Microbubbling in Transformer Oil due to Vibration

S. M. Korobeynikov, A. L. Bychkov, A. Yu. Ryzhkina, M. V. Sviridenko,
Novosibirsk State Technical University,
20, K. Marx Ave., 630092 Novosibirsk, Russia

L. A. Darian,
(JSC "IDGC Holding")
26, Ulanskii per., 107996, Moscow, Russia;

and **A. V. Melekhov,**
Institute of Laser Physics, SB of RAS,
13, Institutskaya St., 630090 Novosibirsk, Russia

ABSTRACT

Vibration is a prevalent process in oil filled power equipment, especially in transformers and electrical reactors. The most common cause of vibration is an alternating action of magnetic forces. If vibration takes place in narrow gaps, pressure inside gap increases and decreases periodically. In some cases pressure becomes negative, which could lead to bubble appearance and gas generation. Experiments and calculations show that there is cavitation inside non-magnetic microgaps. In case of non-degassed transformer oil microbubbles appear inside gap, dash out of gap and then float due to buoyancy force.

Index Terms — **Bubbles, failure analysis, vibration, magnetic cores, gases.**

1 INTRODUCTION

IT is well known that oil-immersed power transformers and reactors emit increased noise and vibration [1]. The main reasons of vibration are magnetostriction and magnetic forces in places where magnetic materials are close to nonmagnetic ones, e.g. microgaps in a magnetic circuit. Magnetostriction is core size reduction under a magnetic field. Core size decreases periodically with the change of alternating current and its relative value ($\delta l_1/L$) depends on the magnetostriction constant λs:

$$(\delta l_1/L) = \lambda s \quad (1)$$

Here L is magnetic field length (total length of magnetic core).

The second reason of vibration is realized in case of the reactor mainly. Transformers and reactors are very similar devices; magnetic core and windings are permanent parts of their structures. However, there is principal difference between them. This is obvious presence of non-magnetic gaps in the core in case of the reactor. The gap size changes due to magnetic forces during current flow. The magnetic pressure causes mechanical strength inside metal that results in a longitudinal size of core loss and an increasing of the gap. If the gap doesn't have solid ingradient, its relative change could be estimated as

$$(\delta l_2/L) = (B_m)^2/(2\cdot\mu_0\cdot E) \quad (2)$$

where B_m – core magnetic induction, E – Young modulus. Reactor is usually functioning at currents that produce induction in the core more than 1.5 T, e.g. close to magnetic saturation. Taking into account B_m ~1.5 T, E= $2\cdot10^{11}$ Pa, λs ~ (0.4-1.5)x10^{-6} [2] one could get an estimation of longitudinal core size, ($\delta l_1/L$) = (0.4-1.5)x10^{-6}, ($\delta l_2/L$) = 6x10^{-6}.

Both these factors will lead to a gap increase at the moment of maximum current. The gap decreases when current decreases. The pressure inside the gap decreases during the gap expansion phase, which could lead to cavitation and gas generation.

The goal of this paper is gassing research in the model of oil-filled equipment due to vibration.

2 EXPERIMENTAL SETUP

An electric steel maiden pot core with a controlled nonmagnetic gap was used. The total length of the magnetic core was L=12.5 cm. The crosscut gap inside the core was filled with fulled-board, and its thickness determined the gap size. A power supply of 50 Hz frequency was used. The voltage on the reactor model was changed from 0 up to 230 V. Core saturation was measured at a voltage of 70-100 V depending on the gap size. The core consists of two parts that were pressed opposite each other by means of a frame. A decrease in pressing force allows vibration and local pressure variation in the liquid to go from negative to positive values with a frequency of 100 Hz.

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A reactor model was inserted into a hermetically sealed cubic plexiglass cell. Optical recording was performed with the help of a microscope and a video camera connected with a PC. Vibration was detected with the help of a Corsar instrument intended for estimation of the core pressing rate. An instrument sensor was mounted on the cell wall.

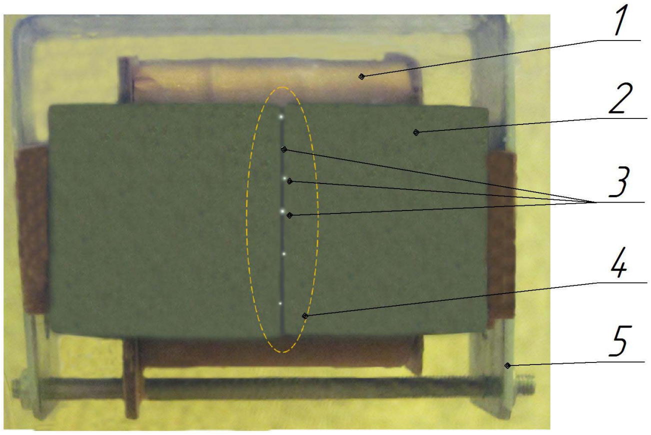

Figure 1. The sketch of experimental sample. 1 – winding, 2 - core, 3 - vertical microgap (dark line) with floating microbubbles (white dots), 4 – dashed line is bubble detection area, 5 – frame.

3 RESULTS

Non-degassed transformer oil GK was usually used at room temperature 20±2 °C. The cell volume was fully filled. In case of a gap of 100-200 µm (gap is oil filled or partially fulled-board), bubbles don't appear. Intense gassing was registered both at the gap absence and slackening of the frame tension. Because of the fact that the microgap plane was oriented along the buoyancy force, nucleating bubbles moved along the gap line. 10-20 microbubbles were registered simultaneously in the microscopic field (Fig. 1). Voltage inception was 60 V; bubble quantity slightly increased when voltage had increased. Bubbling frequency was approximately 1 sec^{-1}. Bubble radius varied from 40 to 60 µm, lifting the vertical speed to 0.3-0.4 mm/s due to buoyancy force. It was surprising that the horizontal bubble speed (moving away from the gap) was approximately the same as the vertical one. The vibration spectrum at voltages of more than 70 V had higher frequencies up to 1 kHz; in addition to the basic frequency of 100 Hz. This facts point to microbubble oscillation. It should be noted that transformer oil degassing suppressed bubbling. However, gas generation in the form of dissolved gas took place in this case, too.

The gas generation caused by vibration was studied at a voltage of 220 V. Samples of liquid with dissolved gases were taken after 16 hours of vibration experiments. Determination of gases that appear in liquid was performed chromatographically in the case of experiments with degassed oil. Diagnostic gas concentrations of H_2, CH_4, C_2H_4, C_2H_6, and C_2H_2 were measured. It was found that hydrogen, methane and low amounts of ethylene and acetylene were detected in transformer oil (Table 1).

Table 1. Dissolved gas concentration

Gas	Concentration before action, µl/l	Concentration after action during 16 hours, µl/l
Hydrogen H_2	<5	27.5
Methane CH_4	<1	11.6
Acetylene C_2H_2	<0.5	0
Ethylene C_2H_4	<0.1	0.8
Ethane C_2H_6	<0.1	0.7

4 DISCUSSION

Vibration is an invariable part of oil-filled high voltage equipment operations, especially reactors and transformers. It is well known that high frequency ultrasound action leads to bubbling and liquid destruction. Here we try to show how the low frequency vibration could lead to the same results in some cases.

The model of gas bubble formation consists of cavitation in narrow gaps at the wall vibration. The pressure inside a gap will increase when the gap is reduced and will decrease when the gap is expanded. The pressure inside a gap can be deduced from the solution of a well known one-dimensional problem concerning viscous liquid movement in a narrow gap under the influence of alternating pressure [3]

$$P(x) = P_0 + \frac{12 \cdot \eta \cdot \omega \cdot (a^2 - x^2) \cdot \Delta l}{l^3} \cdot \sin 2\omega t \quad (3)$$

where P_0 – atmospheric pressure, η – viscosity, ω – circular frequency of vibration (double operation frequency), l – gap, Δl – gap change due to vibration (vibration amplitude), a – depth of gap, x – distance from gap mouth inside gap. One can see that in the case of small gaps and Δl compared with l, the pressure inside the gap could periodically be both positive and negative. Theoretical estimation shows that pressure inside the gap should be negative when gap value is less than 1.5-2 µm. At these moments, a cavitation microbubble should be formed. If the liquid contains dissolved gas, this gas will diffuse into a bubble. When the pressure inside the gap increases, this bubble should disappear if there is a low gas content. The bubble will not dissolve if there is sufficient gas content in the liquid and therefore inside the bubble.

Real vibration could takes place in a magnetic system of power transformers and reactors, especially. Reactors have non-magnetic gaps in the core that provoke increased vibration due to magnetic forces and magnetostrictive strain. These forces could lead to core loosening and the periodical appearance of narrow gaps.

Gassing took place in both the cases of degassed and non-degassed oil. Bubbling took place in the case of non-degassed liquid. In our opinion, a gassing mechanism consists of the following steps. Microbubbles appear and grow at the period of negative pressure. Model of bubbling schematically shown in Figure 2.

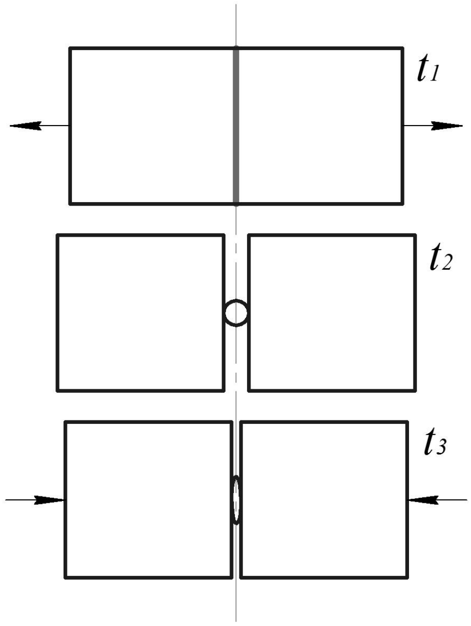

Figure 2. Model of bubbling in narrow gap at wall vibration. Arrows show movement of gap wall at the moments of t_1 – beginning of gap separation, t_2 – moment of gap peak, t_3 – phase of gap reduction. Here is only one emerged bubble, really there could be a lot of bubbles.

The gas content inside a bubble increases due to diffusion of dissolved gases from the surrounding liquid. Then at the period of positive pressure, the bubble collapses. During this action, the gas inside the bubble gets hot; this leads to the deterioration of the transformer oil and appearance of gas, especially hydrogen. If the bubble contains a lot of gas the collapse doesn't lead to bubble disappearance. During the next actions of negative pressure, the bubble increases in size and can be ejected from the microgap into the bulk of liquid. If the gas amount inside the bubble is too low (case of degassed liquid), the bubble dissolves and disappears during the collapse phase.

It is noteworthy to consider gases content that was created at the period of vibration in oil. Here one should mention that some dissolved gases were usually used as the markers of certain processes in oil filled equipment. E.G. hydrogen points on partial discharges, acetylene – arc processes, ethane – temperature increase, etc. More complex processes diagnose by consideration of gases combination. There are several well known dissolved gas analysis (DGA) techniques, which are applied for both data analysis and data interpretation. In our opinion method of nomograms is the most convenient technique to diagnose 13 processes in power transformers [4]. This method deals with relative concentrations of hydrogen, methane, ethane, ethylene and acetylene. The corresponding diagram forms certain pattern. However, the pattern that was formed on the basis of our data didn't refer to any known process. This pattern is presented in Fig. 2. That is why if, in real high voltage equipment, this sequence of diagnostic gases registers, it will signify that vibration cavitation takes place in the equipment. In our opinion we have found new diagnostic feature corresponding to vibration cavitation.

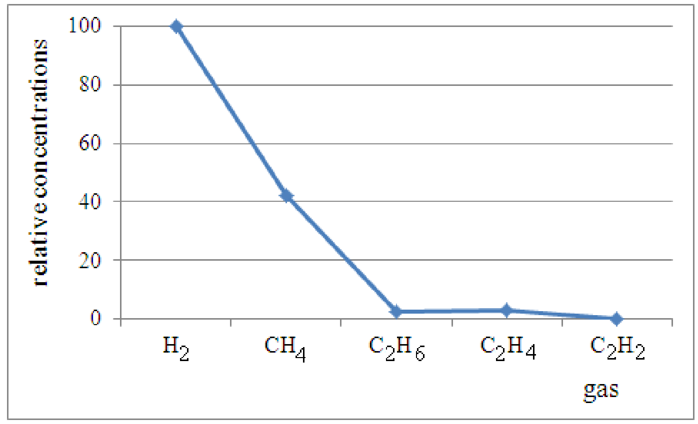

Figure 3. New pattern corresponding to vibration cavitation.

5 CONCLUSION

Vibration in narrow gaps can lead to cavitation inside transformer oil. It results in gas generation. Bubbling takes place in the case of non-degassed liquid. The theoretical model doesn't contradict experimental data on the optical bubbles recording and the increase of dissolved gas in oil, especially hydrogen.

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REFERENCES

[1] S. Ming, J. Pan, M.P. Norton, S. Wende and H. Huang "The sound-field characterisation of a power transformer", Appl.Acoustics, Vol. 56, pp. 257-272, 1999.

[2] Mac E., Van Valkenburg, edited by M. Wendy Middleton), *Reference Data for Engineers*. 9th ed., Butterworth-Heineman, Woburn, MA, USA, 2002.

[3] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics*. Vol. 6, 2nd ed., Butterworth-Heinemann, Oxford, UK, 1987.

[4] O. Vanegas, Y. Mizuno, K. Naito and T. Kamiya, "Diagnosis of Oil-insulated Power Apparatus by using Neural Network Simulation", IEEE Trans. Dielectr. Electr. Insul. Vol. 4, No. 3, 290-299, 1997.