Study on Bubble Evolution in Oil-paper Insulation during Dynamic Rating of Power Transformers

Meng Gao, Yuqin Ding, Tonglei Wang, Tao Wen, Qiaogen Zhang
State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University
No. 28, Xianning West Road, Xi'an, Shaanxi, 710049, P.R. China

***Abstract*—Solid insulation tends to absorb moisture during the operation and maintenance in oil-immersed transformers, which could be dangerous to the insulation especially under rating conditions. As has been reported, wet insulation could cause bubble effect in turn-to-turn insulation when the load of transformer increases rapidly. Primarily, this study theoretically analyzed the degradation of dielectric strength caused by gas bubbles generated from oil-paper insulation. The results showed that bubbles with diameter over 10μm in strong electrical field could easily lead to the partial discharge in turn-to-turn insulation. This paper mainly focus on clarifying the evolution of thermal bubble formation. The experimental platform consist of an oil-paper insulation system and an adjustable heating system was established to study the influence of water and gas content on bubble evolution temperature. Results showed that the inception temperature of bubble formation was greatly influenced by gas content and moisture content in paper, which could well explain the high probability of bubble evolution in old and wet oil-impregnated transformers. Then, a mathematical model was founded to calculate the bubble evolution temperature considering the solubility of gas and moisture in transformer oil at a certain temperature. Finally, based on the above results, this paper provided a strategy for managing the risk of insulation failures in oil-immersed transformers caused by thermal bubbles in dynamic rating conditions.**

Keywords—bubble evolution; oil-paper insulation; dynamic rating; power transformers

I. INTRODUCTION

Bubble effect usually appears in moistened cellulose insulation, which can lead to partial discharge or even insulation breakdown in oil-paper insulation systems. Researchers in 1980' believed that it was the moistened paper insulation with high temperature which eject bubbles into the oil. To avoid the bubble evolution in windings, standard IEC 60076-7 set a limit of 160℃ in hottest point during dynamic ratings of oil-immersed transformer. However, it is considered that the temperature of bubble evolution could be much lower in wet oil-paper insulation systems.

According to theory of liquid boiling, balance exists between internal and external pressure on the boundary layer of the bubble. Pressure P_i Inside the bubble mainly results from the vapor pressure of gas components; external pressure P_o consists of outside atmospheric pressure and static pressure of insulating oil. The surface tension σ is caused by Intermolecular forces of liquid on gas-liquid boundary. The relation between differential pressure and surface tension can be expressed as:

$$P_i - P_o = \frac{2\sigma}{r} \tag{1}$$

Where r denote the equivalent radius of the bubble. Thus, only when saturated vapor pressure in bubble catch up with its total external pressure, can the bubble exist in liquid. It should be emphasized that saturated vapor pressure of pure water at 100℃ is about 101.32kPa, fairly close to standard atmospheric pressure. When temperature goes down, the vapor pressure drops rapidly. However, previous researches show that water vapor could lead to bubbles at temperature below 100℃. In this case, pressure in bubbles maintained by water vapor can hardly overcome the atmospheric pressure, let alone meeting the criterion of bubble existence. In this perspective, the conclusion draw in previous researches that phase transition of overheated water directly leads to bubble effect seems contrary to physical laws. In this paper, we mainly focused on the influence of moisture and gas content on bubble inception temperature. Based on the experimental data, a mathematical model was set to explain the variation of bubble evolution temperature with moisture and gas content in paper.

II. EXPERIMENTAL SETUP

The test sample was a copper conductor with controllable heater and Pt100 probe embedded in it, which was wrapped with Kraft paper to be similar in construction with the winding of transformer considering of the heat transfer and the moisture migration. The outer diameter of the conductor was 12mm and the total thickness of the insulation paper was 0.4mm. The power of the heating systems could be up to 200W, while the Pt100 probe has an accuracy of ±0.1℃ and a dynamic response over 3℃/s, which is sufficient to meet requirement in temperature measurement. The moisture content in Kraft paper was varied using a humidity chamber and the insulation oil was dried and degassed in an oven for 24h continuously.

As is shown in Fig. 1, the test sample was immersed in processed oil with N_2 blanket in an excellent transparent Plexiglass vessel. Between the vacuum pump and the vessel, a pressure regulating valve was set to keep the vessel pressure at stable state. Below the vessel, a gas-liquid isolation cylinder was introduced to control the liquid surface height.

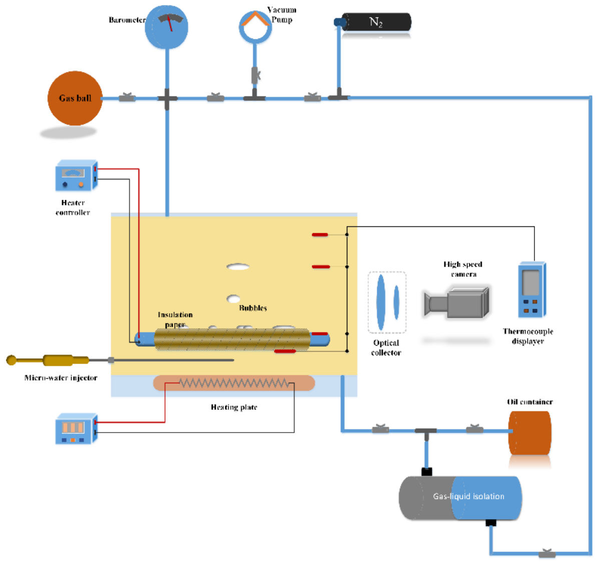

Fig.1. The sketch of experimental setup.

III. EXPERIMENTAL RESULT

A. Influence of moisture content

We made combinations of processed oil and Kraft paper with 4.65% water content in mass. The bubble phenomenon and the growing speed of moisture content in blanket gas is shown in Figure 2. The bubble begin to appear at conductor temperature of 98.1℃ and the amount of bubbles increases faster with the rise of temperature before 80min.

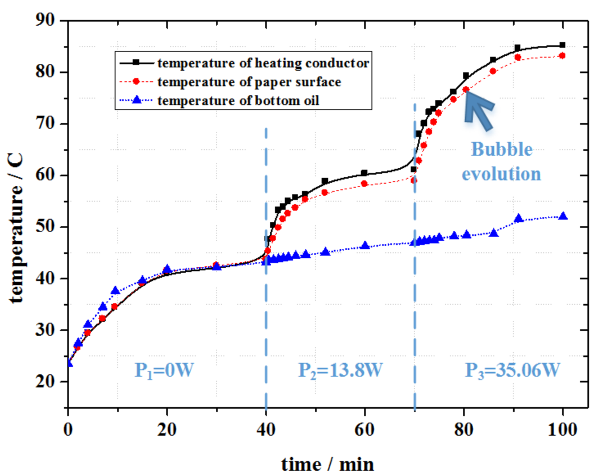

Fig 2. Bubble evolution temperature vary with conductor temperature, W%=5.4%.

As we can see from Fig.2 that bubbles appear at 98.1℃. The heating power was 35.06W. as to the evolution speed, bubble amount was about 20 per second. When the paper surface temperature reaches 105℃, bubbles began to appear at both the edge and the surface of the paper. With the increase of conductor temperature, the diameter of bubbles began to enlarge and the amount began to increase .

From Fig.3， As we can see, that bubbles appear at higher temperature. In the experiment, the amount of bubbles was much more less and diameter was small. After that, the bubble

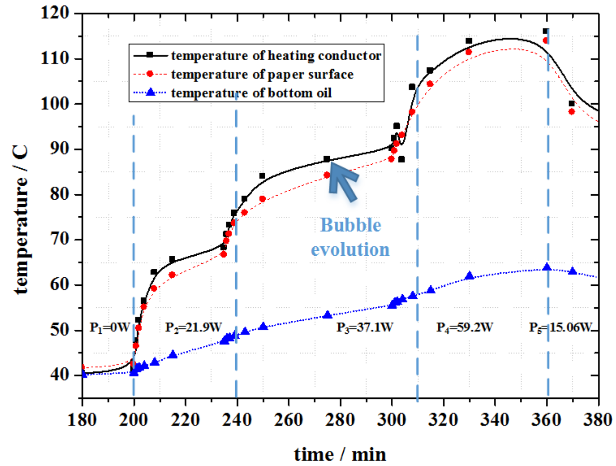

Fig. 3. Bubble evolution temperature vary with conductor temperature, W%=1.4%.

effect seems not that violent anymore with the continuous increase of temperature.

B. influence of gas content

In the experiment, we change the gas content in paper-oil insulation system with a pressure regulating valve. And the test sample was sealed in the vessel at a fixed gas pressure for 12h.

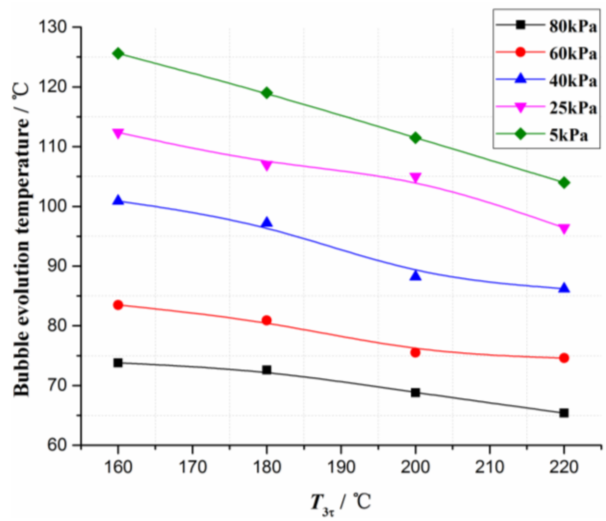

Fig 4. Bubble evolution temperature vary with gas content, W%=2.4%.

In Fig.4, $T_{3\tau}$ stands for the steady temperature of the conductor, corresponding to the heating power. At a certain vacuum pressure, the evolution temperature drops with the increase of $T_{3\tau}$. That means faster temperature rise is conductive to the bubble formation. It is more important that the gas content relates to bubble formation, which could be easily seen from the figure. Based on the above results, we set a model to explain the phenomenon.

C. Modeling

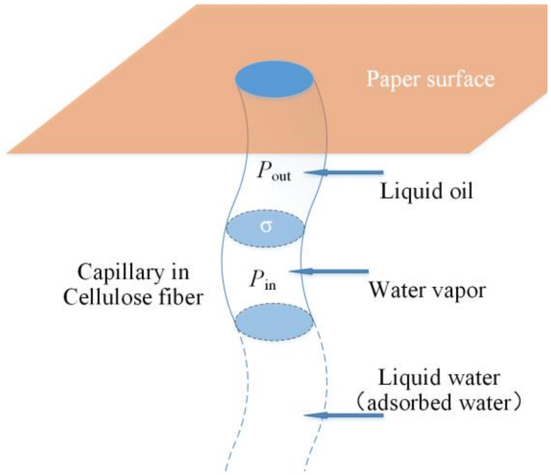

Fig.5. Structure of the capillary in a single fiber

Insulating paper in transformer are usually made from wood pulp. As to its micro-struture, large number of inter woven exists in and on the surface of the paper, where lies in a narrow, long capillary. As to fig.5, a small amount of water and gas molecules that is attached to the capillary wall after degassing. However ,when temperature rises, the locked water molecules moves out of its location thermally and vaporize, which was call phase change. The vaporized water push the oil in the capillary out and its volume grows rapidly.

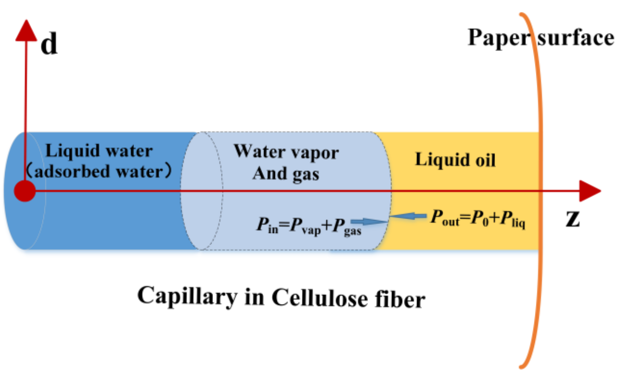

Fig 6. Model of pressure balance in the capillary

$$P_{in} = P_{vap} + P_{gas} \quad (2)$$

$$P_{vap} = 10^{7.97-1668.2/(T+228)} \quad (3)$$

$$P_{gas} = \frac{nRT}{V} \quad (4)$$

$$V = V_0 + \frac{\pi d^2}{4} x \quad (5)$$

Suppose the gas expansion process was the quasi-static process. Thus, saturated vapor pressure P_{vap} can be considered a partial pressure of water vapor at temperature T. which was shown as formula (3); n stands for the molecular weight of the gas, and gas partial pressure P_{gas} according to the laws of thermodynamics at temperature T. At the beginning of the expansion process, the gas volume was V_0, and enlarged to V_t after a period of t. Capillary axial was displacement x. The formula (8) was as follows:

$$\frac{nRT}{V_0 + \frac{\pi d^2}{4} l} + 10^{7.97-1668.2/(T+228)} = P_0 + P_{liq} \quad (6)$$

IV. CONCLUSION

The experiment platform was set up to study the influence of the moisture and the gas content on the bubble evolution temperature. The experiment results could show that both moisture and the gas content had huge impact on the bubble evolution temperature. The model was drown from the basic rule, which take both water vapour and gas content into consideration. By the calculating, results, the evolution temperature could be easily obtained.

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