

Spray Fire Tests with Hydraulic Fluids

GÖRAN HOLMSTEDT

Department of Physics, Lund Institute of Technology
P.O. Box 118, S-221 00 Lund, Sweden

HENRY PERSSON

Division of Fire Technology, National Testing Institute
P.O. Box 857, S-501 15 Borås, Sweden

ABSTRACT

Two test series simulating the hazards associated with the accidental release of hydraulic fluid near to a source of ignition have been carried out with six hydraulic fluids; mineral oil, organic ester, phosphate ester, water in oil emulsion and two polyglycols in water solution.

In one of the test series the fluids were sprayed ($1-4 \text{ kg min}^{-1}$) through different nozzles at various hydraulic pressures into a diffusion flame under a semi-open hood which collected all the combustion gases; thus the rates of generation of smoke and gases (O_2 , CO , CO_2) could readily be measured.

In the other test series the fluids were sprayed ($7-30 \text{ kg min}^{-1}$) through various nozzles at various hydraulic pressures into a diffusion flame or against a hot metal plate in a large fire hall. The flame length, temperature and radiation and the auto-ignition temperature were measured.

The correlation between the two test series regarding rates of heat release between 1 and 20 MW was very good. As a result a test method is proposed. In this test method the flammability hazard of hydraulic fluid spray fires is measured in terms of their combustion efficiency, net heat of combustion, radiant fraction and smoke and toxic rate of production.

Keywords: Hydraulic fluids, Spray combustion, Combustion efficiency, Smoke, Toxic gases, Auto-ignition temperature, RHR-measurements.

INTRODUCTION

Hydraulic fluids have been the subject of concern due to the fire hazards associated with them especially in industries where "hot processes" are used, such as steel-making plants, steel-rolling mills, forge workshops etc. In Sweden, for example, a number of fires have been caused by leaking hydraulic fluid which has led to very expensive damage [1].

The most common source of leakage in hydraulic systems is from fittings, valves, steel reinforced rubber hoses and steel and copper pipes. The high pressure in the hydraulic system leads to leakage in the form of very fine sprays. Hydraulic fluids which,

when held in bulk are not particularly flammable, can therefore through leakage, in the form of fine sprays, atomize and upon ignition lead to very large flames.

The risk of hydraulic fluid fires can be minimized in many ways; engineering, through the introduction of warning- and fluid-stop systems, hose break valves, double pipes, sprinklers etc., and chemically, by changing the composition nature of the hydraulic fluid. A fluid spray's tendency to combust is influenced by many factors such as droplet size distribution, the fluid's flash-point, auto-ignition temperature, heat of combustion etc. The droplet size can increase, for example, through the addition of certain polymers, which have high molecular weights. These polymers, which reduce the tendency to formation of mists, are on the other hand very sensitive to shear forces and degrade quickly in the hydraulic system due to the wear caused by the moving parts of pumps, filters and valves [2].

A number of hydraulic fluids, which have a higher flash-point and auto-ignition temperature and a lower heat of combustion than mineral oil, have been developed and are normally called "fire-resistant hydraulic fluids". These include oil in water emulsions, water in oil emulsions, polyglycols in water solutions, phosphate esters, halogenated hydrocarbons and organic esters. It is then necessary to introduce modifications into the hydraulic system for many of these fluids, in order to make seals and metals compatible with the fluid. The problem of toxic substances can also arise with the fluids and their combustion products; this is especially the case with fluids containing phosphates and halogenated hydrocarbons.

The concept "fire-resistant hydraulic fluids" is a diffuse concept which relates to manufacturers' or institutions' classification rules based on small-scale tests [2-12]. The tests, which are normally carried out with a limited quantity of fluid (0.05-0.5 kg min^{-1}), very often give no quantitative information about any combustion property. Instead the fluid is "passed" or "failed". Fluids which, according to such tests have been classified as fire-resistant, however, have caused severe damage in industrial environments and have under other tests [11, 13] given results which indicate that the difference between their combustion properties and the combustion properties of mineral oil is not so large.

Two test series have been carried out with six hydraulic fluids. In these tests the combustion efficiency, radiant fraction, water content, auto-ignition temperature and rate of production of smoke and toxic gases were determined.

EXPERIMENTAL METHOD

Test equipment

Two sets of test equipment have been used. In one of the test series the hydraulic fluid was sprayed (1-4 kg min^{-1}) through different nozzles at various hydraulic pressures into a diffusion flame under a semi-open hood which collected all the combustion gases, Fig. 1. The hood was connected to an evacuation system through an exhaust duct and equipped with shields to collect the combustion gases. The openings on both sides of the spray were in total 10 m^2 and the entrance opening of the hood 9 m^2 . During the

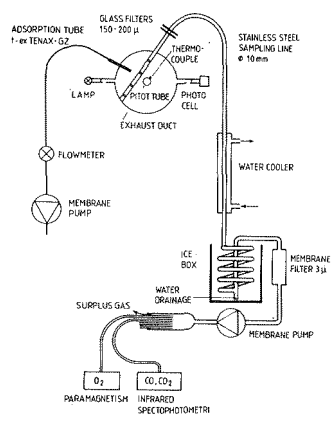
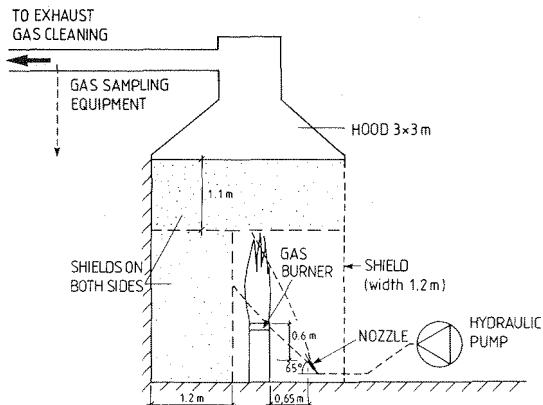


Fig.1 Experimental equipment ($1-4 \text{ kg min}^{-1}$)
 a) semi-open hood b) analytical equipment

test air was evacuated at a rate of approximately $4 \text{ Nm}^3\text{s}^{-1}$, giving an average speed of the cold gas so low ($<0.5 \text{ ms}^{-1}$) that it did not interfere with the spray flame. In the exhaust duct, where the gases were well mixed, mass flow (pilot tube, thermocouple, velocity profile), optical smoke density and gas composition (O_2 , CO , CO_2) were measured as shown in Fig. 1. The test equipment is presented in more detail in ref. 14. In the other test series the fluids were sprayed ($7-30 \text{ kg min}^{-1}$) through different nozzles at various hydraulic pressures through a diffusion flame or against a hot metal plate in a large fire hall ($18 \times 22 \times 20 \text{ m}$), Fig. 2. The flame length, temperature and radiation were measured.

Fluid spray

The fluid flow to the spray nozzle was provided by a hydraulic pump. The pressure in the system could be adjusted between 0 and 30 MPa using a pressure limiting valve, and the temperature between 10 and 90°C using a thermostatically controlled electrical heater mounted on a 160 l hydraulic reservoir. The hydraulic pressure in the nozzle was measured using a pressure transducer of strain gauge

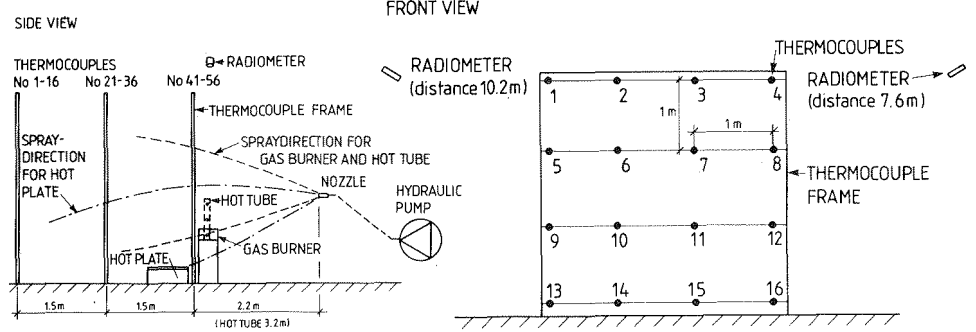


Fig.2 Experimental equipment in a large fire hall ($7-30 \text{ kg min}^{-1}$).

type (34.5 MPa, 0.25% accuracy, 0.1 ms time constant), the temperature using a thermocouple and the fluid flow using a turbine wheel gauge (30 l min^{-1} , 1% accuracy, 1 s time constant). The flowmeter was calibrated for the different fluids at the working temperature by measuring the amount of fluid which flowed through it in a given time.

To simulate real leakages which can give rise to many different types of sprays, four different hydraulic pressures and four different nozzles were used. In this way the number density and size distribution of the drops could be varied in order to avoid that the results being too dependent on a single spray form. Information about the nozzles used, (manufactured by Spraying Systems Co.) which give homogeneous sprays is given in Table 1.

Table 1. Data regarding the nozzles

| test equipment | nozzle | cone angle, deg. | hydraulic pressure, MPa | fluid flow, l min^{-1} | med. vol. diam., μm (H_2O , 21°C) |
|-----------------|--------|------------------|-------------------------|---------------------------------|--|
| semi-open hood | Ty 0.4 | 60 | 5, 10, 15, 25 | 1 - 2.5 | 70 - 50 |
| semi-open hood | Ty 0.7 | 60 | 5, 10, 15, 25 | 2 - 4 | 130 - 90 |
| large fire hall | D3/31 | 65 | 15, 25 | 7 - 9 | 110 - 90 |
| large fire hall | D5/56 | 30 | 15, 25 | 23 - 27 | 200 - 150 |

Ignition sources

The sprays were ignited by a diffusion flame from a porous propane burner ($0.3 \times 0.3 \text{ m}$) with a power of 200 kW. In addition a hot steel plate was used as the ignition source in some tests in the large fire-hall. The plate ($0.65 \times 0.75 \times 0.02 \text{ m}$) was heated from below with a thermostatically controlled electrical heater. Due to radiation losses the steel plate was insulated during the heating period. Just before the test the insulation was withdrawn whereupon the surface temperature slowly started to decrease. During a test the surface temperature, as indicated by three thermocouples fell by less than 25°C .

Hydraulic fluids

The results of the tests were used to compare the combustion properties of the different hydraulic fluids with the combustion properties of mineral oil. To complement the manufacturers' data, the water content and the heat of combustion were determined and are given together with other values in Table 2.

Table 2. Tested hydraulic fluids

| | min.oil | org.ester | phosph.ester | water in oil em. | pol.glyc.I in w.s. | pol.glyc.II in w.s. |
|---|---------|-----------|--------------|----------------------------|---------------------------|---------------------|
| density, kg m^{-3} | 892 | 920 | 1125 | 964 | 1055 | 1064 |
| viscosity, cSt (40°C) | 66.8 | 40.0 | 43.0 | 110 (38°C) | 43 (38°C) | 45 |
| flash-point, $^\circ\text{C}$ | 212 | 280 | 245 | data missing | - | - |
| auto-ign. temp., $^\circ\text{C}$ | 350 | 460 | 545 | data missing | - | - |
| water cont., % of weight | 0 | 0 | 0 | 38 | 35 | 35.2 |
| heat of comb., kJ kg^{-1} (H_2O liq.) | 45.0 | 39.8 | 32.4 | 29.2 | 16.9 | 14.6 |
| heat of comb., kJ kg^{-1} (H_2O gas) | 42.3 | 37.7 | 30.3 | 26.6 | 14.7 | 12.5 |

+ manufacturers' data

Test procedure

The temperature of the hydraulic fluid was kept constant at 37 ± 2 °C. The pressure was adjusted to the desired value and the fluid was allowed to circulate back to the reservoir. For the experiments under the semi-open hood the ignition source was allowed to burn for 30 s before the spray was turned on by shifting the fluid flow from recirculating to the spray nozzle with an electrically controlled three-way valve. The spray was allowed to burn for another 30 s with the ignition source on. For the experiments in the large fire-hall the corresponding times were 5 and 20 s. The experiments were repeated using different pressures, nozzles, hydraulic fluids and ignition sources. In all about 150 tests were carried out.

CALCULATIONS

Rate of heat release and combustion efficiency

In the experiments under the semi-open hood the rate of oxygen consumption was measured. This is a way of estimating the rate of heat release as the heat of combustion per unit of oxygen consumed is approximately the same for most fuels [15]. The rate of heat release, q , is given by [16]:

$$q = 17.2(X_{O_2}^o - X_{O_2}^s)\dot{V}_s/\alpha \quad \text{where}$$

q = rate of heat release, MW

$X_{O_2}^o$ = volume % of oxygen in the incoming air

$X_{O_2}^s$ = volume % of oxygen in the exhaust gases

\dot{V}_s = volume flow of the exhaust gases, m^3s^{-1} (25 °C, 0.1 MPa).

α = expansion factor for the fraction of air that is depleted of its oxygen (≈ 1.1)

The total inaccuracy, including the factors which have been neglected in the formula above (CO and H₂O content) is estimated to be 25 kW or $\pm 10\%$ of the calculated value. Starting from the calculated rate of heat release the combustion efficiency can be derived from:

$$\emptyset = (q - q_{ign})/(\dot{m} \cdot Q) \quad \text{where}$$

\emptyset = combustion efficiency

q_{ign} = power of the ignition source = 0.2 MW

\dot{m} = mass flow of the hydraulic fluid, $kg s^{-1}$

Q = heat of combustion of the hydraulic fluid, $MJ kg^{-1}$ (H₂O gas)

Production of smoke and toxic gases

In the experiments under the semi-open hood the volume flow, light obstruction, and the CO- and CO₂ concentrations in the exhaust gases were measured. The smoke potential is given by [17]:

$$D_o = 10 \log (I_o/I) \cdot \dot{V}_t / (\dot{m} \cdot L) \quad \text{where}$$

D_o = smoke potential, $ob m^3g^{-1}$

\dot{V}_t = volume flow exhaust gases, m^3s^{-1} (at exh. gastemp. and press).

\dot{m} = mass flow of the hydraulic fluid, gs^{-1}

L = diameter of the exhaust duct, m

In a similar manner the CO- and CO₂ potential, $l g^{-1}$, can be calculated. The total inaccuracy is estimated to be $\pm 10\%$ of the calculated value.

Radiant fraction

The radiation was measured using two Medtherm radiometers (10 kWm^{-2} , 3% accuracy) placed at different distances on either side of the flame axis. It is difficult to calculate the total radiated power from only two point measurements. The flames from nozzles Tg 0.4, Tg 0.7 and D3/31, however, were approximately spherical and small compared with the distance, r , to the radiometers, so that the power could be estimated by the measured radiation multiplied by $4\pi r^2$. The flames from nozzle D5/56 were comparable in length to the distance to the radiometers. In this case the total radiation was calculated by regarding the flame as a cylinder which radiated with uniform intensity and with a length equal to the flame length. The difference in calculated power from the two radiometers was less than 10%.

RESULTS

Rate of heat release and combustion efficiency

Tests were carried out under the semi-open hood with six hydraulic fluids at four pressures using two different nozzles. The rate of heat release and the generated heat per gram sprayed organic ester as a function of time are shown in Figs. 3a and b, respectively. When the ignition source is on the rate of heat release stabilizes at 0.2 MW. Thirty seconds later when the spray is applied the rate of heat release increases and stabilizes at a new level. The generated heat per gram fluid, and consequently the combustion

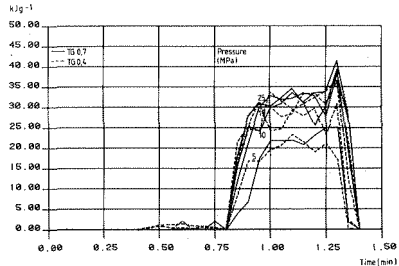
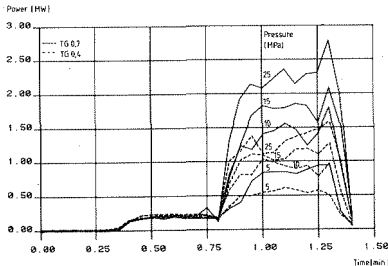


Fig.3 a)RHR for organic ester as a function of time.

b)Generated heat per gram sprayed org. ester as a function of time.

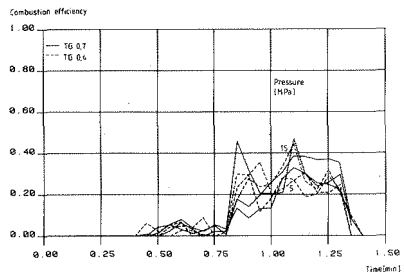
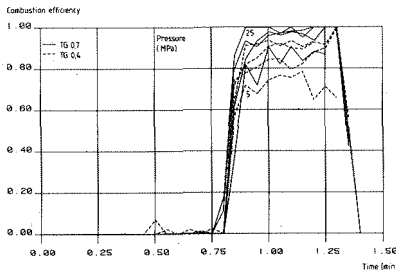


Fig.4 a)Combustion eff. for min.oil as a function of time.

b)Combustion eff. for polyglycols I in water solution as a function of time.

efficiency, is, as shown in Figs. 3b, 4a and 4b, relatively independent of the hydraulic pressure and the nozzle used. The results are given in more detail in ref. 18. In Table 3 the combustion efficiencies are given for the hydraulic fluids tested.

Production of smoke and toxic gases

The smoke-, CO- and CO₂ potential were also found to be relatively independent of the hydraulic pressure and nozzle used. In Figs. 5a and b the CO- and CO₂ potential are shown as a function of time and in Table 3 the potentials for the tested hydraulic fluids are given.

Table 3. Test results

| | min.oil | org.ester | phosph.ester | water in oil em. | pol.glyc.I in w.s. | pol.glyc.II in w.s. |
|---|---------|-----------|--------------|------------------|--------------------|---------------------|
| combust.efficiency,% | 90 | 80 | 70 | 60 | 25 | 30 |
| radiant fraction,% ₃ -1 | 32 | 20 | 32 | 20 | 10 | 10 |
| smoke potential,cm ³ g ⁻¹ | 0.2 | 0.2 | 2-6 | 0.4 | 0.1 | 0.1 |
| CO pot.,l g ⁻¹ (25°C,0.1 MPa) | 0.03 | 0.035 | 0.1 | 0.035 | 0.02 | 0.02 |
| CO ₂ pot.,l g ⁻¹ (25°C,0.1 MPa) | 1.7 | 1.3 | 0.8 | 0.6 | 0.2 | 0.2 |

Radiant fraction

It was also found that the radiant fraction was relatively independent of the hydraulic pressure and the nozzle used. In Figs. 6a and b the measured radiation level and the radiation energy per gram sprayed fluid are shown. In Table 3 the radiant fraction is given for the fluids tested.

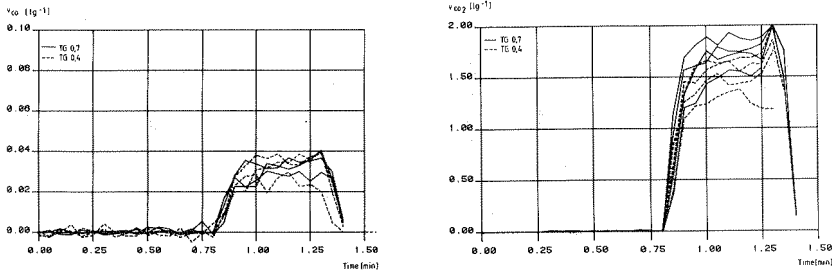


Fig.5 a)CO-potential for w.i.oil emulsion b)CO₂-potential for mineral oil as a function of time.

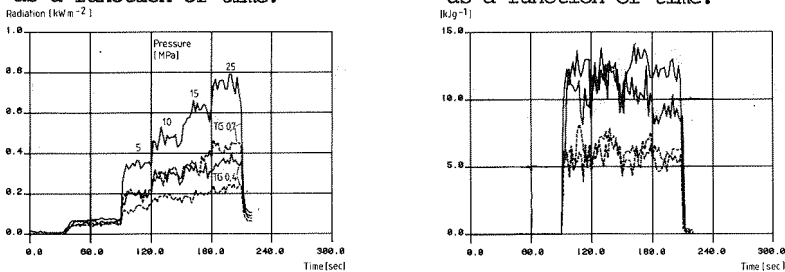


Fig.6 a)Radiation level from flames of min.oil(—) and org.ester (- -)as a function of time. b)Radiation per gram fluid as a function of time(Fig 6a divided by the mass flow).

Flame length

The length of the flames in the tests carried out in the large fire-hall was estimated from pictures and video recordings. The geometry of the flames were somewhat different depending on whether the fluid was sprayed freely in the air, which was the case with a diffusion flame as the ignition source, or if the fluid was sprayed close to the floor which was the case with the hot plate. In Figs. 7a and b some typical pictures are shown from comparable tests with the diffusion flame. In Fig. 7c comparable tests are shown with the hot plate. In the tests using the hot plate, the mineral oil and organic ester started a heavy pool fire in the fluid which hit the floor. The pool fire stabilized the flames which increased in intensity and gave rise to a strong turbulence rumble and a heavy smoke generation. Under the same test conditions phosphate ester and water-in-oil emulsion only gave rise to a small pool fire on the floor and the two polyglycols in water solution produced only a small local fire at the ignition source.

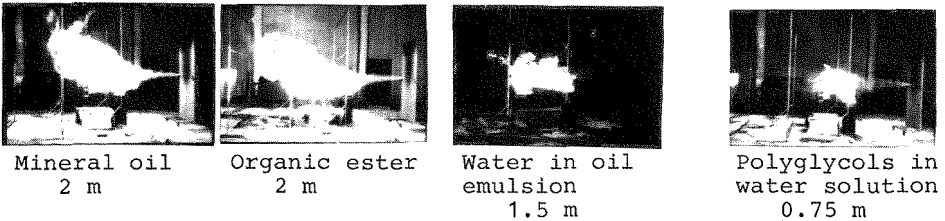
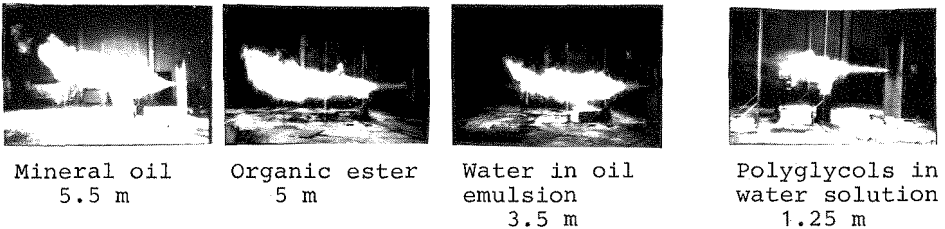
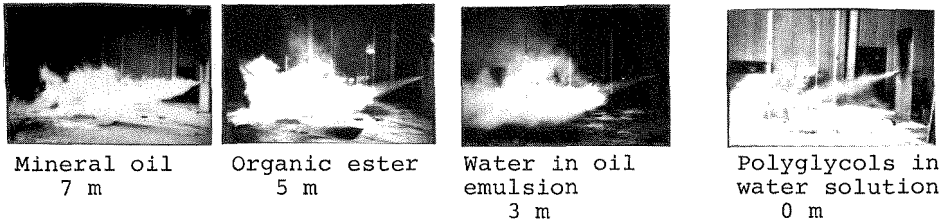


Fig.7 a) Flame lengths from free sprays with nozzle D3/31
(7 kg min^{-1}) at 15 MPa:s pressure.



b) Flame lengths from free sprays with nozzle D5/56
(23 kg min^{-1}) at 15 MPa:s pressure.



c) Flame lengths from sprays close to the floor with nozzle
D5/56 (23 kg min^{-1}) at 15 MPa:s pressure.

Auto-ignition temperature

The auto-ignition temperature of the fluids was determined by testing the fluid sprays against a hot surface at various temperatures. In Table 4 the highest surface temperature at which ignition did not occur and the lowest temperature at which ignition did occur are shown together with the auto-ignition temperature given by the manufacturers. The results are in good agreement since a difference of 50 to 100 °C between different test methods is not unusual [19].

Table 4. Auto-ignition temperature

| | mineral oil | | organic ester | | phosphate ester | | water in oil em. | | pol.glyc.I in w.s. | | pol.glyc.II in w.s. | |
|-------------|-------------|------|---------------|------|-----------------|------|------------------|------|--------------------|------|---------------------|------|
| | no ign. | ign. | no ign. | ign. | no ign. | ign. | no ign. | ign. | no ign. | ign. | no ign. | ign. |
| | °C | | °C | | °C | | °C | | °C | | °C | |
| hot plate | 300 | 350 | 400 | 450 | 500 | 550 | 350 | 400 | >900 | | >900 | |
| manuf. data | | 350 | 468 | | 545 | | missing | | - | | - | |

DISCUSSION

The risks of injury on personnel and damage to property which arise from hydraulic fluid fires are caused by spray flames, secondary fires and the presence of smoke and toxic gases. Flame length, rate of heat release, radiation and the generation of smoke and toxic gases are the most important factors which it is necessary to determine to be able to assess the hazards.

The flame length is dependent on the extent of the leakage as well as on the combustion properties of the fluid. In the aerosol the droplets are not uniformly distributed with respect to size and number. The smaller droplets are easily retarded and cause the spray to mix with the surrounding air [20]. If the droplets combustion time is short the flame length depends on the quantity of air which must be entrained to give complete combustion. A long flame is therefore correlated with a large combustion air requirement which in turn is correlated with a large rate of heat release. There are difficulties involved in measuring the flame length because of the turbulent nature of the flame and possible obstruction by smoke. An alternative to measuring the flame length is therefore to measure the rate of heat release [11]. This apparent correlation between the flame length and the rate of heat release is shown for comparable tests in Table 3 and Figure 7.

The results from the two test series show that sprays from hydraulic fluids can burn when they hit an ignition source, in spite of this they are sometimes classified as fire-resistant in small-scale tests. The combustion efficiency is influenced by a number of properties such as the size- and number distribution of the droplets, and the type of hydraulic fluid etc. Comparable tests in the two test series have shown that the combustion efficiency for hydraulic fluid spray fires differs with the hydraulic fluid used but is relatively independent of hydraulic fluid pressure, nozzle size and spray angle. The same conditions seem to be valid for the radiant fraction and smoke- and toxic gas potential. In Figure 8 the total and radiant heat output per gram sprayed fluid are shown as a function of the fluids net heat of combustion. The net heat of combustion of a hydraulic fluid seems to be the most important parameter which controls the combustion efficiency in spite of differences in the auto-ignition temperature of a few hundred degrees C.

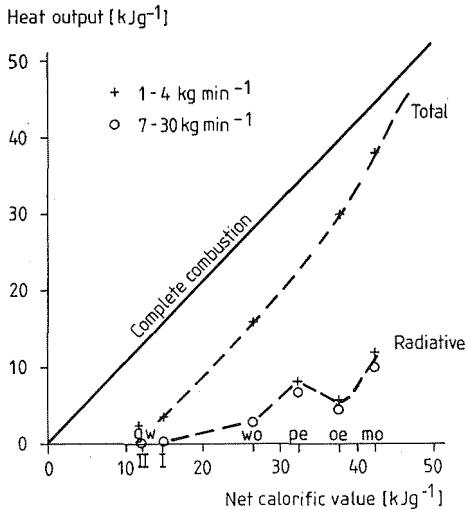


Fig.8 Total and radiation output from burning hydraulic fluid as a function of the fluids net heat of combustion

The tests showed that a spray fire close to the floor often led to a pool fire and that thin thermocouple wires through the spray led to small fires which stabilized the spray fire. These test series have therefore been performed with the ignition source on during the whole test. Tests which assess the ability of free fluid sprays to stabilize themselves when the ignition source is withdrawn are often dependent on the choice of spray nozzle. The size of the ignition source does not seem to have a pronounced influence on the combustion efficiency of the fluids. The combustion efficiency was hardly affected when fluid flow rates varying from 1 to 30 kg min⁻¹ were sprayed against a 200 kW propane burner as well as when a constant flow of 2 kg min⁻¹ mineral oil was sprayed against four different diffusion flames varying from a cigarett lighter to 200 kW [21].

CONCLUSION

The results from the two test series show that sprays of hydraulic fluids can burn when they hit an ignition source in spite of the fact that they have been characterized as fire-resistant on the basis of small scale tests. To assess the fire hazards associated with hydraulic fluids, the testing method should determine the combustion efficiency, net heat of combustion, radiant fraction and smoke- and toxic gas potential of the fluid.

ACKNOWLEDGMENT

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