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Hot Layer Formation during the Crude Oil Fires

Abstract

The paper presents the research results on hot layer formation during the crude oil fires, the conditions for creating a hot layer, mechanisms of the boilover and its accompanying dangerous phenomena. The research was carried out in The Main School of Fire Service in Warsaw.

In the experiments, crude oil was burned in tanks with the diameter of 1.4 m and two different heights – 0.7 and 1.4 m.

Keywords: burning rate; temperature distribution; heat transfer, boilover

Formatowanie się warstwy gorącej podczas pożarów ropy naftowej

Streszczenie

W artykule przedstawiono wyniki badań nad formowaniem się warstwy gorącej, warunków tworzenia się warstwy gorącej, mechanizmu wyrzutu i zjawisk towarzyszących podczas pożarów ropy naftowej, które zostały przeprowadzone w Szkole Głównej Służby Pożarniczej w Warszawie.

W eksperymentach spalano ropę naftową w zbiornikach o średnicy 1,4 m i dwóch różnych wysokościach – 0,7 i 1,4 m.

Słowa kluczowe: szybkość spalania; rozkład temperatury; transfer ciepła, wyrzut

INTRODUCTION

Many efforts have been made to prevent the accidents involving hazardous substances. However, such incidents still occur, because of residual risks or mistakes and negligence in safety management systems [1]. A major source of a risk connected with processing and storage of hazardous substances has been activity of the refinery and storage facilities of petroleum products, especially the storage of large quantities of crude oil and its products. Fires of storage tanks containing crude oil are not common, mainly because of a small number of storage bases and implementation of systemic preventive measures. Nevertheless, even incidental, fires of storage tanks may generate enormous risk for human, environment and economic assets. The fire, which was the most tragic, the biggest and the most difficult to extinguish since World War II in Poland took place in the refinery in Czechowice in 1971. The fire of crude oil stored in tanks (52 457 m^3) lasted about 60 hours and its consequence was an ejection of burning oil. The flooded area formed around the tank after the ejection had a radius of 350 m. The column of smoke was visible from several kilometers away and was responsible for the formation of condensation cap over the refinery and the surrounding area, which persisted for a long time. The victims of the ejection were 37 people who died and 104 who were seriously injured [2]. Through the years 1951–2003, 480 fires of storage tanks with different types of fuels, took place. In many cases those fires were accompanied by the boilover phenomenon (e.g. Louisiana, USA) [3].

Boilover usually arises as a result of the vaporization of a water phase during a tank fire. Extensive damage is caused by the spillage of burning material and very intensive heat radiation, also ejection of burning fuel mass outside the tank increases the fire area many times as compared to the original surface of the tank fire, and in the consequence can increase the range of threats.

Previous studies have shown, that necessary for the boilover formation is the coexistence of three elements [4]: (i) open tank fire, (ii) the layer of water located at the bottom of the tank, (iii) hot layer in a flammable fuel. On the other hand, the risks generated by the "simple" fire of crude oil and then boilover can be divided into: primary, occurring as a result of a heat flux and its direct impact on the environment, and secondary, connected with a boilover phenomenon resulting in spreading of the fire area and thermal radiation and arising of the toxic products into environment [5].

Implementing of appropriate steps for prevention of fires in general or for minimalization of their effects needs detailed studies on the mechanisms of fires and their spreading as well as accompanying phenomena that can be fatal. Their results may serve as the basis for development of emergency plans and guidelines for fire brigades conducting emergency rescue in the petrochemical and chemical industries. A fundamental problem in the development of general knowledge regarding burning of oil fuels lies in a heterogeneity of fire scenarios and small repeatability of the phenomena and processes that can lead to liquid fuels fires.

The aim of the present study was the assessment of heat transfer during the fires of the REBCO crude oil, the most commonly used in Poland, conditions for creating a superheated layer and the mechanisms of the boilover and its accompanying dangerous phenomena.

1. EXPERIMENTAL

The study has been conducted by The Main School of Fire Service in Warsaw, Poland. The oil used in the experiments has been the crude oil imported from Russia under the trade name REBCO, the most commonly used in Polish refineries. Its main properties were as follows:

1) density at 20 °C – 0,870 g/cm^3;
2) sulfur content – 1,8%$_{wt}$;
3) paraffin content – 6,0%$_{wt}$;
4) water content and impurities – 1,05%;
5) the salt content – max 300 mg/l;
6) carbon content – 85,54%$_{wt}$;
7) hydrogen content – 11,69%$_{wt}$;
8) heat of combustion – 42,0 MJ/kg;
9) engler distillation (Fig. 1.).

Five experimental fires of tanks with crude oil have been performed on the testing area (2 experiments with the tanks of the height of 140 cm, and 3 experiments with the tanks of the height of 70 cm, Table 1.). The tanks were cylindrical and were made of the standard carbon constructional steel, their wall thickness was 10 mm. Two tanks with the same diameter and different heights have been used:

a) The diameter of Ø = 140 cm and height h = 140 cm.
b) The diameter of Ø = 140 cm and height h = 70 cm.

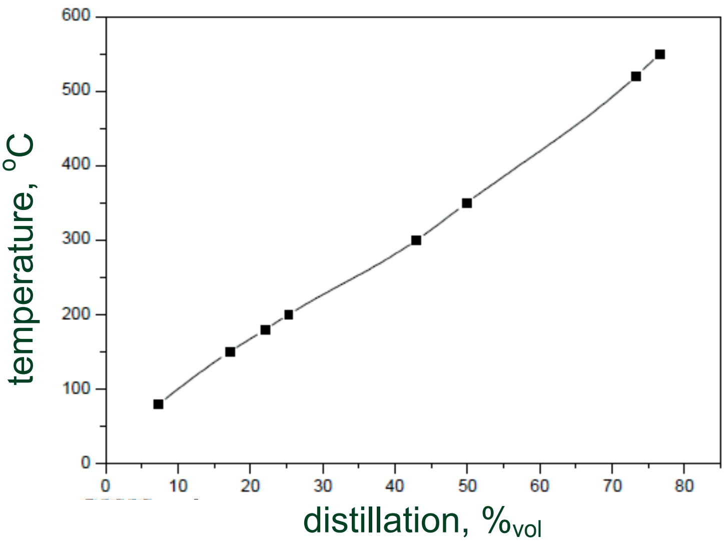

Fig. 1. Engler distillation curve for REBCO oil

The design of all experiments has been similar. Experimental tanks have been filled with water – the water layer was 18 cm in the tank of the height of 140 cm and 15 cm for tank of the h = 70 cm. On the layer of water the REBCO oil has been poured until the height of 135 cm and 68 cm from the bottom of the tank, in the tanks of the height (h) 140 cm and 70 cm, respectively. The tanks have been equipped with the thermocouples aimed to record the temperature changes in the oil layer, in the water and on the outer wall of the tank. The temperature was measured: (i) in the axis of the tank, (ii) at the walls of the tank, 5 cm from the wall, (iii) on the outer wall of the tank. The experimental unit (Fig. 2.) has been also equipped with a radiometry to measure the heat flux, and the pressure sensors for measurement the linear burning rate. In the tanks of the h=70 cm the special thermocouple array was also used. The probes were placed on the border of the fuel-water separation. The needed spacing of thermocouples was achieved by placing them on a special stand (Fig. 3). The recording of the data was started after oil ignition.

The following parameters have been measured in the tank of the height of 140 cm:

- the rate of formation and spreading of a superheated layer,
- the oil burning rate,
- time to boilover

In the second tank (h = 70 cm) the value of radiation heat flux has been additionally measured.

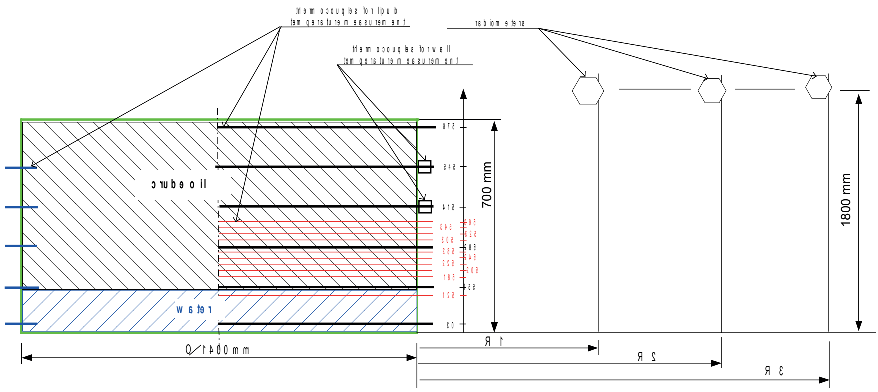

Fig. 2. The experimental unit (Ø = 140 cm, h = 70 cm)

Fig. 3. Location of thermocouples in the tank 70 cm high

The heat flux density was measured with the help of three radiometers produced by the Captec Company (France) characterized by:

- response time – <0,2 sec,
- sensitivity – 5 mV/W/cm^2,
- thickness – 170 microns,
- temperature range – water-cooled sensor.

The radiometers were placed on the height of 1,80 m and in distances R1, R2, R3 from the wall of the tank (Fig. 2.).

2. RESULTS

Table 1. Parameters recorded during the experimental fires

	tank with h = 70 cm			tank with h = 140 cm	
	experiment 1.	experiment 2.	experiment 3.	experiment 1.	experiment 2.
t_w [min]	97	95	87	395	187
v_{wp} [mm/min]	9,27	7,64	6,91	5,94	11,03
v_{ls} [mm/min]	3,85*	1,51	1,67	1,87	5.56*
v_{wp}/v_{ls}	2,41	5,06	4,14	3,18	1,98
T_{wp} [°C]	258,5	293,2	363,4	392,2	402,1

*) the test was performed immediately after flooding of the reservoir with water and oil. In other cases, experiments started 12 hours after filling the tanks with water and oil.

t_w – time to boilover,

v_{wp} – speed of superheated layer transfer,

v_{ls} – linear burning rate,

T_{wp} – maximum temperature of the superheated layer.

The results of all the experiments have been summarized in Table 1. The data from Experiment 1 (tank of the h=140 cm) were shown in Fig. 4. The lines represented temperature recorded by the thermocouples located on different heights from the bottom of the tank: 5 cm, 25 cm, 45 cm, 70 cm, 95 cm, and 120 cm. The thermocouple located at the height of 5 cm was used to measure the temperature of the water layer. The other thermocouples had measured the temperature of the oil. Dynamics of temperature changes (for oil and water layers), might indicate a formation of superheat layer in a crude oil. Large variations in temperatures recorded by the thermocouples, especially those located on the heights of 120 cm and 95 cm from the bottom of the tank were the result of decreased thickness of the oil layer during combustion. Maximum temperature recorded on the outer wall of the tank reached the value of 506.5 °C. This temperature was recorded at 2 hours and 37 min after oil ignition, by the thermocouple located at the height of 120 cm (from the bottom of the tank), i.e. in the area of direct exposure of flame on the inner wall of the tank. The lowest temperature measured on the outer wall of the tank prior to discharge was 58°C, and was recorded at the height of 5 cm from the bottom of the tank. The temperature curves showed also that the variations in temperatures of superheated layer ranged between 155°C – 200°C.

The thickness of superheated layer of the oil decreased by 15 cm during the first 19 minutes of combustion in relation to the initial thickness. At the time of 2 hours and 15 min, the height of water-oil layer was 25 cm above the bottom of the tank.

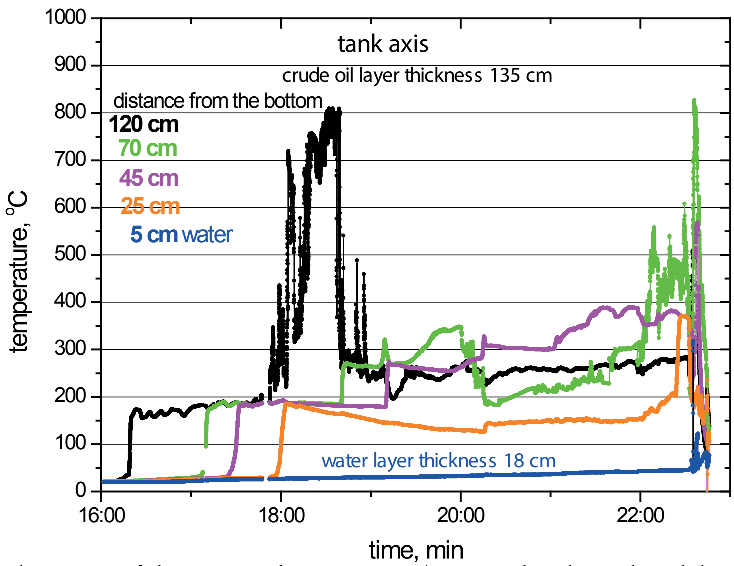

Fig. 4. The course of changes in oil temperature (measured in the tank with h=140 cm)

It was observed, that after the formation of the hot layer, the crude oil was still heating and finally the temperature of whole oil layer reached about 400°C. It occurred approximately 180 min after the formation of the hot layer. After that, a rapid heating of the water layer and boilover took place.

In the experiments using tanks of the height h=70 cm (Experiments 1–3, Table 1), the thermocouple arrays were located in a manner allowing the measurement of temperature on the border of oil-water (Fig. 5). The thermocouples were placed just above the water surface in a layer of oil, with one exception (thermocouple no 10), which was located below the oil surface.

The rapid changes in temperature indicated by the thermocouple at the height. 120 cm during 18 to 19 minutes of experiment were probably caused by the temporary damage to the measuring cables.

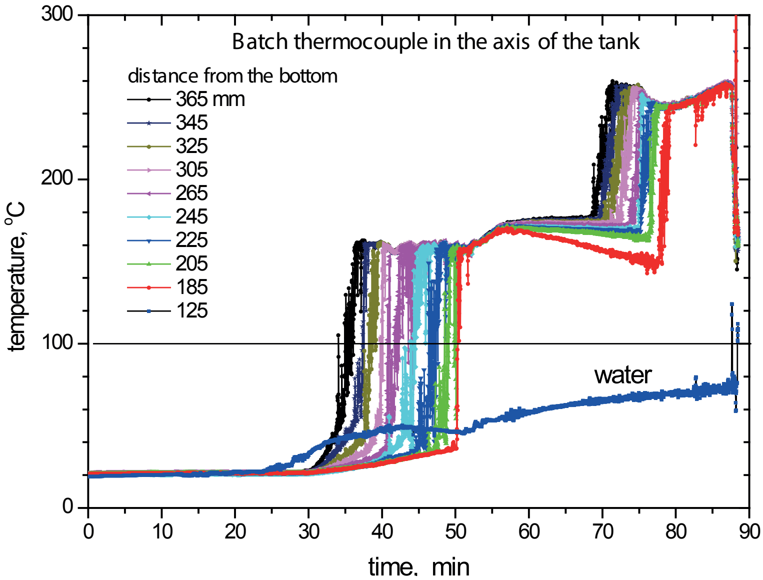

Fig. 5. The course of temperature changes (tank h = 70 cm, recorded by the thermocouple array)

Figure 5 has shown the profile of the temperature in the axis of the tank and as a function of the duration of fire (one of the series of experiments). Two stags can be noted, during which the temperature is maintained for a while at the same level and followed by evaporation of fractions with a similar boiling point. 30 minutes after ignition of fire, the first hot zone was formed and it moved down the tank (this phenomenon was evidenced by recordings of the thermocouples showing the same temperature). In this phase, the temperature of the oil reached about 150°C and the temperature of water was approximately 40°C. Next, after about 20 minutes, the second zone was formed and reached the temperature around 260°C. At that time, a layer of water was heated to the temperature of about 80°C.

After the next 78 min a rapid increase in temperature recorded by the thermocouple 9 located close to the layer of water was observed and at 87 min it came to a rapid boil of water and boilover. So, the course of the temperature curves demonstrated on Fig 5 has shown that the temperature of the hot layer did not grow continuously but in some steps: in the first stage temperature did not exceed 200°C, and then after about 30 min it increased up to 300°C. That preceded the occurrence of the boilover phenomenon.

The value of the heat flux was maintained at the same level from the beginning of the experiment until the boilover, and its value was around 0.2 and 0.1 kW/m^2 at a distance of 10 m and 25 m from the center of the fire, respectively. At the time of boilover the values of the heat flux rose sharply to 6,55 and 2,92 kW/m^2. The main parameters of boilover for experiment were shown in Table 1 and the stages of boilover in Fig. 6.

Fig. 6. Stages of boilover

3. DISCUSSION

The prerequisite for the occurrence of the boilover phenomenon is propagation of the hot zone into the cold oil at a rate far higher than the rate of coming down the burning surface. Processes of heat transfer inside the fuel were described by many researchers [6, 7, 8, 9, 10, 11, 12], which analyzed also conditions for the occurrence of boilover and the mechanisms of heat transfer. From the theoretical point of view, the modeling of heat transfer should be easy, especially because liquid fuels have similar physic-chemical and flammable properties.

This is apparent in the comparative analysis, especially of homogeneous liquid fuels, for which the ability to initiate combustion, the combustion rate and the rate of surface flame spread do not differ significantly. In practice, a fundamental problem in the development of general knowledge regarding burning of oil fuels lies in the heterogeneity of fire scenarios and the small repeatability of the phenomena and the processes that can lead to the fires of liquid fuels.

During the real fires, when a hot layer reaches the water layer at the bottom of the tank as a result of overheating, the boiling of water is very intense and boilover can occur. The superheated layer moves in a monophasic manner, gradually increases its thickness and at the end reaches the water layer, generating the boilover [10, 11, 12, 13, 14, 15, 16].

The data presented here and study of Stawczyk et al. [6] showed that the movement of the superheated layer of oil occurring in two stages might cause boiling water [6], but it hadn't always caused boilover. The heat transfer in the oil layer continued (as a second stage of the formation of the superheated layer) until boilover.

It is possible, that in the first stage of overheating the energy carried out by the hot zone was not enough to produce sufficiently intense boiling of water, capable to take out a significant amount of unburned oil. A significant amount of heat was absorbed by the water layer and used for its heating by about 50°C; the large heat capacity of water offset the impact of the hot layer [6]. At the end, a reduction in the thickness of oil layer (due to burning) caused the supply of heat from the flame which was enough to heat the oil to the temperature that occurred during boilover.

The data regarding physical properties of oil fuels, particularly their density and viscosity are not sufficient for assessment their abilities to boilover. It has been supported by the results of the present study, in which the time to boilover after experimental burning of oil was very long, despite the high density and viscosity of the oil. It seems, that the most important feature is the amount of water contained in a suspension or a layer of a crude oil.

CONCLUSION

The size of the tank plays an important role in the outcome of thermal effect of the heat flux on the environment: boilover from a larger tank possess a greater threat, which is associated with a larger quantity of flammable liquid contained. Increase of temperature of hot layer was not continuous but occurred in two stages which preceded the occurrence of boilover phenomenon.

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