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Thermally Induced Bubble Inception in Oil-Impregnated Paper Insulation: Influencing Factors and Activation Mechanism

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Abstract – Thermally induced bubbles in oil-impregnated paper can weaken transformer insulation during rapid temperature rise. This paper investigates bubble inception in single-layer oil-impregnated insulating paper by considering gas-state, external-pressure and electric-field conditions. Specimens with controlled moisture and free-gas contents were heated in a sealed chamber, while external pressure and AC electric field were independently adjusted. Results show that increasing paper free-gas content decreases the bubble inception temperature, especially under low-moisture conditions. External-pressure tests reveal that the inception process is governed by a multi-component internal pressure rather than by water vapour alone; free gas dominates under low-moisture/high-gas conditions, whereas water vapour dominates under high-moisture or low-gas conditions. The AC electric field further reduces the inception temperature mainly through physical activation of gas nuclei, and the effect is more pronounced in dry paper. These findings provide an integrated bubble-inception criterion for assessing bubbling risk in transformer oil-paper insulation.

Keywords: Bubble inception temperature, Electric field, External pressure, Gas content, Oil-paper insulation

1. Introduction

Oil-immersed power transformers are often subjected to rapid load variation, emergency load transfer and temporary overload. Under such conditions, the winding hot-spot temperature and its rate of rise may increase markedly. Elevated temperature accelerates the ageing of cellulose insulation and mineral oil, and thermal decomposition produces carbon oxides and hydrocarbons [1], [2]. More importantly for short-term insulation reliability, rapid heating can also induce bubbles in oil-impregnated paper, especially in winding turns and lead insulation [3]-[5].

Thermally induced bubbling differs from gas supersaturation caused by cooling or pressure reduction, and also differs from gas evolution during severe overheating or discharge. In transformer windings, bubbles generally originate from heated paper rather than bulk oil [6]-[9]. Once generated, bubbles may accumulate in inter-turn paper layers, distort the local electric field, initiate partial discharge and reduce breakdown strength. Migrating bubbles may also enter oil ducts and form bubble bridges under the combined action of oil flow and electric field [10]-[13].

Early overload studies demonstrated the engineering significance of bubbling in distribution and power transformers. Kaufmann observed gas bubble behaviour under loading above nameplate rating [6], while Heinrichs reported bubble formation in transformer windings at overload temperatures and noted that small mechanical disturbances can affect the visual identification of bubble inception [7]. McNutt et al. further related short-time failure modes to transformer overloading [8]. Later studies by Oommen and co-workers highlighted the roles of paper moisture, gas saturation and pressure in empirical bubbling criteria [15], [16].

Subsequent research focused mainly on moisture and material state. Koch and Tenbohlen showed that material quality and ageing affect bubble evolution in oil-paper insulation [9]. Perkasa et al. compared bubble and water-droplet formation in mineral- and ester-oil-impregnated paper, and reported moisture-dependent bubbling behaviour at overload temperatures [3], [17]. Zhou et al. modelled transient moisture equilibrium in oil-paper insulation [18], while Sakai et al. examined critical bubbling temperatures under overloaded transformer conditions [19]. Przybylek analysed the influence of cellulose ageing on water sorption and bubble evolution [20]. These studies confirmed that moisture is a primary factor, but they also imply that a single moisture-temperature threshold is insufficient when gas content, pressure and electric field vary simultaneously.

Recent studies have further emphasised the diagnostic and dielectric implications of bubbles. Transient moisture equilibrium models indicate that paper moisture at the instant of inception may differ from the initially measured

moisture content [18]. Bubble-containing oil-impregnated pressboard exhibits enhanced discharge activity and accelerated deterioration [10], [11]. Microbubble discharges and gas dissolution have also been investigated in insulating oil [12]-[14]. However, the separate roles of residual free gas, external pressure and electric field in the activation of bubble nuclei remain insufficiently clarified.

Transformer loading guides and dynamic thermal models provide the operational background for bubbling assessment. International loading guides and transformer thermal models are commonly used to estimate winding hot-spot temperature during cyclic, emergency or short-time overload operation [21]-[24]. However, these models mainly describe heat accumulation and thermal ageing, whereas bubble inception additionally depends on the local gas state, external resistance and interfacial activation process. Thus, a hot-spot temperature limit alone cannot fully characterise the short-term insulation risk when rapid temperature rise occurs in gas-containing oil-paper insulation.

Moisture migration and oil-paper equilibrium are also important because the paper moisture content during heating may differ from the initially measured value. Moisture equilibrium charts, transient moisture diffusion models and coupled multi-physics approaches have been developed to estimate water distribution in transformer insulation systems [25]-[28]. These studies support the distinction between the initial paper moisture W1 and the inception-time moisture W2 adopted in this paper.

Gas-state assessment provides another indispensable source of information. Dissolved-gas analysis is widely used to identify incipient thermal and electrical faults in oil-filled transformers, and carbon oxides are closely related to cellulose degradation and gas generation [29]-[31]. In addition, micro-bubbling and diagnostic gas-bubble dissolution in transformer oil indicate that gas transport and gas persistence cannot be neglected when interpreting bubble-related insulation phenomena [14], [32].

Although the hot-spot temperature limit is widely used in transformer loading assessment, the bubble inception temperature is not a fixed material constant. It depends on the thermodynamic state of the oil-paper system and on the resistance that a gas nucleus must overcome before visible growth. In many previous studies, moisture content was treated as the dominant variable, and empirical bubbling curves were established by correlating inception temperature with paper moisture [15], [16], [19], [20]. Such treatment is useful for engineering estimation, but it may obscure the contribution of other state variables. In particular, residual gases trapped in paper pores, the external oil pressure and the electric field acting on gas-filled cavities can alter the pressure balance of bubble nuclei without necessarily changing the moisture content itself.

Another difficulty lies in the definition of the inception state. Observable bubbles are usually the result of growth, coalescence and detachment of microscopic nuclei rather than the initial creation of a gaseous cavity. Therefore, the measured bubble inception temperature should be interpreted as an apparent activation temperature under a given observation criterion. From this perspective, gas content, external pressure and electric field should not be regarded merely as secondary test conditions; rather, they determine whether pre-existing nuclei in cellulose pores and surface pits can be activated during rapid heating.

Existing studies have separately reported the effects of moisture, material ageing, pressure or electric field on bubbling phenomena, but a unified interpretation of these factors remains limited. In particular, it is still unclear under which conditions bubble activation is dominated by water-vapour pressure and under which conditions residual free gas becomes decisive. The role of the electric field also requires further clarification, because it may affect the interfacial force balance of gas nuclei before any discharge occurs. These unresolved issues motivate the present analysis of bubble inception from the viewpoint of multi-component internal pressure and field-assisted nucleus activation.

This paper investigates thermally induced bubble inception in single-layer oil-impregnated paper under controlled gas-state, external-pressure and electric-field conditions. The objectives are to clarify how free-gas content modifies the inception temperature, how pressure-response normalisation can distinguish water-vapour-dominated and free-gas-dominated regimes, and how AC electric field lowers the activation barrier of bubble nuclei. The results are then interpreted using a multi-component internal-pressure framework.

2. Experimental Models and Methods

2.1 Specimen and test platform

The experiments were performed using a sealed oil-paper test chamber capable of controlling oil moisture, temperature, pressure and electric field. The test system included a heating circuit, a pressure-control loop, an electrical circuit and an optical observation unit, as shown in Fig. 1. Mineral transformer oil and insulating paper were used to prepare oil-impregnated paper specimens. For the single-layer tests discussed here, 0.08 mm paper was tightly

wrapped around a heated metal shell, and the paper edge was sealed to suppress end effects.

The paper temperature was calibrated rather than being directly replaced by the conductor temperature, because the thermal conductivities of metal, paper and oil differ significantly. The bubble inception temperature, T_{inc}, was defined as the paper temperature at the instant when the first bubble was observed to detach from or appear on the oil-impregnated paper surface. Each group was repeated five times where applicable to reduce the influence of visual and thermal fluctuations.

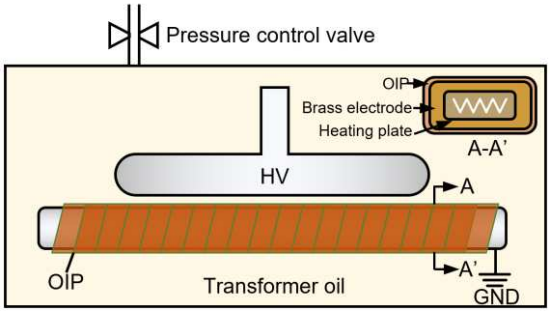


Fig. 1. Schematic diagram of the sealed chamber, heating circuit and single-layer oil-impregnated paper specimen used for bubble inception tests

2.2 Parameter control and data processing

Paper moisture was adjusted by controlled conditioning before oil impregnation. W_1 denotes the initial paper moisture content before heating, while W_2 denotes the paper moisture content at the bubble inception moment. This distinction is necessary because water migrates from paper to oil during heating. Paper free-gas content, V, was controlled by varying the vacuum-degassing pressure and was expressed in $\mu L \cdot L^{-1}$. The residual gas was considered to consist mainly of oxygen and nitrogen.

For external-pressure tests, the chamber pressure P_{atm} was adjusted to 101, 85, 70, 55 and 40 kPa. Four combinations of moisture and gas content were considered to distinguish the dominant pressure source during inception. For electric-field tests, an AC voltage was applied across the oil-paper system. The paper electric field E_p was estimated using a series-dielectric relation between the oil and paper layers.

$$\begin{cases} E_p \cdot d_p + E_o \cdot d_o = U_0 \\ E_p \cdot \varepsilon_p = E_o \cdot \varepsilon_o \end{cases} \tag{1}$$

where E_p and E_o are the electric field strengths in paper and oil, d_p and d_o are the corresponding thicknesses, ε_p and ε_o are their relative permittivities, and U_0 is the applied RMS voltage. Taking ε_p approximately equal to $2\varepsilon_o$ gives

$$E_p = \frac{U_0}{d_p + \frac{d_o}{2}} \tag{2}$$

The electric-field tests were mainly performed in the range E_p = 0~12.5 $kV \cdot cm^{-1}$ to avoid premature bubble discharge before the inception analysis.

Tab. 1. Main experimental variables

Variable	Symbol	Range or condition
Initial paper moisture	W_1	1.29%~5.39%
Paper free-gas content	V	280~7000 $\mu L \cdot L^{-1}$
External chamber pressure	P_{atm}	40~101 kPa
Paper electric field	E_p	0~12.5 $kV \cdot cm^{-1}$
Heating power	P_{heat}	195~250 W

3. Results

3.1 Influence of gas content on bubble inception

Figure 2 summarises the dependence of T_{inc} on paper free-gas content. Increasing V lowers T_{inc}, confirming that free gas trapped in paper pores and surface pits participates in the development of thermally induced bubble nuclei. This effect is much stronger in low-moisture paper. For W_1 = 1.29%, increasing V from 280 ppm to 7000 ppm produced a pronounced decrease in T_{inc}; for W_1 = 5.39%, the variation was comparatively weak.

The interaction between gas content and moisture becomes clearer in the T_{inc}-W_2 envelope. At different V values, the envelope opens toward the low-moisture side, which means that gas content becomes more influential as paper moisture decreases. Conversely, at high W_2, the curves for different gas contents approach each other because the water-vapour pressure increases rapidly with temperature and masks the free-gas contribution.

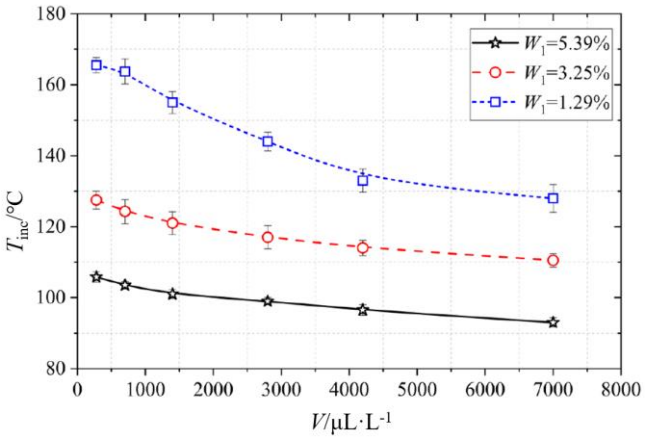


Fig. 2. Effect of paper free-gas content V on bubble inception temperature T_{inc} under different initial moisture contents W_1.

Additional comparisons at heating powers of 195 W and 250 W showed that the T_{inc}-W_2 envelopes remained similar, indicating that the gas-content effect cannot be reduced to a

heating-rate effect. Paper free-gas content and temperature rise rate should therefore be regarded as independent influencing factors. When moisture is low and gas content is high, gas content may become the dominant factor governing T_{inc}.

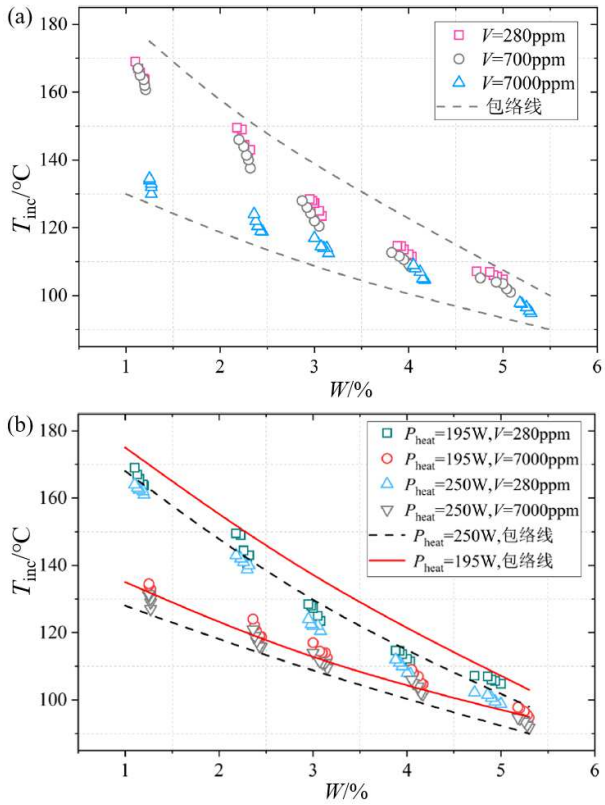


Fig. 3. T_{inc} -W_2 envelopes at different paper free-gas contents and heating powers. (a) influence of paper free-gas content; (b) comparison under different heating powers.

3.2 Influence of external pressure

External-pressure tests were used to identify whether bubble inception was controlled primarily by water vapour or by free gas. In all tested groups, lowering P_{atm} reduced T_{inc}. This result is consistent with the physical requirement that a bubble nucleus can grow only when its internal gaseous pressure overcomes the external pressure and capillary resistance.

The pressure-response data were normalized to compare different groups on the same scale. The measured T_{inc}-P_{atm} relation was compared with the calculated water-vapour-pressure relation and the calculated free-gas-pressure relation. The normalized variables were defined as

$$P_{norm} = \frac{P_{atm} - \min(P_{atm})}{\max(P_{atm}) - \min(P_{atm})}$$
$$T_{inc} = \frac{T_{inc} - \min(T_{inc})}{\max(T_{inc}) - \min(T_{inc})} \quad (3)$$

The closeness between measured data and the two idealised pressure-control relations was quantified as

$$r_w = \sqrt{\frac{1}{5}\sum_{i=0}^{4}(T_{w_norm} - T_{norm})^2}$$
$$r_g = \sqrt{\frac{1}{5}\sum_{i=0}^{4}(T_{g_norm} - T_{norm})^2} \quad (4)$$

where r_w represents the deviation from the water-vapour-pressure relation, and r_g represents the deviation from the free-gas-pressure relation. A smaller value indicates a closer match; therefore, $r_w/r_g > 1$ means that the measured response is closer to the free-gas relation, whereas $r_w/r_g < 1$ indicates a closer water-vapour relation.

As shown in Table 2, only the low-moisture/high-gas condition has $r_w/r_g = 2.73$, indicating that its pressure response is closer to the free-gas-pressure relation. In the other three conditions, $r_w/r_g < 1$ and the response is closer to the water-vapour relation. Therefore, water vapour and free gas jointly contribute to the pressure required for bubble nucleus activation, but their relative participation depends on the combined moisture and gas conditions.

Tab. 2 Normalized participation indices under different moisture and gas-content conditions

Condition	r_w	r_g	r_w/r_g	Dominant response
W_1=1.29%, V=280μL·L^{-1}	0.023	0.072	0.32	Water vapour
W_1=1.29%, V=7000μL·L^{-1}	0.082	0.030	2.73	Free gas
W_1=5.39%, V=280μL·L^{-1}	0.009	0.105	0.09	Water vapour
W_1=5.39%, V=7000μL·L^{-1}	0.015	0.068	0.22	Water vapour

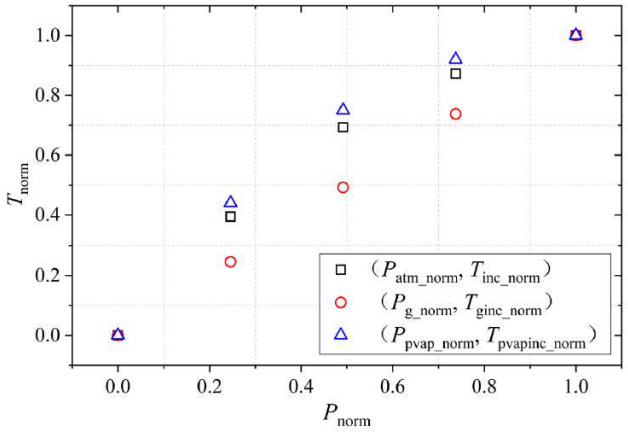


Fig. 4. Normalized comparison of measured pressure-response data with water-vapour-pressure and free-gas-pressure models.

3.3 Influence of electric field

The electric-field tests show that an AC field can reduce T_{inc} within the examined field range. Optical observations indicated that bubbles generated under electric field were generally smaller and more numerous than those generated without electric field. When the field strength became excessive, bubble-related discharge appeared; therefore, the analysis was limited to the range in which the field assisted inception without directly causing discharge.

At E_p = 0~12.5 kV·cm^{-1}, increasing E_p decreased T_{inc}. The decrease was most evident for low-moisture paper. When E_p increased from 0 to 12.5 kV·cm^{-1}, the specimen with W_1 = 1.29% exhibited a T_{inc} reduction close to 20 ℃, whereas the influence was much weaker at higher moisture content. To describe this effect, the field-induced temperature reduction was defined as ΔT_E, the difference between T_{inc} at E_p = 0 kV·cm^{-1} and at E_p = 12.5 kV·cm^{-1}.

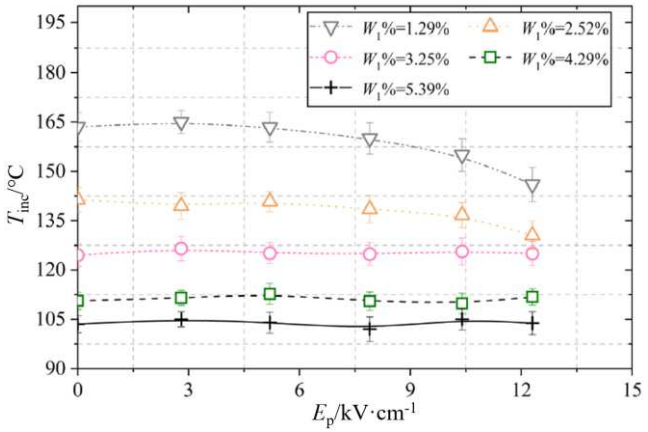


Fig. 5. Effect of AC electric field strength E_p on bubble inception temperature T_{inc} under different initial moisture contents.

The dependence of ΔT_E, on moisture, heating power, gas content and oil moisture indicates that the field effect is weakly related to temperature rise rate. For a fixed paper moisture content, changes in ΔT_E, were within approximately 5 ℃ when heating power was varied. The effects of gas content and oil moisture on ΔT_E, were not monotonic. In contrast, the paper moisture content showed a clear correlation: drier paper exhibited a larger field-induced decrease in T_{inc}.

For low-moisture conditions, ΔT_E, changed almost linearly with the bubble inception temperature measured without electric field. The empirical relation can be expressed as

$$\Delta T_E = 0.482 T_{inc} - 59.4 \quad (5)$$

This relation indicates that the field-induced reduction becomes larger when the no-field thermal threshold is higher. Thus, dry insulation, although less susceptible to purely thermal bubbling, is more sensitive to electric-field-assisted activation.

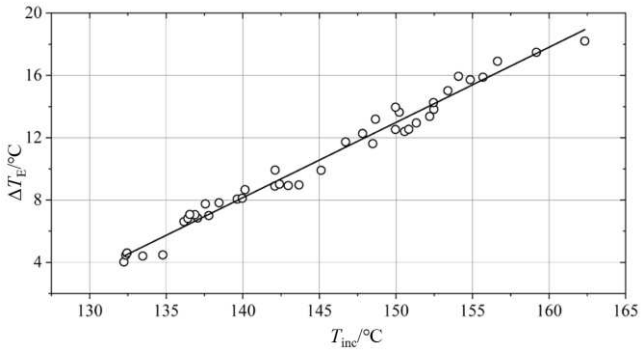


Fig. 6. Linear fitting between no-field bubble inception temperature T_{inc} and field-induced temperature reduction ΔT_E,.

4. Discussion

4.1 Multi-component pressure-driven activation

The combined gas-content and external-pressure results indicate that thermal bubbling in oil-impregnated paper is not a conventional boiling process governed only by water vapour. The nucleus is more likely activated from microscopic gas cavities retained in fibre lumens, inter-fibre pores and surface pits after oil impregnation. During heating, the pressure inside such cavities is supplied by water vapour, residual free gas and possible reaction-product gases from thermally stressed cellulose. Thus, bubble inception is governed by a balance between multi-component internal gaseous pressure and the external resistance imposed by oil pressure, capillary force and confinement by the cellulose network.

A simplified activation criterion can be written as

$$P_w(T,W) + P_g(T,V) + P_r(T,O_2,W) \geq P_{atm} + \rho g h + \frac{2\sigma}{R_{eff}} + P_{conf} \quad (6)$$

where P_w is the water-vapour pressure associated with paper moisture, P_g is the free-gas contribution, P_r denotes reaction-product gases generated at elevated temperature, $P_{atm} + \rho gh$ is the external static pressure, $2\sigma/R_{eff}$ is the capillary pressure related to the effective nucleus radius, and P_{conf} represents confinement by the fibre network and oil-paper interface.

In this criterion, the left-hand terms represent the pressure sources that promote nucleus activation, whereas the right-hand terms represent the resistance to nucleus growth. The existence of pre-existing cavities reduces the energy barrier compared with homogeneous nucleation, because a new gas-liquid interface does not need to be created from a fully dissolved state. Heating increases P_w rapidly through the temperature dependence of water

vapour pressure and also increases P_g through thermal expansion and gas release from the surrounding oil-paper medium. The relative contribution of these two terms, however, depends strongly on the moisture-gas state of the paper.

When paper moisture is high, P_w rises sufficiently to satisfy the activation criterion at a relatively low temperature; therefore, additional free gas only weakly reduces T_{inc}. When paper moisture is low, P_w is insufficient and the same increment of P_g accounts for a larger fraction of the required internal pressure. This explains why increasing V causes a pronounced decrease in T_{inc} under low-moisture conditions but has a limited effect under high-moisture conditions. In this regime, gas content can become the dominant factor, even though moisture remains the primary factor in wetter paper.

The normalized pressure indices in Table 2 further support this mechanism. If water vapour alone controlled inception, all measured pressure-response curves would follow the vapour-pressure relation. Instead, the low-moisture/high-gas condition is closer to the free-gas-pressure relation, indicating a transition from vapour-dominated to gas-dominated activation. Therefore, the apparent bubble inception temperature should be interpreted as the result of competition between internal gaseous pressure and external mechanical resistance, rather than as a single moisture-temperature threshold.

4.2 Role of pressure and electric field in lowering the activation barrier

External pressure affects both the absolute threshold and the shape of the T_{inc} response. A decrease in P_{atm} lowers the right-hand side of (6), so the same internal pressure can activate a nucleus at a lower temperature. However, because water vapour and free gases have different temperature dependences, the pressure-induced change in T_{inc} is not a uniform shift. The pressure response therefore contains information on the dominant internal-pressure component.

The pressure-normalisation method is useful because external pressure acts as a controlled perturbation to the activation criterion. If water vapour is the dominant internal pressure source, a reduction in external pressure should produce a temperature response close to that predicted by the saturated vapour-pressure relation. If free gas is dominant, the response should instead follow the gas-pressure relation more closely. Thus, the normalized pressure response provides a mechanistic fingerprint rather than only a phenomenological trend. The fact that the low-moisture/high-gas condition deviates from the vapour-pressure relation indicates that the inception process in this regime cannot be explained by water evapouration alone.

The electric-field effect is different in nature. The field does not mainly alter gas composition or chemical gas generation; instead, it physically assists the activation of nuclei. A gas-filled microscopic cavity in a dielectric medium experiences Maxwell stress under AC field. The resulting deformation can elongate the nucleus along the field direction and modify its effective curvature. Since capillary resistance is proportional to $2\sigma/R_{eff}$, an increase in effective radius or a decrease in curvature lowers the pressure barrier for activation.

This explanation is consistent with studies on field distribution, bubbles and electrohydrodynamic bubble dynamics in dielectric liquids. Non-uniform field distribution in transformer oil and bubble-related breakdown in liquid dielectrics have been recognized as important insulation issues [33], [34]. Meanwhile, visualization experiments on gas bubbles in electric fields show that electrostatic forces can deform bubbles, change detachment diameter and alter gas-liquid bubbling dynamics [35], [36]. These findings support the assumption that the AC field in the present oil-paper system can reduce the activation barrier by modifying the shape and interfacial force balance of microscopic nuclei before visible discharge occurs. Electric-field forces may promote earlier detachment and suppress growth into larger bubbles, but detachment alone cannot explain a T_{inc} decrease of more than 10°C within a short formation period. The more plausible mechanism is that electric-field-induced deformation modifies the interfacial force balance and reduces the activation barrier before macroscopic detachment occurs.

The stronger field effect in dry paper can also be explained by (6). Dry paper has a higher no-field T_{inc} because P_w is small. Consequently, the activation condition relies more heavily on assistance from free gas, interfacial geometry or electric-field-induced reduction of the capillary term. In wet paper, P_w already dominates the pressure balance, so the same field-induced reduction represents a smaller relative change in the total activation condition.

4.3 Implications for transformer insulation assessment

The results suggest that bubbling-risk assessment should move beyond a single hot-spot temperature limit or a single moisture-temperature curve. Paper moisture remains a primary factor, but dry paper is not necessarily safe when residual gas content is high or when the local electric field is enhanced. Conversely, high-moisture paper remains susceptible even at relatively low gas content because

water-vapour pressure can dominate the activation process.

For practical transformers, gas-state information from dissolved gas analysis, moisture assessment, external-pressure condition and electric-field distribution should be integrated when evaluating rapid-load or overload operation. External pressure, including oil static head and local hydraulic conditions, should also be considered because it changes the resisting pressure in the activation criterion. The proposed framework therefore provides a physical basis for integrating thermal state, gas state, pressure condition and electric-field information in bubbling-risk prediction.

The present study focuses on single-layer oil-impregnated paper specimens, which are advantageous for isolating the effects of gas content, external pressure and electric field. However, practical transformer windings contain multilayer paper insulation, oil ducts and non-uniform temperature and electric-field distributions. In such structures, moisture migration, local oil pressure, gas transport and bubble detachment may be more complex than those in the present test model. Therefore, the proposed criterion should be regarded as a physical basis for interpreting bubble activation rather than a direct replacement for full winding-scale thermal and dielectric assessment.

Nevertheless, the identified mechanisms remain relevant to practical insulation systems. Residual gases can exist in paper pores after impregnation or maintenance, external pressure varies with oil head and hydraulic conditions, and local electric fields may be enhanced near winding edges, spacers or defects. These factors can jointly modify the activation margin of microscopic gas nuclei. Future work should combine the present single-layer mechanism with multilayer heat-moisture transfer models and electric-field simulations to predict the spatial distribution of bubbling risk in actual transformer windings.

5. Conclusion

Thermally induced bubble inception in oil-impregnated paper was investigated under controlled gas-state, external-pressure and electric-field conditions. Increasing paper free-gas content lowers the bubble inception temperature, and the effect becomes pronounced in low-moisture paper. External-pressure normalisation shows that bubble activation is governed by the combined internal pressure of water vapour and free gas: water vapour dominates under high-moisture or low-gas conditions, whereas free gas dominates under low-moisture/high-gas conditions. AC electric field further reduces the inception temperature mainly by physically assisting nucleus activation, with a stronger influence in dry paper. The findings support an integrated bubble-inception criterion that incorporates moisture, residual gas, external pressure and electric-field condition for transformer oil-paper insulation assessment.

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