oil pressure, the oil flow rate increased, and the maximum ignition distance increased. The oil flow rates at different pressures are showed in Table 2. Considering the weak effect of oil pressure on the oil droplet size (discussed later), these results indicate that the ignitability of the oil spray studied here was mainly controlled by the oil flow rate rather than the droplet size. A typical oil spray flame is shown in

Figure 2. When a 1 mm orifice-diameter nozzle was used, the maximum ignition distance also increased. At 80 psig and at the 20 cm location, the oil spray was ignited and the flame propagated to the nozzle. At 100 psig, the maximum ignition distance became 70 cm. Hereafter, the open flame was always placed 20 cm from the nozzle exit.

(2) Effect of the hydraulic fluid type

Hydraulic fluids can be categorized using different parameters. The kinematic viscosity is a parameter that is often used to categorize the non-fire-resistant hydraulic fluids. The viscosity significantly affects the atomization of fluids and would be expected to affect the oil spray ignition. The ignitability of different hydraulic fluids was tested with the open flame as the heat source located 20 cm from the nozzle. The ignitability was also dependent upon the oil temperature and oil pressure for a certain type of hydraulic fluid with a given orifice-diameter nozzle. When the oil pressure was fixed, the minimum oil temperature that resulted in an ignition was obtained (minimum ignition temperature), and when the oil temperature was fixed, the minimum oil pressure that resulted in an ignition could also be obtained (minimum ignition pressure). Table 3 shows the minimum ignition temperature and minimum ignition pressure for eight non-fire-resistant hydraulic fluids with the nozzle orifice-diameter of 0.5 mm. The minimum ignition temperature was the lowest oil temperature at which the oil spray, at 100 psig, was ignited and the spray flame propagated to the nozzle and burned when the open flame heat source was removed. The minimum ignition pressure was the lowest oil pressure at which the oil spray, at 20ºC, was ignited and the spray flame propagated to the nozzle and continued to burn when the open flame was removed. The oil pressure was changed in increments of 10 psig. The minimum ignition temperature and ignition pressure increased with an increase of viscosity, with auto transmission fluid (ATF) having the lowest minimum ignition temperature and pressure, and track hydraulic fluid (THF) having the highest ones. The only exception was for THF which has a slightly smaller viscosity compared with that of AW 68, but had a higher minimum ignition temperature and ignition pressure. AW 46 and Premium 46 both have the same viscosity but different flash points. Flash point is the lowest temperature at which a liquid gives off enough flammable vapor sufficient to form an ignitable mixture with air, which can be measured according to the ASTM standard D92-01. For AW 46 and Premium 46, their minimum ignition temperatures and ignition pressures were the same, implying the viscosity has a stronger effect on the minimum ignition temperature and ignition pressure than the flash point. When the oil temperature was increased, the hydraulic fluid viscosity decreased. The viscosity has a strong effect on the oil atomization [22]. A lower viscosity results in finer oil droplets. When the oil flow rate and the oil droplet size both reach certain values it becomes possible for the oil spray to ignite, and the flame to propagate to the nozzle and stabilize. But increasing the temperature slightly decreased the mass flow rate at the same pressure due to the decreasing density, while increasing the pressure increased the mass flow rate at a constant temperature. The oil spray ignition was controlled by the degree of oil atomization, the oil flow rate and the distance from the open flame to the nozzle. When the oil flow rate was high enough, the higher viscosity oil required higher temperature or pressure to generate the same size droplets as the lower viscosity oil.

It should be noticed that the viscosity values used in the above analysis were the ones measured at 40ºC. Actually, the oil viscosity is always affected by the oil temperature. All oils tend to increase in viscosity with decreasing temperature and decrease in viscosity with increasing temperature. The rate of change is an inherent characteristic of the oil itself, dependent on chemical structure. This characteristic is generally referred to as the viscosity index. Oils with a low viscosity index show a marked change in viscosity with temperature and those with a high viscosity index show a small change. For typical non-fire-resistant hydraulic oils the values of viscosity index ranges from 85-95, very close to each other. So it was assumed that the effect of temperature-dependent viscosity on the oil spray ignition was similar for all oil.

The surface tension of oil also affects the oil atomization because it represents the force that resists the formation of new surface area. The minimum energy required for atomization is equal to the surface tension multiplied by the increase in oil surface area. An oil with a higher surface tension is more difficult to atomize than one with a lower surface tension. For most pure liquids in contact with air, the surface tension decreases with an increase in temperature and is independent of the age of the surface [22]. For the hydraulic fluids used in this study, because the surface tension data were not available, the effect of the surface tension on the oil spray ignition could not be examined quantitatively.

(3) Effect of the nozzle orifice diameter

The effect of the nozzle orifice diameter on the ignitability of hydraulic fluids was examined using the impingement-type pressure nozzles with different orifice diameters. Figure 3 shows the minimum ignition pressures for three fluids measured with the oil temperature kept constant at 20ºC. With the increase of the orifice diameter, the minimum ignition pressure decreased. With the same orifice diameter, the minimum ignition pressure for AW 46 was smaller than that for AW 68, but larger than that for AW 32, because of the similar pattern of viscosity. When the orifice diameter was over 1 mm, the minimum ignition pressure became nearly the same for each of the three fluids. Figure 4 shows the minimum ignition flow rate calculated from the minimum ignition pressure for three fluids versus the nozzle orifice area. For all three fluids, the minimum oil ignition flow rate increased linearly with the nozzle orifice area. With the increase of the orifice area, the minimum ignition flow rate increased. Any oil flow rate below the minimum oil ignition flow rate would not cause an oil spray ignition. Figure 5 shows the average oil droplet Sauter Mean Diameter (SMD) at the minimum oil ignition flow rate versus the orifice diameter. The SMD was estimated from the droplet size data measured by the nozzle manufacturer with water as the fluid. The density difference between the hydraulic fluid and water was considered when the estimation was made. The average oil droplet diameter changed from 37 μm to 108 μm. The fact that the minimum ignition flow rate was proportional to the area of the orifice implies that the droplet size in this range had only a small effect on the minimum ignition flow rate.

The oil droplet SMD is strongly influenced by the oil properties of density, viscosity, and surface tension. In practice, the significance of oil density is diminished by the fact that most oils exhibit only minor difference in this property. This is also true for surface tension. However, viscosity varies by almost two orders of magnitude in some applications, so its effect on oil droplet SMD can be quite large [22]. Lefebvre [22] analyzed the effects of oil density, surface tension and viscosity on the SMD and obtained the following equation for the estimation of the SMD of liquid droplets from a pressure nozzle:

$$SMD = 2.25\sigma^{0.25}\mu_L{}^{0.25}m^{0.25}\Delta p^{-0.25}\rho_A{}^{-0.25}$$

where σ is the liquid surface tension in kg/s^2, μ_L the liquid dynamic viscosity in kg/ms, ρ_A the air density in kg/m^3, m the liquid flow rate in kg/s, and Δp the nozzle pressure differential across nozzle in Pa.

(4) The effect of oil temperature of hydraulic fluids

For some mining equipment, the oil temperature inside the hydraulic lines can be as high as 70ºC, especially in the summer time. The increase of the oil temperature also affects the ignitability of the hydraulic fluid sprays. Figure 6 shows the effect of the oil temperature on the minimum ignition pressure for oil AW 32 at three temperatures: 20ºC, 45ºC and 70ºC using the 0.5 mm orifice-diameter nozzle. With the increase of the oil temperature, the minimum ignition pressure decreased for a given orifice-diameter nozzle. This is because the oil atomization and oil droplet evaporation were enhanced with the increase of oil temperature, and a smaller quantity of oil was needed to generate a sufficient amount of oil vapor to reach the lower flammability limit.

3.2. Ignition of hydraulic fluids using a hot surface as the heat source

The ignition of hydraulic fluids using a hot surface as the heat source was tested with the 0.5 mm orifice-diameter nozzle. The oil was pressurized at 100 psig, and the minimum hot surface temperatures for oil spray ignition were determined. The oil temperatures were kept at their respective minimum ignition temperatures. Table 4 shows the range of hot surface ignition temperatures for different hydraulic fluids. The lower value is the minimum hot surface temperature at which the oil spray was ignited at least once, while the higher one is the maximum hot surface temperature at which the same oil spray was not ignited at least once. Only the minimum value is used in the following discussion. The minimum hot surface ignition temperatures for ATF and Compressor oil were 350ºC and the ignitions were very repeatable. This value was consistent with the result obtained by Holmestedt at al. for mineral oil (Holmstedt & Persson, 1985). AW 68 had the largest minimum hot surface ignition temperature, 440ºC, while diesel fuel had the smallest one, 330ºC. The minimum hot surface ignition temperature tends to be higher for fluids with large viscosities. However, the viscosity only seemed to affect the oil atomization, not the combustion. Diesel fuel has a flash point of about 60ºC while the flash point for AW 32 is 220ºC, implying that the flash point has little effect on the minimum hot surface ignition temperature.

The effect of the oil pressure on the minimum hot surface ignition temperature was examined by increasing the oil pressure to 200 psig. At 200 psig, the minimum hot surface ignition temperatures were about 30 to 40ºC lower for AW 68 and THF and about the same for ATF. With the increased pressure, more oil was sprayed onto the hot surface. For the limited heat capacity of the hot surface, more oil impinging on the surface cooled the surface, making the ignition more sensitive to the local flow conditions. It was observed that, if the ignition did not occur in the first several seconds, it was not likely to occur with the continuing oil spray because the hot surface temperature also decreased at the same time. Some ignitions occurred immediately after the oil spray was stopped because the hot surface was no longer cooled and regained a temperature high enough to ignite the nearby oil vapor. It must be noted that hot surface ignition is very sensitive to the experimental conditions. All results obtained in this study may be only true under these specific conditions and may not apply to other conditions such as oil spraying on a hot exhaust manifold or a turbocharger. But these results will help understand what may happen in other conditions.

Nozzles with orifice diameters of 0.2 mm and 1.0 mm were also used for the hot surface ignition tests. The 0.2 mm orifice-diameter nozzle could not generate enough oil droplets capable of reaching the hot surface at both 100 and 200 psig. The very fine droplets did not have enough momentum to overcome the rising convection waves from the hot surface. The 1.0 mm orifice-diameter nozzle resulted in nearly the same minimum hot surface ignition temperatures as the 0.5 mm orifice-diameter nozzle.

The ignition of oil spray by a hot surface is a very complicated physical and chemical process. Sommer studied the ignition of fuel droplet streams by a hot plate, and his experimental results indicate that the ignition event is evaporation and diffusion controlled and occurs when a preferred mixture composition has developed to establish self-supporting combustion (Sommer, 1986). Close to the hot surface evaporation occurs at a very high rate such that a fuel vapor cloud develops around each droplet. Diffusion and mixing of air with this vapor occurs in regions of low temperature which do not trigger the ignition event. In order for an ignition to occur, a location in the gas has to exist where (a) the temperature is at or above the autoignition temperature; (b) the fuel concentration is between the lower flammability and upper flammability limit; (c) the fuel/air mixture stays in a high temperature zone for a sufficient time. Such a location will not exist until the surface is significantly hotter than the autoignition temperature because of the dropping temperature gradient with increasing distance from the surface. Babrauskas reviewed some available oil autoignition and hot surface ignition data and found that there is no relation between flash point and autoignition temperature (Babrauskas, 2003). The autoignition temperature is primarily determined by a fuel’s reactivity while the flash point is primarily determined by its volatility. Hot surface ignition is affected both by the chemical reactivity and the volatility of the fuel. According to Babrauskas’s analysis, assuming the hot surface ignition temperature is 200ºC above the autoignition temperature generally provides a more realistic estimate. Although diesel fuel has a low flash point, 60ºC, it has a high autoignition temperature, 225ºC (Kuchta, 1985). Its minimum hot surface ignition temperature was 330ºC under these test conditions or about 100ºC lower than the 425ºC predicted from the above assumption.

Results obtained by other researchers show that the ignition of hydraulic fluids by a hot surface was also much dependent on the degree of oil atomization and local flow conditions. Goodall and Ingle investigated the effect of the degree of oil atomization on the ignition of combustible fluids by hot surfaces in an enclosed volume (Goodall and Ingle, 1966). The combustible fluid under test was injected vertically downwards onto a heated bottom plate surface with various degree of atomization. The distance between the nozzle and the bottom hot plate was only 7.6 cm. They found that, with a high degree of atomization spray, ignition temperatures were higher than those for a liquid jet and a low degree of atomization spray. This was attributed to a reduction of spray penetration to the surface of the bottom plate in the enclosed. Parts conducted manifold spray ignition tests of aircraft hydraulic fluids (Parts, 1979). The spray was directed downwards at the center of a horizontal manifold. The angle between the manifold major axis and the direction of the spray was 60 degrees. The test fluids were pressurized at 1000 psig with nitrogen. The manifold surface was cooled significantly upon the impingement of high-pressure fluid sprays. Therefore, in comparison with fluid stream impingement, ignition occurred less readily. Consequently, the spray ignition temperatures of fluids were generally higher than the corresponding values for fluid stream impingement.

In this study, all tests were conducted in open air inside a large structure, and the oil spray was directed horizontally, not downwards, to the hot surface. In order to examine the effect of the relative direction of the oil injection with respect to the hot surface on the ignition, the oil spray was directed vertically downwards to the hot surface from the 0.5 mm orifice-diameter nozzle which generated a 90º full cone spray. No ignition occurred because the oil vapor was blown away by the air flow entrained by the spray. The ignitability of oil streams from a plain orifice nozzle with an orifice-diameter of 0.79 mm at 100 psig was also tested. The oil stream was directed downward onto the hot surface 30 cm away. It was found that the minimum hot surface ignition temperatures were about 500 to 530ºC for all hydraulic fluids. When the nozzle was less than 15 cm away from the hot surface, few ignitions could occur at the same hot surface temperature because the oil vapor was blown away. But with a drip of oil falling on the hot surface at the same temperature, the ignition immediately occurred. Myronuk investigated the effect of local airflow velocity on the minimum hot surface ignition temperatures and found that higher local surface air speeds always necessitated higher surface temperatures for ignition of aircraft hydraulic fluids (Myronuk, 1980). Forced air flow was not present in this study.

3.3. The ignition of hydraulic oil jets impinging on a vertical surface

When the oil was injected from a plain orifice, it was very likely that an oil jet was formed if the oil pressure was not high enough or the orifice diameter was not small enough. Although the oil jet would not ignite with an open flame, this does not mean that there is no fire risk for the oil jet with an open flame. When an oil jet impinges on a vertical surface, the ignitability of the spray formed from the break up of the primary jet may be enhanced significantly if fine droplets are generated from the impingement. Experiments were conducted to test the ignitability of such secondary sprays using a plain orifice with a diameter of 0.79 mm at 200 psig to generate an oil jet. The AW 32 and 46 oils were used in the tests. The oil jet horizontally impinged on a vertical steel surface. The methane flame was used as the ignition source. It was found that the secondary spray was ignited and burning sustained when the open flame was removed only when the distance between the nozzle and the vertical surface was within a certain range, approximately 0.5 to 1.2 m. Figure 7 shows the typical flames from the burning of the secondary spray of AW 46. At the center of the impingement area, no oil was burning because it was too fuel rich. When the nozzle was too close to the vertical surface, the jet was broken up but not enough fine oil droplets were generated because the liquid core of the jet was too thick. Under these conditions the secondary spray could not be ignited. When the nozzle was far away from the surface, the liquid core inside the primary jet already developed into a spray before impinging on the vertical surface (Faeth, 1990). Only the impingement from the thin liquid core of the primary jet could generate enough fine droplets for an ignition to occur. The structure of the oil jet was dependent on the oil property, oil temperature, oil pressure and the orifice size. Maragkos and Bowen studied the combustion hazards due to impingement of pressurized release of liquid fuels (Maragkos and Bowen, 2002). They measured the mass flow rate for both the primary spray and the secondary spray resulted from an impingement of the primary spray on an obstruction, and found that the mass flow ratio between the secondary spray and the primary spray was significant, typically between 20% and 80%, depending on the specific release conditions. The ratio was a function of downstream impingement distance, release pressure, and orifice size. The ratio depends less on surface roughness and impingement angle. Compared with the primary spray, a roughly 50% reduction in the Sauter Mean Diameter of the secondary spray was measured in their tests. They also demonstrated that an impinging spray of high-flashpoint fuel, released at low pressure and at temperatures significantly below its flashpoint, was relatively easily ignited with a low-energy electrical discharge (100 mJ) and capable of sustaining flame propagation.

3.4. Fire-resistant hydraulic fluids

Four kinds of fire-resistant hydraulic fluids were also tested with the methane open flame and the hot surface as the heat sources. These fire-resistant hydraulic fluids were a high water containing fluid, a water glycol, a water-in-oil invert emulsion, and a polyol ester base synthetic fluid. The test conditions were the same as for the non-fire-resistant fluids. With the open flame as the heat source, the high-water containing emulsion and water glycol could not be ignited. For the water-in-oil invert emulsion, when the fluid temperature was increased to about 60ºC at 100 psig, the emulsion spray was ignited and the spray flame sustained when the open flame was removed. The only visual difference compared with the non-fire-resistant fluid was that the spray flame height was slightly shorter, and the burning was less intense. For the synthetic fluid, when the fluid was heated to 50ºC, the spray was ignited and the spray flame sustained after the removal of the open flame. This result was very close to that obtained for the non-fire-resistant THF. When the hot surface was used as the heat source, the high-water containing fluid and water glycol could not be ignited by the hot surface up to 700ºC. However, the synthetic fluid and water-in-oil invert emulsion oil sprays were ignited when the fluids were heated to their minimum ignition temperatures. The minimum hot surface ignition temperature was 450ºC for synthetic fluid and 490ºC for water-in-oil invert emulsion. Although the synthetic fluid and water-in-oil invert emulsion are classified as “fire-resistant”, their fine oil sprays were still ignitable with both open flame and hot surface as the heat source under these test conditions. The key condition for the oil spray ignition is that the fluid is released in the form of very fine droplets. In this study, this was achieved by increasing the fluid temperature to the minimum ignition temperature at 100 psig. In real applications, the fine oil droplets can be generated from the rupture of the high pressure hydraulic fluid lines, up to 5000 psig, high oil temperatures from the compression and friction inside the hydraulic system or the combination of both high temperature and high pressure.

4. Conclusions

A series of ignition tests for several non-fire-resistant hydraulic fluids were conducted with either an open flame or a hot surface as the heat source. The following conclusions can be drawn from this study.

(1) When an open flame is used as the heat source, the test results show that lower viscosity fluids are easier to ignite than those with higher viscosities. Under the experimental conditions of this study, all fluids tested were ignited and the spray flame propagated to the nozzle when the oil flow rate was larger than the minimum ignition flow rate for a given orifice size with the open flame placed 20 cm from the nozzle.

(2) For oil droplet sizes ranging from 40 to 100 µm, the droplet size had very little effect on the minimum ignition flow rate. With the increase of the oil temperature, the minimum ignition flow rate decreased.

(3) When a hot surface was used as the heat source, the minimum hot surface ignition temperatures ranged from 350ºC to 440ºC. The fluid viscosity appeared only to affect the atomization and not the combustion, while the flashpoint had no impact on the minimum hot surface ignition temperature.

(4) Hot surface ignition was also dependent on the degree of atomization, the relative direction of oil spray with respect to the hot surface and the local flow conditions.

(5) An oil spray from the impingement of a primary oil jet onto a vertical surface was ignitable with the open flame. This ignition only occurred when the vertical surface was in a certain distance range from the nozzle.

(6) Of the four types of fire-resistant hydraulic fluids, only high-water containing fluids and water glycol exhibited strong fire resistant characteristics with the open flame and the hot surface. The synthetic fluid and water-in-oil invert emulsion were ignited and burned when released in the form of fine droplets.

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Table 1. Kinematic viscosity and flash point for non-fire-resistant hydraulic fluids

Hydraulic fluid	Kinematic viscosity, cSt	Flash point, ºC
ATF	36.1	185
Compressor oil	50	232
AW 32	30.4	220
AW 46	43.7	226
AW 68	64.6	235
Premium 46	46	186
THF	58.4	235
AW 68*	68	218
Diesel fuel	1.9 ~ 4.1	60

(AW 68* was from a different manufacturer than AW 68)

Table 2. Oil flow rates at different pressures

0.5 mm orifice-diameter nozzle		1.0 mm orifice-diameter nozzle	
Pressure, psig	Flow rate, lpm	Pressure, psig	Flow rate, lpm
80	0.36	80	1.50
100	0.40	100	1.68
120	0.44	120	1.84
140	0.47	140	1.98

Table 3. Minimum oil temperature and pressure resulting in an ignition

Hydraulic fluid	Minimum oil temperature at 100 psig, ºC	Minimum oil pressure at 20ºC, psig
ATF	14	70
Compressor oil	28	120
AW 32	17	80
AW 46	24	110
AW 68	30	160
Premium 46	24	110
THF	48	180
AW 68*	35	160
Diesel fuel	0	20

Table 4. Minimum ignition hot surface temperatures

Hydraulic fluid	Minimum hot surface ignition temperature, ºC
ATF	350-360
Compressor oil	350-370
AW 32	390-430
AW 46	390-450
AW 68	440-480
Premium 46	420-450
THF	430-460
AW 68*	400-450
Diesel fuel	330-370

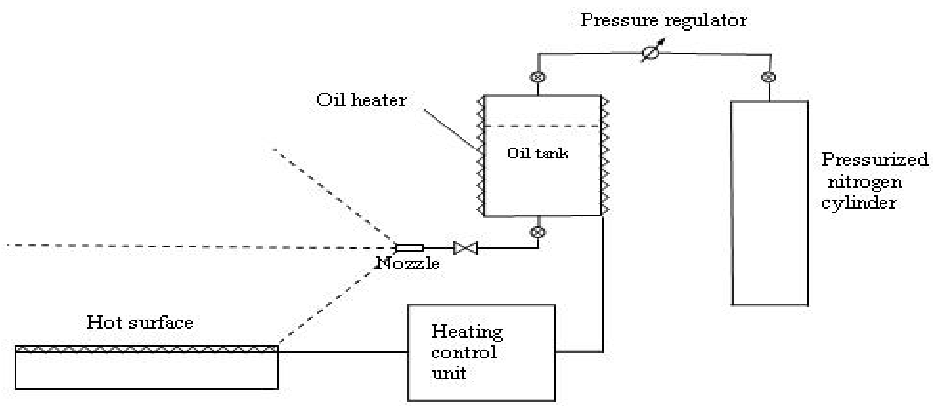

Figure 1. Experimental setup with a hot surface as the heat source

Figure 2. A typical hydraulic oil spray flame

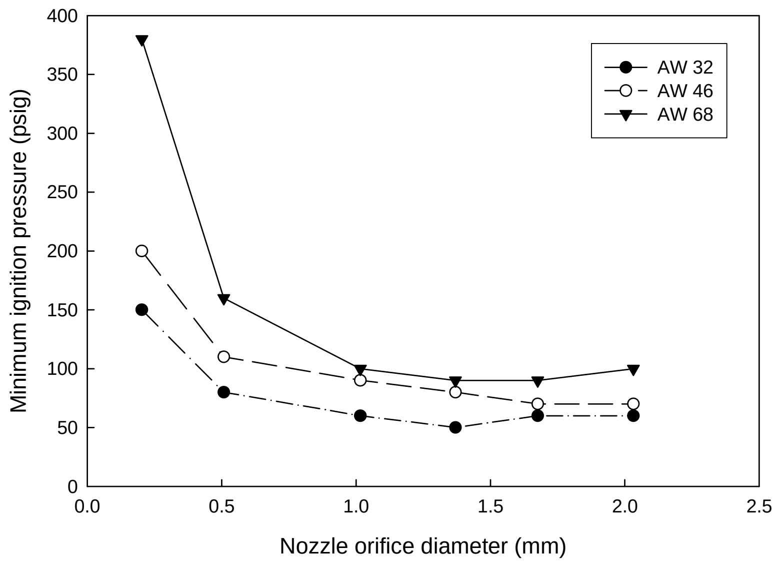

Figure 3. Minimum oil pressure versus nozzle orifice diameter

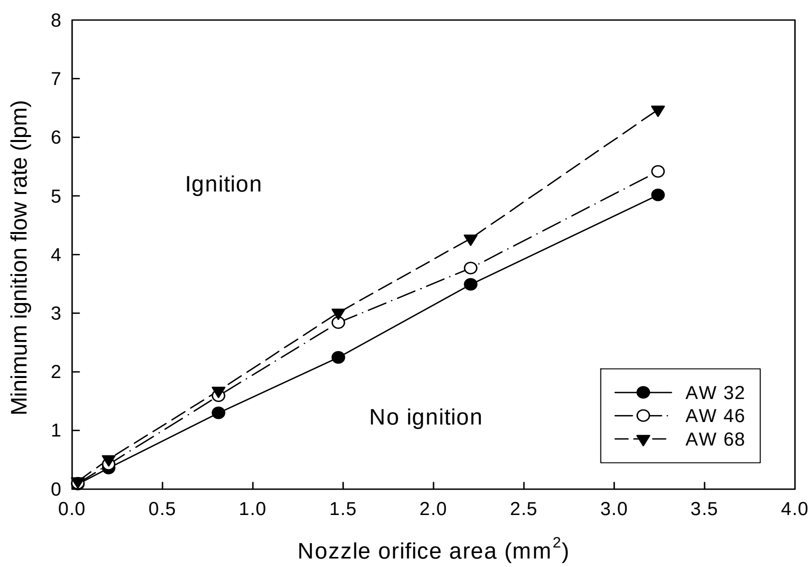

Figure 4. Minimum oil flow rate versus nozzle orifice area

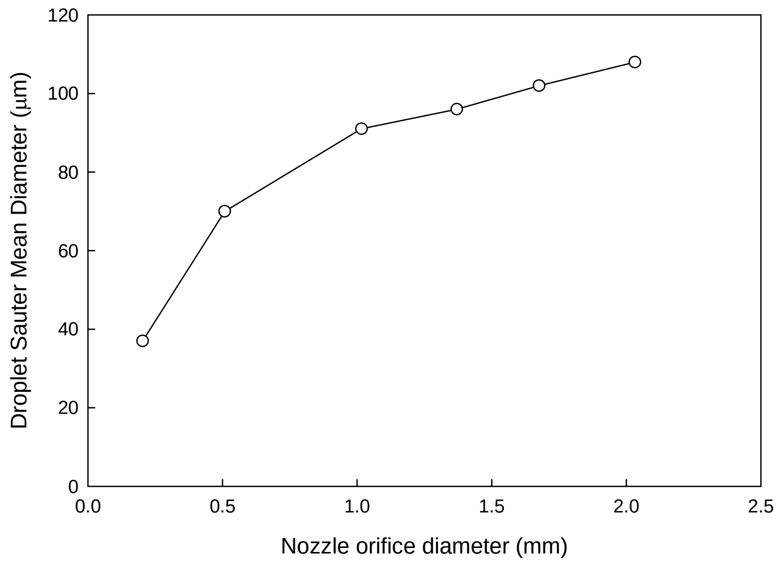

Figure 5. Droplet Sauter Mean Diameter for different orifice diameter

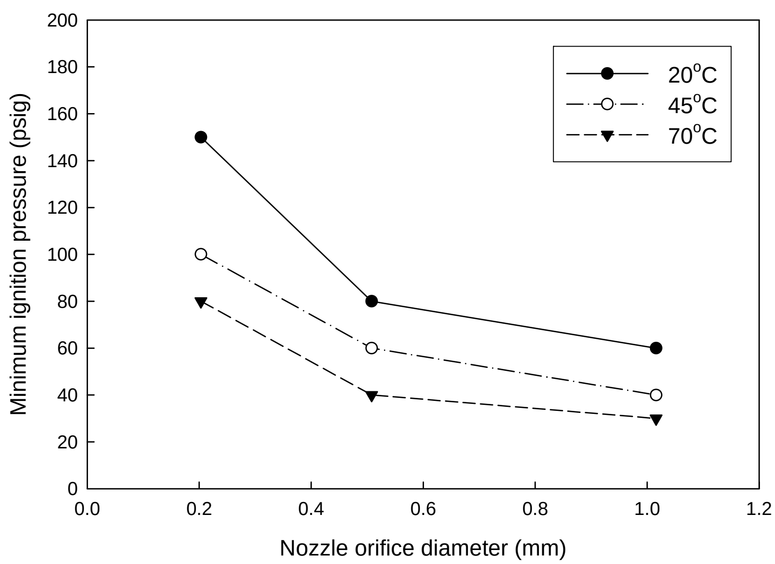

Figure 6. The effect of oil temperature on the minimum oil pressure

(a)

(b)

Figure 7. Typical oil spray flames from the impingement of oil jets onto a vertical surface
(a) oil temperature: 30ºC; (b) oil temperature: 45ºC.