Short-term thermal stability of transformer and motor oils at wide range of moisture contents

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Abstract. Method of controlled pulse heating of a wire probe was used for studying heat transfer and thermal stability of energy oils and motor oils in the presence of low quantities of moisture. The technique of two-pulse heating is the most suitable method for monitoring the actual state of oils. A distinct signal-response accompanying the appearance of moisture in the tested sample has been revealed.

1. Introduction
The oil-filled systems incorporated into the energy and transport equipment are exploited in conditions of significant fluctuations of the temperature values of both environment and working fluid of the system. The limiting case of temperature changes is shock loads accompanied by a high-power local heat release. Such processes may be accompanied by oil contamination with volatile impurities. Moisture is considered to be the most dangerous impurity [1]. It presents in small amounts but substantially reduces the performance characteristics of an oil, in particular, its thermal stability [2] and electric strength [3, 4]. Moreover, moisture as a component of the atmosphere and a common heat transfer fluid is able to penetrate into the oil system also during the routine operation modes. Exceeding the maximum level of moisture content in the oil causes the increased wear of equipment. Under the action of additional factors, this circumstance can lead to its emergency shutdown. In the case of transformer oils, it is necessary to monitor trace amounts of moisture at a level of hundredths-thousandths of one percent. Moisture content in the oil of operating transformer should be in the range of 10–20 particle per million (ppm). When the moisture content is more than 40 ppm, the risk of an emergency increases many times.

In this regard, it is important to find out the effect of moisture on the intensity of heat transfer in oil and its short-term thermal stability under conditions of a high-power local heat release. The solution of the inverse problem will contribute to the development of the indirect method for detection of moisture in oil. By the term “short-term thermal stability” we shall mean the preservation of oil contact continuity with the surface of the heater for the given parameters of heat release. When setting this research the authors relied on a general approach to the study of liquid media under conditions of a high-power local heat release [5,6]. A modified version of the method of controlled pulse heating of a thin wire probe was used as a research tool. A probe was immersed in the studied oil sample and served as a heater and a resistance thermometer simultaneously. The moisture content in the samples ranged from 18 to 700 ppm. The characteristic heating time was from 2 to 15 ms, depending on the task. Thickness of the
heated substance layer that generates a response signal was several microns. A relative version of the method was applied. In this case the microscopic movement of a probe due to its thermal expansion may be neglecting.

The dried oil sample serves as the reference sample. The moisture content, the initial temperature of the sample and the characteristic temperature of its superheating with respect to the thermostat temperature were the experimental parameters. The objects of study were samples of transformer and diesel oils.

2. Experimental

The methods for measurement of thermophysical properties of substances, which are based on supplying the input pulse to the probe and recording the response signal [7], find wide application in the study of complex fluids [8–10], in particular oils and their components [11–13]. An idea of controlling the power of the probe heating directly during the impulse underlies the methodology used in our experiments. This idea turned out fruitful in relation to carrying out comparative experiments on different samples under the given conditions of heat release. A thermometric platinum wire 20 µm in diameter and 1 cm in length was used as a probe. The characteristic thermal relaxation time of this probe is of the order of 1 µs. This fact allows one to change heating parameters in the real time. In turn, the high value of the ratio of surface area of the probe to its volume provides sufficient sensitivity to the presence of moisture in oils. At an appropriate choice of the probe heating mode, the method allows the detection of its trace amounts [2, 14].

In the present study, a technique of heating by two successive pulses was used. The weight-average probe temperature $T$ evolution over time $t$ was tracked. The experiments were performed at atmospheric pressure.

2.1. Two-pulse heating technique

The probe heating was carried out by two successive pulses with different power, figure 1. The first pulse provided the rapid heating of a probe, and, consequently, the wall layer of a fluid from the initial value $T_0$ to the selected value $T_1$. Its characteristic duration was $t_1 \sim 10^{-4}$ s. After a pause, the second pulse of a duration of $t_2 \sim 10^{-3}–10^{-2}$ s was switched on. The substance was heated to a temperature $T_2 > T_1$, where $(T_2 - T_1) \sim 10$ K. Choice of the $T_1$ value and the pause duration was made based on the properties of the reference sample. The recorded course of the heating curve $T_{wt}(t)$ was compared with similar values obtained in experiments on the reference sample with known moisture content $T_{cl}(t)$. The presence or absence of symbaticity of the temperature curves allows to judge about a change in the moisture content level with respect to the reference sample. As a rule, starting with specific values of $T_1$ and $T_2$, an increase of the moisture content intensifies the heat exchange between probe and the sample, in such a case, $\Delta t > 0$ [2, 14]. At the same time, the state of moisture in oil depends on the initial temperature $T_0$. In this regard, experiments were carried out at different values of $T_0$, $T_1$ and $T_2$.

2.2. Oil samples and their preparation

The initial sample of transformer oil contained 18 ppm moisture. The watered sample was obtained during the dispersion of water droplets in the initial sample in an ultrasonic disperser. It contained about 200 ppm moisture.

In the course of studying the diesel motor oil we prepared samples with three levels of moisture content: initial sample (≈ 300 ppm), dried sample (≈ 100 ppm) and watered sample (≈ 700 ppm). The initial sample was oil decanted from the power plant of a diesel locomotive during its scheduled repair. Dewatering the original sample was carried out with silica gel. Watering the dried sample was carried out with saturated water vapor through the free surface.
3. Results and discussion

3.1. Experiments with samples of transformer oil

Experiments with samples of transformer oil were performed at atmospheric pressure in the cell of a LOIP FT-311-80 liquid cryostat. The temperature value $T_0$ served as a parameter in the experiments. The range of its change was from 294 to 233 K. The temperature maintenance accuracy in the measuring cell was 0.1 K. The maximum temperature of the probe heating was set equal to $T_2 = 520$ K. The experimental results for transformer oil are shown in figure 2. In the experiments, we recorded changes in the time dependences of the temperature of a probe placed first in the oil sample with 18 ppm moisture content and then in the sample with watering level of 200 ppm. The $t_2$ values for a given heating mode were determined by the experimental curves. Then the $t_2$ values obtained for samples with different water content were compared with each other.

Figure 2 shows that the moisture additives significantly increase the value of $t_2$, which is recorded equivalent of the heat transfer intensity for a given heating mode. Following the condition of heat balance in the probe–substance system, this means that a moisture additive intensifies the heat transfer in oil. The scale of this effect proved to be dependent on the initial temperature $T_0$. The greatest difference in the $t_2$ values was observed at $T_0 = 293$ K and was 1.32 ms, see figure 2. The $\Delta t$ value was decreased systematically with decreasing temperature $T_0$ and became close to zero at $T_0 = 253$ K. From the data presented in figure 3, it follows that the $t_2$ values for discussed samples are becoming virtually indistinguishable in the bottom of the temperature $T_0$ range, namely from 233 to 253 K. We attribute this result to the crystallization of moisture in the sample in this range of variation of the initial temperature. The $t_2(T_0)$
Figure 2. Experimental probe temperature histories for transformer oil samples. The water content is 18 ppm (reference sample, solid lines) and 200 ppm (watered sample, dashed lines). The value of initial temperature $T_0$ serves a parameter: 293 (lines 1 and 4), 273 (lines 2 and 3), 253 (lines 5 and 6) and 233 K (lines 7 and 8). The value of $T_2$ is equal to 520 K.

dependence was of monotonic character for the reference sample, which can be explained by an increase in the superheating degree ($T_2 - T_0$). This dependence proved to be non-monotonic for the watered sample, obviously due to changes of the moisture state in the course of changing the oil temperature.

3.2. Experiments with samples of diesel motor oil
Experiments with samples of diesel motor oil were performed at elevated $T_0$ values (from 293 to 366 K), on the basis of the conditions of its application, for four values of the maximum temperature $T_2$, figure 4. The length of the second pulse $t_2$ for a given pulse heating mode was the measured parameter. The $T_2$ values were chosen directly in the vicinity of the temperature of spontaneous boiling-up of dried sample at given heating conditions (atmospheric pressure, pulse length 15 ms). Boiling-up was accompanied by the natural intensification of heat transfer, see figure 4.

The increase of value $T_0$ in the samples with the selected moisture content was carried out in three stages, figure 5. At the first stage, continuous heating of the sample from room temperature to 333 K was carried out at a rate of $\approx 1.5$ K/min; at the second stage, the sample temperature was maintained at the previously achieved value of 333 $\pm$ 1 K for approximately 30 min; at the third stage, continuous heating of the sample with the same rate was continued. As shown in figures 4 and 5, the length of the second pulse $t_2$, which was obtained in the samples with different water content, differs significantly. This result allows us to formulate the following conclusions. Under the conditions of a high-power local heat release the moisture additives reduce the short-term thermal stability of oil, but increase the intensity of its heat transfer;
Figure 3. The values of second pulse length $t_2$ for transformer oil samples with water content of 18 ppm (symbols 1) and 200 ppm (symbols 2) against the value of initial temperature $T_0$. The value of $T_2$ is equal to 520 K.

Figure 4. Experimental probe temperature histories for dried diesel motor oil sample (a) and watered sample (b) at three values of initial temperature $T_0$: 307, 335 and 365 K. The value of temperature $T_1$ serves a parameter: 575 K (lines 1), 584 (lines 2), 595 (lines 3), 602 (lines 4). Arrows indicate the lines with boiling-up.
Figure 5. The values of pulse length $t_2$ for diesel motor oil samples with water content of 100 ppm (left), 300 ppm (middle) and 700 ppm (right) against the value of initial temperature $T_0$. The value of temperature $T_1$ serves a parameter: 575 (symbols 1), 584 (symbols 2), 595 (symbols 3), 602 K (symbols 4).

an increase in the heat transfer intensity is observed in both the continuous oil and boiling-up oil. Naturally, the decrease in boiling-up temperature was observed with the increase in water content. The proposed method proved to be convenient for the development of indirect method of detection the moisture in oils.

4. Conclusions
The developed method of controlled pulse heating was applied to the study of heat transfer and thermal stability of oils under conditions of a high-power local heat release. The probe heating mode suitable for monitoring the actual state of oils in electrical and motor equipment in the practically important range of changes in the initial temperature and moisture content was found. A distinct signal-response accompanying the appearance of moisture in the initial oil was revealed. Physical basis of such a response can be “decoded” in the experiments with model two-component mixtures.

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