Automated software to determine thermal diffusivity of oil-gas mixture

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Abstract. The paper presents automated software to determine thermal diffusivity of oil-gas mixture. A series of laboratory tests covering transformer oil cooling in a power transformer tank was conducted. The paper also describes diagrams of temperature-time dependence of bubbling. Thermal diffusivity coefficients are experimentally defined. The paper considers a mathematical task of heat flow distribution in a rectangular parallelepiped, alongside with the solution of heat conduction equation in a power transformer tank, which represents a rectangular parallelepiped. A device for temperature monitoring in the tank is described in detail. The relay control diagram, which ensures temperature monitoring against transformer overheating is described.

1. Introduction
Contingency overload of a transformer is accompanied by local oil overheating at a surface of an active part of the transformer followed by intensive release of gases from oil, which are caused by gas relay actuation and shutdown of the transformer. Overheating of winding isolation and a magnetic circuit reduces transformer lifetime, and the actuation of gas relay often leads to unreasonable shutdown of the transformer at short-term overloads. Therefore, there is an urgent need to increase the cooling efficiency of oil transformers.

The purpose of this work is to study the cooling efficiency of a transformer based on oil-gas transformer bubbling [1-9], which can be achieved by regulating the thermal diffusivity via emerging oil-gas bubbles. Gas-insulated bubbling of transformer oil via the utility model “Installation for cooling the oil transformer” [1] is based on the principle that heat release from an active part of the transformer is ensured by transformer oil with oil-gas mixture, circulating in it.

2. Materials and methods
The first thermocouple is installed on the upper interior surface of a tank with transformer oil. The second thermocouple is placed 23 centimeters apart below the top layer of transformer oil, the third thermocouple is placed at a distance of 38 centimeters, and the fourth one is placed below at a distance of 58 centimeters.

Thermoelectric TXA transducers were used as thermocouples. If applied continuously, this thermocouples measure temperatures in the range from minus 200 to plus 1000 °C.

Thermocouples are adjusted to inputs of analog-digital converter ADAM 4018+-B. The processed signal is transmitted in the RS-485 format to the ADAM 4520-D2E module. It, in turn, transforms the
RS-485 protocol to the RS-232 format. From the last module, the data are transmitted through the COM port to the computer. The utility of ADAM – ADAMView software accepts and processes the input signal.

The WinSpector program triggers the memory location, to which the information is sent from sensors and these locations are registered in the appropriate data entry fields in the output writer of the experiment to determine thermal diffusivity of transformer oil with emerging oil-gas mixture bubbles. Then, this program is launched and experimental output data are recorded. For temperature control inside a tank (maintenance of operating temperatures) against transformer overheating, the relay, which if necessary puts into operation the compressor with oil-gas mixture, is used. Relay regulation and control are ensured by software, which controls variable frequency drive through the LPT port.

Upper and lower temperature limits are set in the corresponding data entry fields of the program, which is supported by the first thermocouple. In case these limits are violated, the program sends signals through LPT control outputs to the relay.

The relay control diagram is shown on TKE 56D relay (Fig. 1). For simplicity, the diagram is assembled on a tandem transistor KT972A and operates in the B class mode. The corresponding transistors are opened in case +5V are supplied through the signals of LPT port to the transistor control input.

![Relay control circuit](image)

**Figure 1. Relay control circuit**

3. Calculations.
Let us consider the heat flow in a rectangular parallelepiped (Fig. 2).
Initially oil is placed in a tank at a temperature of \( T_0 = 15^\circ\text{C} \), which over time reaches \( T_u = 50^\circ\text{C} \) corresponding to the temperature of a heater. Let us consider rectangular parallelepiped limited by \( x, y \) and \( z \) respectively \( 0 < x < d/2, \ 0 < y < b/2, \ 0 < z < l, \ t > 0 \). The temperature is calculated through a conductivity equation:

\[
\frac{\partial T}{\partial t} = a \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right), \quad 0 < x < \frac{d}{2}, \ 0 < y < \frac{b}{2}, \ 0 < z < l, \ t > 0 ,
\]

with the following initial condition:

\[
T|_{t=0} = T_0 ,
\]

where \( a = \frac{\lambda}{cp} \) – thermal diffusivity coefficient, \( \lambda \) – heat conductivity coefficient and \( T_0 \) – ambient temperature. Heat exchange with the environment on surface \( S \) is described under the Newton’s law:

\[
-\lambda \frac{\partial T}{\partial x} |_{S} = \alpha (T|_S - T_0)
\]

where \( S \) – wall surface, \( \alpha \) – environment heat transition coefficient (oil – metal – air).

The ambient temperature does not change in the experiment, \( T_0 = \text{const} \) and \( T_u = \text{const} \).

Let us denote \( h = \alpha / \lambda \), then the boundary conditions may be as follows:

\[
\left. \frac{\partial T}{\partial x} \right|_{x=0} = 0, \quad \left. \frac{\partial T}{\partial x} \right|_{x=\frac{d}{2}} + h \left. \left( T \right|_{x=\frac{d}{2}} - T_0 \right) = 0 ,
\]

\[
\left. \frac{\partial T}{\partial y} \right|_{y=0} = 0, \quad \left. \frac{\partial T}{\partial y} \right|_{y=\frac{b}{2}} + h \left. \left( T \right|_{y=\frac{b}{2}} - T_0 \right) = 0,
\]

\[
T|_{z=0} = T_0 \quad T|_{z=l} = T_u .
\]

By solving the task through a folding technique, it is possible to get the following:
\[
T = 10 \left[ \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \sin\left(\frac{\chi_n d}{2}\right) \sin\left(\frac{\mu_n b}{2}\right) \cos\left(\chi_n x\right) \cos\left(\mu_n y\right) \times \right.
\]
\[
\times \left\{ \frac{\text{sh} \left( \sqrt{\chi_n^2 + \mu_n^2} \cdot (1 - z) \right)}{\text{sh} \left( \sqrt{\chi_n^2 + \mu_n^2} \cdot 1 \right)} + 
\]
\[
+ 2 \sum_{k=0}^{\infty} \frac{\pi k \sin \left( \frac{\pi k}{l} z \right)}{l} \exp \left( -a \left( \chi_n^2 + \mu_n^2 + (\pi k/l)^2 \right) t \right) \right\} \right] \left( T_n - T_0 \right) + T_0 ,
\]

where equations to define \( \chi_n \) and \( \mu_n \) can be as follows:

\[-\chi_n \sin \left( \frac{\chi_n d}{2} \right) + h \cos \left( \frac{\chi_n d}{2} \right) = 0 , \quad h \cos \left( \frac{\mu_n b}{2} \right) - \mu_n \sin \left( \frac{\mu_n b}{2} \right) = 0 ,
\]

where \( \chi_n \) and \( \mu_n \) - constants of transcendental equations.

4. Experiment

The obtained mathematical formula formed the basis for the software program to analyze the output data of an experiment aimed at determination of the coefficient of thermal diffusivity of transformer oil with emerging oil-gas mixture bubbles. The designed software allows, according to experimental diagrams, obtaining coefficients of thermal diffusivity for oil-gas mixture.

Figure 3 shows that temperature, even at times over 10 h, is not fully set. Heating of underlying substrates in the operating mode of the installation takes place mainly due to molecular thermal diffusivity. Thermal diffusivity coefficients within these series of experiments reached approximately \( 10^{-7} \) m²/s.

Fig. 3, b-c illustrates experimental diagrams of temperature-time dependence for various locations of thermocouples depending on their distance to the surface. Fig. 3, b shows that at a depth of 0.23 m, it is heated to the temperature of 50 °C in the presence of emerging oil-gas mixture bubbles within 16 min., and with two and three activated compressors at a depth of 0.38 m (Fig. 3, c). Thermal diffusivity coefficients within these series of experiments reached approximately \( 10^{-5} \) m²/s.

The described experiments showed that oil cooling with bubbles is twice more efficient than without them.
Figure 3. Experimental diagrams of temperature-time dependence at a depth of 0 (I), 0.23 (II), 0.38 (III) and 0.58 (IV) m from the fluid surface under the following conditions:

\( a \) – without compressors, with working compressors: \( b \) – with one compressor, \( c \) – with two compressors

5. Conclusions

The automated installation is designed.

The software program to analyze the output data of the experiment to determine the coefficient of thermal diffusivity of transformer oil with emerging oil-gas mixture bubbles is created.

The software program to record the output data of the experiment to determine the coefficient of thermal diffusivity of transformer oil with emerging oil-gas mixture bubbles is created.

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