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Review

Bubbling Phenomena in Liquid-Filled Transformers: Background and Assessment

Ghada Gmati [1], Ungarala Mohan Rao [1], Issouf Fofana [1,*], Patrick Picher [2], Oscar Arroyo-Fernàndez [2] and Djamal Rebaine [1]

[1] Department of Applied Sciences, University of Quebec in Chicoutimi, Saguenay, QC G7H 2B1, Canada; ggmati@etu.uqac.ca (G.G.); mohan13.nith@gmail.com (U.M.R.); drebaine@uqac.ca (D.R.)
[2] Hydro-Québec's Research Institute, Varennes, QC J3X 1S1, Canada; picher.patrick@ireq.ca (P.P.); arroyo.oscar@ireq.ca (O.A.-F.)
* Correspondence: ifofana@uqac.ca

Abstract: The degradation of the insulation system in liquid-filled power transformers is a serious concern for electric power utilities. The insulation system's ageing is accelerated by moisture, acids, oxidation products, and other decay particles (soluble and colloidal). The presence of these ageing by-products is detrimental to the insulation system and may further lead to premature ageing and serious consequences. The ageing mechanisms of oil-paper insulation are complex, highly interrelated, and strongly temperature-dependent. The operating temperature of the transformer insulating system has a direct relationship with the loading profile. The major aspect that is witnessed with the fluctuating temperatures is moisture migration and subsequent bubble evolution. In other words, gas bubbles evolve from the release of water vapor from the cellulosic insulation wrapped around the transformer windings. The models presented in the existing standards, such as the IEC Std. 60076-7:2018 and the IEEE Std. C57.91:2011, are mainly based on the insulation temperature, which acts as a key parameter. Several studies have investigated the moisture dynamics and bubbling phenomenon as a function of the water content in the paper and the state of the insulation system. Some studies have reported different prototypes for the estimation of the bubble inception temperatures under selected conditions. However, there are various attributes of the insulation system that are to be considered, especially when expanding the models for the alternative liquids. This paper reviews various evaluation models reported in the literature that help understand the bubbling phenomenon in transformer insulation. The discussions also keep us in the loop on the estimation of bubbling behavior in alternative dielectric liquids and key attributable factors for use in transformers. In addition, useful tutorial elements focusing on the bubbling issue in transformers as well as some critical analyses are addressed for future research on this topic.

Keywords: transformers; insulation; bubbling; moisture; mineral oil; ester liquids

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1. Introduction

The condition monitoring aspects of power transformers have seen noticeable changes in recent years [1]. Furthermore, new guidelines and recommendations for safety, reliable operation, and diagnostic approaches, along with strategic tools, have been introduced. This is because the overall ageing of the transformer population increases the risk of catastrophic failures and unscheduled outages [2], which can result in significant costs of up to tens of millions of dollars in some cases, in addition to an operator's reputation. In addition, the increasing demand for electricity and the growth of renewable energy sources have put additional stress on the power grid, leading to a higher likelihood of transformer failures [3]. As such, the costs associated with transformer failures are expected to continue to rise in the coming years, making it increasingly important for utilities and other organizations to invest in proactive maintenance and modernization strategies to mitigate the risk of failure and minimize the financial impact of any failures that do occur [3].

There have been a wide range of practices and approaches to protecting and safeguarding these important machines [4]. Known as enemy number one of transformer insulation, moisture has always been a critical parameter for monitoring and diagnostic practices [5]. This is because moisture plays a significant role in the degradation of solid insulation. High moisture in the insulation system invites different failures and affects the life expectancy of the transformer [6]. To date, the moisture behavior of solid insulation impregnated with mineral oil has been widely emphasized [7–9]. One of the main issues that is witnessed with excessive water content in the cellulosic insulation is bubbling, or the release of water vapor from the insulation [10]. These vapor bubbles act as weak points (under high electric field intensity) or impurities and may lead to a complete breakdown of the insulation system. Generally, the generation of bubbles is higher when the transformer is overloaded [11]. In other words, the bubbling phenomenon is accelerated when high temperatures in the insulation system are reached. It is to be noted that direct physical access to the solid insulation of in-service transformers is not possible. Therefore, the industry generally relies on the indirect assessment and monitoring of the solid insulation [4,12,13]. Indirect methods to estimate the moisture in cellulose insulation alone have been a topic of important research [12–14].

The water in paper migrates into the oil under high temperatures [7], whereas temperature decreases cause the migration of water in the opposite direction. The direction of water migration is due to the fact that the hygroscopicity of cellulose decreases and the water solubility in dielectric liquids increases with temperature [8]. This temperature rise is primarily caused by overloading the transformer, while other factors include surrounding temperatures, an inefficient cooling system, or a combination of these factors. At the interface of oil-paper insulation, there is a high scope for the formation of these bubbles. However, this formation is attributable to insulation degradation, ambient temperature, type of liquid, etc. It is to be recalled that water in the transformer is produced by various sources, including paper degradation, moisture ingress, atmospheric conditions, mishandling at maintenance, etc. [7,15]. The main source of the buildup of water in transformers is insulation degradation, as it can release significant amounts of water molecules over time [16], particularly in older or poorly maintained transformers.

Due to the increased risk of bubbling under overloading conditions, transformers need to be accurately monitored. One of the most important ways to avoid bubbling is to make sure that the transformer's hottest-spot temperature (HST) is within the safe limits [17]. To accomplish this, previous investigations about bubbling focused on the influence of moisture on paper while considering the influence of oil pressure and gas content on bubble generation [18,19]. To evaluate the bubbling inception temperature (BIT), some experimental investigations were reported in [18–23]. In addition, numerical methods were reported by various researchers to predict the bubble inception temperature [6,10,18,23].

The present review paper starts with a background on moisture behavior in oil-paper insulation, followed by an overview of the existing literature on estimating the water content in the insulation system. The experimental and numerical modeling investigations of the BIT in the solid insulation system impregnated with esters and mineral oils are also reviewed. Since the bubbling phenomenon is attributable to various factors, the most influential parameters are also discussed, with an emphasis on ester liquids. Moreover, challenges and perspectives on bubble control and mitigation techniques are also addressed, along with potential recommendations for future investigations.

2. Background

This section will cover the effects of moisture on the oil-paper insulation system in transformers. The section will also discuss the methods used to assess moisture in oil-paper insulation systems. Additionally, the mechanisms behind moisture migration and bubbling in oil-paper insulation systems will be explored, including the formation of voids and air pockets and the effects of temperature and electric stress on the insulation.

2.1. Moisture in Oil-Paper Insulation

The water in power transformer insulation is a topic of concern for utility engineers, and therefore it is well documented [16,23–29]. Water plays a significant role in the life and operation of transformers by accelerating the degradation of the insulation system (oil paper) [26]. For this reason, significant drying techniques are used during the production process, and sustained efforts are deployed in the field to ensure a high degree of dryness [28]. The determination of moisture in oil and paper is of high importance to condition monitoring engineers. The moisture content in oil is generally specified in parts per million (milligrams of moisture per kilogram of insulating liquid). The diffusion of water between oil and paper depends on the temperature, the thickness of solid insulation, the area of contact between circulating oil and paper, the type of insulating liquid, and the diffusion time constants. The temperature and type of the liquid have a significant impact due to differences in the moisture solubility of various liquids at different temperatures. The water solubility of different liquids at two different temperatures is tabulated in Table 1.

Table 1. Water solubility in different insulating liquids [29,30].

Water Solubility (ppm)	Mineral Oil	Natural Esters	Synthetic Esters	Silicone Oils
At 20 °C	55	1100	2700	200
At 100 °C	650	-	7200	1100

It is to be noticed that mineral oil and silicon oil have lower water solubility than natural and synthetic esters. This difference is due to the different chemical compositions of various liquids. In fact, minerals and silicon oil are non-polar or slightly polar, contrary to esters, which are polar. The strongest attraction occurs between polar molecules and other polar molecules, like water. The composition of the liquid also influences its ability to dissolve water. This is evident for mineral oil, which is primarily composed of naphthenic, paraffinic, aromatic, and olefin hydrocarbons. The increase in water solubility is impacted by the aromatic content of mineral oil [28]. Generally, 99% of water is accommodated in the solid insulation [28]. More information about moisture in paper when impregnated with mineral oil and esters is reported in [31]. Sparling et al. [28] have studied an example of a transformer with 45,000 kg of oil and 4500 kg of solid insulation. Under a full load condition, 1.2 kg of water is diffused in the oil. This means 26 ppm of moisture in the oil while 97.6 kg of water still remains in the cellulosic insulation [28].

2.1.1. Impact of Moisture

The detrimental aspects of moisture in transformers may lead to dielectric failure and/or catastrophic failures. Recall that the insulating liquid and solid insulation are both subjected to premature ageing as a result of moisture increases. The risk of dielectric failure is directly related to the relative moisture saturation of the oil, and the premature ageing of the solid insulation is directly related to its moisture content [9]. To estimate water content in solid and liquid insulation, various techniques have been reported, and the same are summarized in [12,32]. A detailed review of these methods is presented in the subsequent sections.

2.1.2. Water Removing Techniques

Knowing that moisture is enemy number one of the transformers, not just the oil but also the solid insulation (where most of the water is hidden), the transformer insulation system should be dried off as and when required. It is technically not feasible to make a moisture-free insulation system. Table 2 summarizes the general guidelines for transformer dryness.

Table 2. General guidelines for % moisture by dry weight of paper [33].

Condition	% Moisture in Paper
Dry	0–2
Wet	2–4
Extremely wet	>4.5

The moisture content of paper affects the life expectancy of the transformer. It is reported that the transformer lifespan decreases with the increase in water content in paper [34] but this also depends on the temperature and oxygen content in the liquid insulation [34]. There are many approaches reported in the literature to estimate the lifespan of the transformer, considering the aforementioned factors [35,36].

To remove moisture from paper, several methods have been developed and accepted by the industry [28]. The most popular techniques include hot oil circulation, which consists of circulating the hot oil with many passes; vacuum drying; and hot oil spray [28,35,36]. There are also low-frequency drying and stationary molecular sieve methods for the drying of oil-paper insulation [28]. A detailed discussion of drying and other treatment methods is beyond the scope of this article.

2.2. Moisture Assessment Methods

Understanding how to accurately assess moisture in both the oil and paper components of a transformer is crucial for ensuring its reliability and longevity. For that, this paper discusses in the following sections the assessment methods for water in oil and paper.

2.2.1. Water Content in Oil

Water in transformer insulating liquids is regarded in three states: dissolved, emulsified, and dispersed (free water) [37]. All these states of water can potentially harm the transformer. However, the presence of free water is generally considered the most detrimental, as it can cause physical and chemical damage to the transformer [16,30]. Factors such as the operating temperature, the amount of water present, and the type of insulating fluid used may influence which state of water is dominant. Therefore, it is essential to regularly monitor and control the moisture content in transformer insulating liquids to prevent the harmful effects of water on the transformer [16,30].

The assessment of moisture is attained in many ways, including Karl Fischer titration (KFT), capacitive probes, Fourier transform infrared (FTIR), Fiber Bragg Grating (FBG) sensors, dielectric spectroscopy, etc. [38]. The widely accepted method is KFT, which is described in ASTM standard 1533 [39] and the IEC 60814 standard [40]. However, owing to the loading conditions, transformers are subjected to dynamic thermal excursions, which influence the osmotic behavior of the moisture around the oil-paper insulation. Thus, a single sampling may lead to large errors in the assessment of water content [29]. As discussed, the moisture content of oil can also be indirectly determined by FTIR analysis [41]. Oil FTIR analysis has been used to identify antioxidants, moisture, and oil oxidation products since it directly reveals the molecular species that are present in the oil [41]. Continuous online monitoring over periods of several months allows for a more dependable assessment. Hence, online monitoring is another option to measure the water content of oil. For this purpose, various capacitive probes and FBG sensor technologies are deployed [34], and the details on these technologies are reported in different reports such as [11,28,42,43].

2.2.2. Water Content in Paper

Water has a significant impact on the degree of insulation degradation. It is therefore crucial to accurately assess the water content in the cellulose due to its close relationship with the rate of ageing [44]. The KFT of paper allows the direct determination of water content in paper (WCP) relative to dry cellulose weight [21–23,45,46].

Different methods allowing the determination of the WCP are reported in the literature [12], whereas in References [16,45–49], have reported the indirect determination of the water content in paper using equilibrium curves when knowing the water content in oil is reported. However, this method is applicable at equilibrium conditions, which require a long time to be attained depending on the temperature and the direction of water diffusion (from paper to oil or the reverse). Additionally, due to ongoing fluctuations in the load and ambient temperature, the temperature in a transformer does not remain constant over extended periods. For that, it is required to take into consideration both the steady state of moisture and the transient process [50,51]. It is reported in [44] that the use of equilibrium conditions has a high likelihood of erroneous estimation. Additionally, the water solubility of oils changes with ageing, and that changes the partitioning of water between oil and cellulose. Nevertheless, despite the drawbacks, this indirect approach is still used for quick assessment [44].

Perkasa [52] measured the water content of paper using the Fessler equation [53]. The WCP is calculated according to Equation (1) as a function of the water vapor pressure of the dissolved water on the surface of paper $p_w(\text{atm})$ and temperature of oil T (°C). The water activity (a_w) and the temperature are measured by an appropriate Vaisala sensor [11,42], where $p\prime_w(\text{atm})$ is the water vapor pressure of pure water at the same temperature.

$$\text{WCP} = 2.173 \times 10^{-7} \times p_{w(T)}^{0.6685} \times \text{e}^{\frac{4725.6}{T+273}} \times 100\% \quad (1)$$

$$p_w(T) = a_w(T) \times p\prime_w \quad (2)$$

$$p\prime_w(T) = 0.6112 \times e^{\frac{17.67 \times T}{243.5+T}} \times 9.869 \times 10^{-3} \quad (3)$$

It is not recommended to measure the water content of paper using an equation alone. This is because the system is never in equilibrium with an in-service transformer. The water content in paper is affected by various factors such as temperature, humidity, and the type of paper used, which cannot be accurately accounted for and approximated by an equation. However, equations can be used in conjunction with other methods to estimate the water content of paper.

Garcia et al. [54] proposed a sensor for moisture determination in a paper. The reported prototype uses a metallic mesh electrode. This electrode is based on the characterization of the insulation dielectric response by means of frequency dielectric spectroscopy (FDS). Its sensitivity was tested, and it proved to have good sensitivity and repeatability of the measurements.

Over the years, dielectric response methods have been used to deduce moisture in paper or pressboard from dielectric properties, among them time-domain measurements based on polarization/depolarization current (PDC), frequency-domain spectroscopic (FDS) measurements, and recovery voltage methods (RVM) [32,55]. The lack of methods for on-site moisture monitoring in power transformers and the unsatisfying results from utilizing standard equilibrium procedures were the main drivers for the development of dielectric response methods [32]. These methods can be applied on-site after disconnecting the transformer [16]. Additionally, Koch and Kruger [56] described the DIRANA method as a fast and reliable method for determining the moisture in the solid insulation. In this approach, time and frequency domain measurements are combined, which substantially shortens the measurement time, typically by 25% compared to a pure frequency domain measurement [56].

2.3. Moisture Migration and Its Impact

Due to the loading profile and temperature variations, the water content of oil and paper insulation is never at equilibrium. It migrates from paper to oil and vice versa, depending on the temperature. If temperature increases, the weak hydroxyl bonds are broken easily, and moisture is migrated into oil. On the contrary, if the temperature decreases, the moisture migrates into the cellulosic insulation. It is to be noted that this process is controlled by the absorption limits and solubility limits of the oil and paper insulations, respectively. This process is depicted in Figure 1.

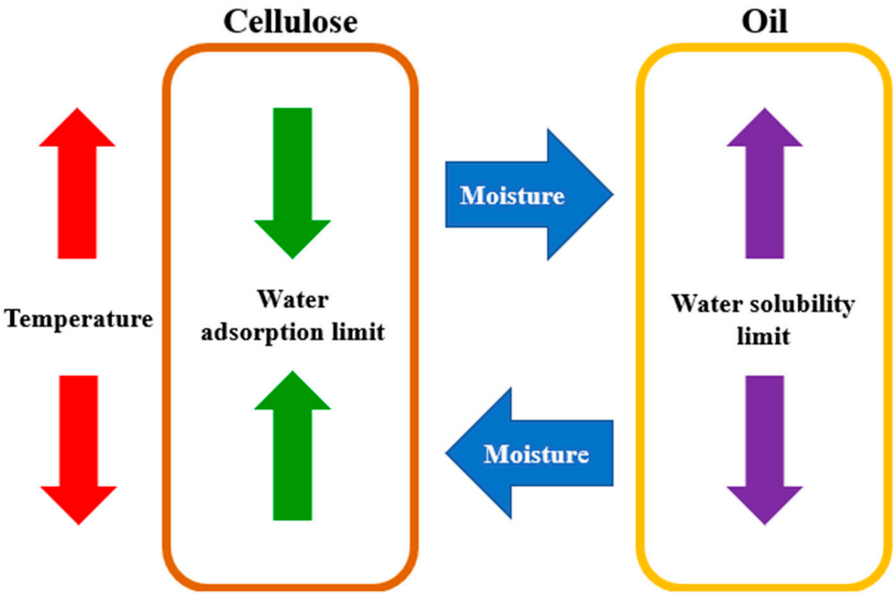

Figure 1. Moisture migration between transformer oil and paper insulation.

Additionally, moisture migration consists of two processes (sorption and desorption). Sorption is the fact that the solid insulation absorbs water, and it releases some or all of the water into the surrounding fluid through a desorption process. Sorption includes adsorption and absorption around the oil-paper insulation. This sorption process is illustrated in Figure 2.

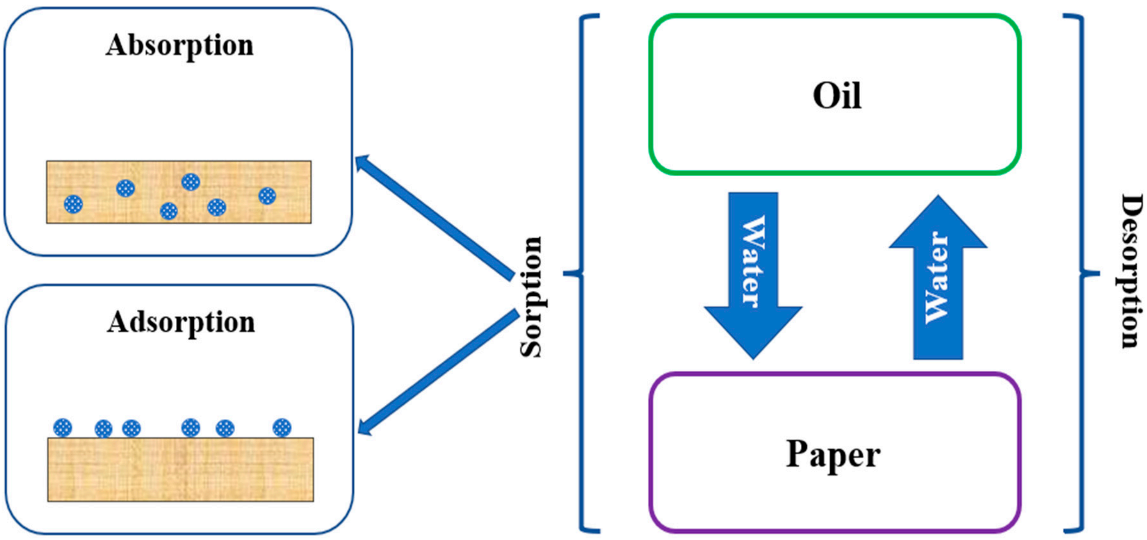

Figure 2. Sorption and desorption processes of paper.

Adsorption refers to the buildup of a liquid or gas layer on the solid surface, whereas absorption indicates the accumulation of gas or liquid inside the solid material. Due to their polar nature, water molecules have a propensity to adhere to the polar regions of the paper surface. When a water molecule attaches, heat is released. In addition, heat is required to remove it from the surface and dissolve the intermolecular connection. For this reason, when the temperature rises, water is released into the oil. As the concentration of water on a surface rises, multiple layers of water molecules are likely to develop [57]. It is to be understood that the sorption and diffusion processes are stochastic and osmotic in nature and are largely influenced by temperature. As discussed above, moisture ingress and the generation of water by chemical reactions involving the oil and cellulosic insulation are the two main sources of water in transformer insulation [58]. The WCP typically increases at a relatively slow rate (below 1% per 10 years) [16]. Water migrations in transformer insulation are associated with two primary concerns. Firstly, if the cellulose paper becomes excessively hot and wet, water bubbles will transfer from the paper to the oil, which could result in a potential flashover between the windings [53]. Secondly, the longevity and life span of cellulose insulation are shortened with increased water concentration [58].

As the temperature rises, the oil's ability to dissolve water increases too, whereas that of cellulose marginally decreases [13]. When the temperature increases, a diffusion of moisture between the paper and the oil occurs until equilibrium is reached. The process of moisture diffusion is significantly slow, as water must travel through solid insulation before reaching the surface and being absorbed by oil. In comparison to the heat transfer and fluid-dynamic processes taking place within the transformer, mass transport processes are considerably slower [59]. The migration of moisture follows a simple physical principle, as described by Equation (4), which expresses the time constant τ of diffusion [60].

$$\tau = \frac{d^2}{\pi^2 \times D} \tag{4}$$

where d is the thickness of the solid insulation and D is the diffusion coefficient expressed in Equation (5).

Various authors reported coefficients for kraft paper and pressboard using diverse methodologies [50,51]. Using various techniques, different researchers reported coefficients for kraft paper and pressboard. The summary of moisture diffusion coefficients reported by various authors for cellulosic-based solid insulation impregnated with different liquids is tabulated in Table 3.

Table 3. Summary of the moisture diffusion coefficients reported by various authors for cellulosic-based solid insulation impregnated with different liquids.

Reference	Insulation Type	Oil Type	Expression
Guidi [61]	Impregnated paper	Mineral oil	$D = 6.44 \times 10^{-14} \times e^{[0.5\times \text{WCP}-7700\times(\frac{1}{To}-\frac{1}{T})]}$
Foss [62]	Impregnated paper	Mineral oil	$D = 1.34 \times 10^{-13} \times e^{[0.5\times \text{WCP}-8074\times(\frac{1}{To}-\frac{1}{T})]}$
	Non-impregnated paper	Mineral oil	$D = 2.62 \times 10^{-11} \times e^{[0.5\times \text{WCP}-8140\times(\frac{1}{To}-\frac{1}{T})]}$
Du [63]	Non-Impregnated pressboard	Mineral oil	$D = 6.7 \times 10^{-13} \times e^{[0.45\times \text{WCP}-7646\times(\frac{1}{To}-\frac{1}{T})]}$
Garcia [64]	Non-impregnated paper	Mineral oil	$D = 3.1786 \times d^{-3.665} \times e^{[0.32458\times \text{WCP}-\frac{8241.6\times d^{-0.254}}{T}]}$
	Impregnated paper	Mineral oil	$D = 0.5 \times e^{[0.5\times \text{WCP}-\frac{10057-133.7\times d}{T}]}$
Zhang [65]	Impregnated paper	Mineral oil	$D = 1.84 \times 10^{-13} \times e^{[0.447\times \text{WCP}-6563\times(\frac{1}{To}-\frac{1}{T})]}$
		Vegetable oil	$D = 7.34 \times 10^{-14} \times e^{[0.497\times \text{WCP}-6940\times(\frac{1}{To}-\frac{1}{T})]}$
Villarroel [66]	Impregnated paper	Mineral oil	$D = 2.5 \times 10^{-9} \times d^{4.3} \times e^{[0.2\times \text{WCP}-\frac{3164\times d^{0.29}}{T}]}$
		Natural ester	$D = 1.2 \times 10^{-7} \times d^{-3.7} \times e^{[0.25\times \text{WCP}-\frac{4491\times d^{-0.5}}{T}]}$

According to the literature, the empirical equation (Equation (5)) developed by Guidi [61] is one of the most commonly used expressions for the diffusion coefficient. This Equation (5) considers the variation of the coefficient with respect to how the coefficient varies with temperature and paper moisture content [61].

$$D = D_G \times \mathrm{e}^{k\times \text{WCP}+E\times(\frac{1}{T_0}-\frac{1}{T})} \tag{5}$$

where k is a dimensionless parameter, D_G is a preexponential factor ($m^2 \cdot s^{-1}$), E is the energy required to break chemical bonds, and T_0 = 298 K.

The values of k, D_G, and E vary from one study to another. This difference can be due to the investigated materials or the methodology applied. The type of fluid, the type of solid insulation, and whether or not the paper is impregnated are parameters that affect water diffusion through solid insulation. Clearly, precise diffusion coefficients are necessary in order to accurately model the dynamics of moisture in transformer insulation.

Since a correlation exists between the moisture dynamics and the load profile that may be safely applied to a transformer, the behavior of moisture inside the insulation appears to be a critical factor. Numerical models combining thermal and moisture dynamic phenomena analyzed the relationship between load, temperature, and moisture in the insulation system [7,61,62].

The operation of transformers with high moisture content can lead to a variety of dangerous scenarios, such as the development of free water in the transformer oil during a cooling cycle, the buildup of excessive water concentration, or the generation of bubbles at the oil-paper interface [7].

These events can threaten the equipment's integrity by reducing the dielectric strength of the oil-paper insulation. Numerous studies (see e.g., [7,67]) have offered experimental evidence about the impact of moisture on the development of partial discharges and degradation of the insulation. All these effects increase the probability of bubbles forming in the power transformer insulation system.

2.4. Bubbling in Oil-Paper Insulation

Another concern is the impact of moisture content on the bubbling phenomenon. In fact, a high amount of water content can result in saturated vapor pressure [68], which limits how much water can evaporate in a given amount of time. When the moisture content is higher, the vapor saturates more quickly, which impacts the bubbling initiation temperature. In general, the bubbling phenomenon is regarded as a significant catalyst for liquid dielectric breakdown [69,70]. In this regard, many investigations [6,18,21,52] have shown that high temperatures, high moisture, discharges, and material breakdown can all cause bubbles in the transformer.

The ability of the bubble to expand depends not only on the pressure exerted on its surface but also on the bubble's surface tension and size [18], as described by Equation (6), the so-called Young-Laplace equation that explains the pressure applied on the interface between bubble and oil.

$$P_{int} = P_{ext} + \frac{2\gamma}{r} \tag{6}$$

where P_{int} (Pa) is the internal pressure of the bubble, P_{ext}(Pa) is the external pressure exerted on the bubble, γ (N/m) is the surface tension, and r (m) is the radius of the bubble.

Temperature is another key parameter when discussing bubbles in insulating liquids [71]. At high temperatures, the surface tension of an insulating liquid is reduced. As a result, the pressure inside the bubble decreases. Thus, the electric field needed for the ignition of a bubble at an elevated temperature is less, and the initiation of breakdown may result. It was also reported that a bubble could occasionally burst during partial discharge and partially dissolve in the liquid. Of course, the type of insulating liquid affects this phenomenon [71]. Oommen et al. [18] reported that there are initially many cavities on the insulation paper surface that are filled with dissolved gases and a small amount of water vapor. The temperature of the paper and cavity rapidly increases during transformer overloading, and the cavity enlarges while also absorbing additional water vapor expelled from the paper. Finally, there would be enough energy and space in the cavity to release a free bubble.

3. Timeline of Experimental Studies: Bubbling Phenomena

Many experimental mechanisms are being developed to investigate the bubbling inception temperature. The first studies have proven that the bubbling formation is due to an increase in moisture, load, and temperature. Most of the studies emphasized the moisture and temperature impacts on the generation of bubbles or bubbling inception temperature. Przybylek [46] was the first to assess how paper ageing affected the bubbling phenomenon. Consequently, numerous other studies have examined papers with different ageing conditions. The desire to better understand reality led many researchers to investigate various types of oil/paper insulation materials (Kraft paper, thermally upgraded kraft paper, aramid, pressboard, mineral oil, synthetic esters, and natural esters). This has led to scientific richness when discussing the bubbling phenomenon. A chronologic evolution of bubble formation studies is provided in Figure 3.

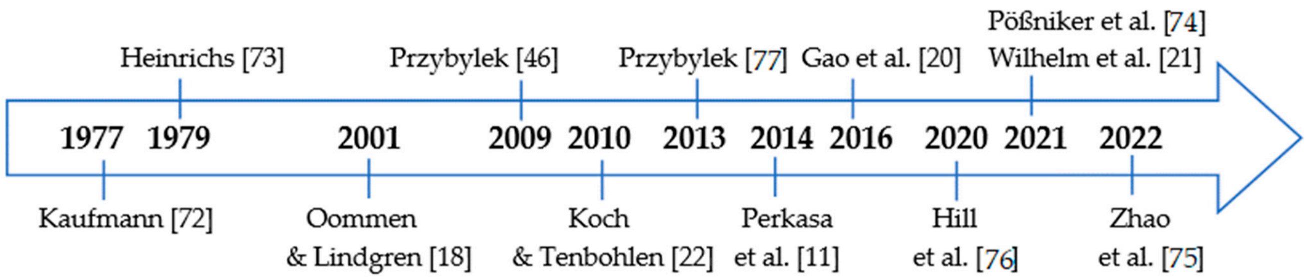

Figure 3. Timeline of research into transformer bubbling [11,18,20–22,46,72–77].

The first observation of bubbles in oil was reported by Kaufmann et al. in 1977 [72]. The authors have explored rain and loads as two responsible factors for bubble formation. The presence of rain served to highlight the moisture intrusion caused by a poor transformer seal. The load was obviously introduced to investigate the effect of temperature rises on the generation of bubbles. They reported that a rate of above 5 mm per minute of precipitation may trigger bubbles at or above the rated load, and overloading the transformer to 175% for a period of 30 min leads to bubble generation in the first 10 to 15 min. The validation of the developed model has been done with real distribution transformer windings and miniature coils [72]. Then, Heinrichs [75] developed an insulated conductor model to study the influence of cellulose degradation on bubble formation. This set-up is composed of a cylindrical heating element covered by a single layer of thermally upgraded kraft paper (TUK). The heating element with a paper sample is immersed in oil with less than 5 ppm of moisture and 0.25% of gas content. The system was gradually heated, and bubbles were initiated at 125 °C. This experiment also investigated the effect of temperature and electric field stresses on the paper-oil system. It was shown that bubbles appear at about 130 to 150 °C. In 2001, Oommen and Lindgren [18] developed a test set-up allowing the investigation of BIT. The set-up consisted of coil models representing transformer windings. In this work, mineral oil and kraft paper were investigated under various conditions: water content, gas content in the oil, and pressure in the system. In 2009, Przybylek [46] worked on the bubble's evolution temperature and developed a set-up for that. The experiment setup consisted of a glass vessel filled with oil and a heating element placed inside a copper tube. A thermocouple fixed to the copper tube on which the paper is wound controlled the bubble's inception temperature. The author recorded the bubbling effect using a high-speed camera. New kraft paper (DP_v = 1357) and aged kraft paper (DP_v = 341), with different moisture levels, have been investigated.

Koch and Tenbohlen [22] also investigated the evolution of bubbles in oil-paper insulation systems. In this work, the age of both paper and oil, the moisture content of the paper, and the type of insulation are considered. For that, a filled oil container includes a heating element wrapped in two layers of paper. To assess the temperature of these paper sheets, an opto-electronic probe is used. A variable transformer controls the heating power. And the bubbling phenomenon was recorded via a camera. Then, in 2013, Przybylek [10] investigated the BIT in cellulose and aramid paper depending on water content. The set-up is composed of a glass container filled with mineral oil and containing a heater. Paper samples (kraft paper and aramid) were wrapped around aluminum tubes. These tubes were then placed in the oil vessel. A thermocouple was inserted into the tubes to measure the temperature of the samples when modifying the load. The rate of temperature rise was about 6 °C/min. The BIT was determined using a camera observing vapor bubbles. Later, Perkasa et al. [11,52,78] studied the formation of bubbles in vegetable and mineral oils. The experimental setup consisted of a glass tube filled with transformer oil and a winding made of two copper conductors, each with four layers of paper samples. A heating element was placed around the tube to heat the oil and the paper sample. The experimental setup also included several thermocouples to measure the hotspot temperatures between different coils. Moisture is controlled using a Vaisala probe.

In 2016, Gao et al. [20] experimented to investigate the bubbling phenomenon in oil-paper insulation. The set-up is composed of a heater incorporated into a copper tube. This allows the paper covering to be heated. This was placed in a test chamber filled with oil. Mineral oil and kraft paper were the materials investigated in this study. Likewise, Hill [77] has also designed his own experimental model. Which is composed of glass vessels containing the liquid insulation and a heating element covered by paper samples. To measure the temperature, a thermocouple is inserted between the paper layers.

Recently, in 2021, H. M. Wilhelm et al. [21] developed an experimental test setup for studying bubble generation in mineral oil-paper insulation systems. The model is composed of an electrical resistor wrapped in two layers of paper, which was exposed to the heating and cooling processes. The solid insulation used is thermally upgraded kraft paper immersed in an oil vessel with different water contents. A copper tube is also used to permit oil expansion. The tests were done with different temperature rise rates. Additionally, in [74], Pößniker et al. developed a small-scale set-up to study the bubble formation of transformer insulation systems. The setup consists of a 150-mm glass test tube with a 25-mm diameter filled with 40 mL of inhibited mineral oil and a 100 W heater centered on two washers. The top two-thirds of the heater element are wrapped with paper tape for the bubble formation test. A thermocouple is attached to the bottom third of the heater for reference temperature readings. Two cameras are used to observe the time and location of the generated bubbles. Aligned with the short-time emergency overloading reported in the IEC 60076-7 standard [79], the maximum temperature of the system in this study is 180 °C. More recently, T. Zhao et al. [75] mounted an experimental setup to study the bubble effect of cellulose insulation impregnated with natural ester. The test platform included a test chamber, an electric heating tube to heat paper samples, and some measurement modules such as a PT100 sensor for temperature measurement and a diffused-silicon pressure sensor. Four glass flasks containing the different test samples are placed in the chamber. In fact, the first sample was wrapped with one layer, and so on, until the fourth sample was surrounded by four layers of paper. The test was done with three different temperature rise rates: 1.8 K/min, 3.3 K/min, and 6.8 K/min.

Table 4 provides a summary of the most significant works that examined bubbling phenomena experimentally.

Table 4. Information on previous experimental studies on bubble formation.

Details	Heinrichs [73] (1979)	Oommen and Lindgren [18] (2001)	Przybylek [46,77] (2009)	Koch and Tenbohlen [22] (2010)	Perkasa et al. [11,52] (2014)	Gao et al. [20] (2016)	Hill [76] (2020)	Wilhelm et al. [21] (2021)	Pößniker et al. [74,77](2021)	Zhao et al. [75] (2022)
Heating source	Cylindrical heater	Coils	Copper tube with heater	Heated tube	Copper conductor	Copper tube	Heated tube	Resistance	Cartridge heater	Electric heating tube
Temperature profiles	Cyclic profile	65 °C	2 °C/min	Rates of 2, 3 and 6 K/min	25 °C/min	By a step of 0.1 °C	Increasing Temperature profile	0.3–5 °C/s	Temperature profile till 180 °C	1.8 K/min; 3.3 K/min and 6.8 K/min
Moisture in paper (%)	0.2–0.5	0.3–8	0.84–6.98	≈1–5	1–6	1.5–5.5	NTUK <0.5%/TUK <0.3%	0.3–2.5	2	3
Moisture in oil (ppm)	<5	-	15	-	-	12	Mineral oil, GTL oil < 10 and Synthetic ester < 50	35	<11	<40
Gas content in oil (%)	<0.25%	0.45–12.3	-	Gas saturated	Degassed	Degassed	-	-	Degassed	-
Paper type	TUK	Kraft paper	Kraft paper/Aramid	Kraft paper/TUK	Kraft paper	Kraft paper	NTUK and TUK	TUK	Kraft paper	Kraft paper and pressboard
Oil type	Mineral oil	Mineral oil	Mineral oil	Shell Diala D/Shell K 6 SX	Shell Diala B)/FR3	Kunlun K125X	Mineral oil, GTL oil and Synthetic ester	Mineral oil	Nytro Gemini X	FR3
Paper thickness	-	-	-	0.065–0.1 mm	-	0.08 mm/layer	NTUK: 48 mm/TUK: 51 mm	0.0755 mm	15 mm	0.05 mm/ 1 mm
Paper condition	-	-	New paper (DP_v = 1357)/Aged paper (DP_v = 341)	Kraft paper (DP_v > 1000)/TUK (DP_v > 1100)	-	Virgin (DP_v = 1400) Processed (DP_v > 1200)	New	DP_v > 1000	-	New/aged
Oil condition	-	-	-	Virgin/Aged	-	Fresh (IFT = 45 mN/m)	New	NN = 0.01 mgKOH/g	-	New
Temperature monitoring method	Thermo-couple	Fiberoptic temperature sensor	Thermo-couple	Opto-electronic probes	Thermo-couple	Pt100 RTD sensor	Thermocouple	-	Thermo-couple	Pt100 RTD sensor
Bubbling monitoring method	Radio influence voltage RIV/visual detection	Partial discharge/visual observation	Camera	Digital recording camera	Visual observation	Visual observation	2 Cameras	Digital recording camera	Camera	Visual
Bubbling inception temperature	130–150 °C	140 °C at 2.5% of WCP	133 °C for new paper, 117 °C for aged paper	172 °C at 1.1% (new insulating materials)	163.5 °C at 1.2% for FR3	160 °C	-	130 °C at 2.5% WCP and 0.2 °C/s	118 °C to 180 °C	-

Several setups for evaluating bubbling phenomena were developed and discussed in the different research works reported in this section. All those experimental models have almost the same components, such as oil and paper as insulating materials, heating elements, and some measuring equipment such as thermocouples, moisture probes, ultra-fast cameras, etc. The existing mechanisms can be divided mainly into two types: sandwiched coils and non-sandwiched ones, as depicted in Figure 4.

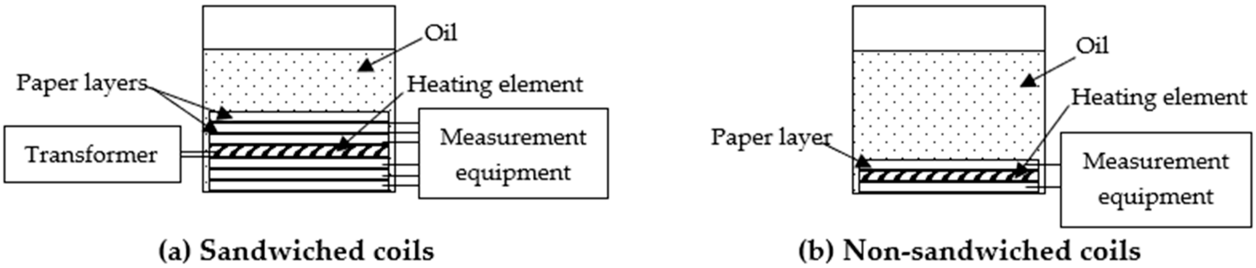

Figure 4. Typical schematic for experimental bubble investigation.

The sandwiched paper model takes into account the thickness of the paper, the diffusion of moisture, and the temperature in the various paper layers.

4. Timeline of Numerical Studies: Bubbling Phenomena

Apart from the experimental models, various numerical models have been developed in the past few years to mathematically evaluate the temperature at which bubbles first appear. Figure 5 shows the numerical models that have been illustrated in chronological order. The evolution and progress of the same follow as below.

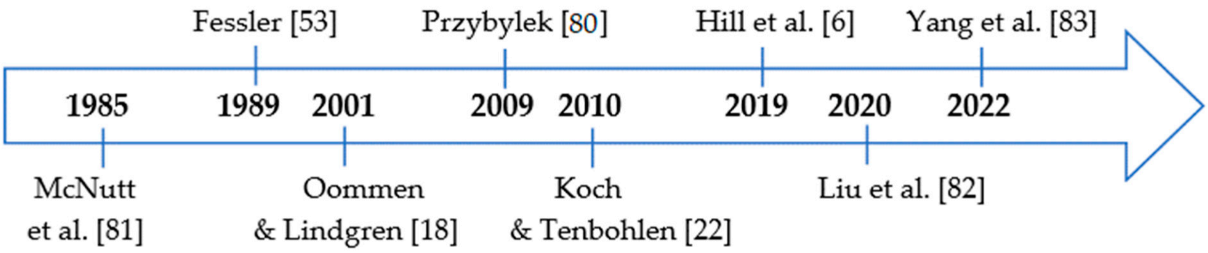

Figure 5. Timeline of mathematical modeling of transformer bubbling [6,18,22,53,80–83].

Several papers explored the bubbling temperature numerically. The first numerical model for assessing the bubble effect was reported by McNutt et al. in 1985 [81]. Fessler et al. [53] later modified their model and proposed a new one. The model used Henry's formula to calculate the partial pressure of each dissolved gas, the equilibrium between the moisture content in cellulose and oil, and the water vapor pressure. However, the model is only appropriate for short-time emergency loading. Based on many experiments, Oommen and Lindgren [18] proposed a mathematical equation to determine the bubbling initiation temperature. Considering the impact of cellulose ageing, Przybylek [80], Koch and Tenbholen [22] adjusted the coefficients in Oommen's equation to propose a new equation for new and aged paper. In 2019, the bubble inception equations were improved by J. P. Hill et al. [6] by modifying the coefficient presented in the equation of Fessler [45] and considering the paper's ageing rate. This is done by introducing the DPv of cellulose. In 2020, Liu et al. [82] and, more recently, Yang et al. [83] created a numerical model to study the evolution of bubbles in oil-paper insulation. This model incorporated various factors, such as the state equation of ideal gas, pressure conditions at the gas-liquid interface, and the formula for calculating saturated vapor pressure. The significant equations of the models are illustrated in Table 5.

Table 5. Bubble inception temperature formulas.

Reference	Formula
Oommen and Lindgren [18]	$\text{BIT} = \left[\frac{6996.7}{22.454} + 1.4495 ln(\text{WCP}) - ln(P)\right] - \left[e^{0.473\text{WCP}} \times \left(\frac{g}{30}\right)^{1.585}\right]$
Przybylek [80]	New paper: $\text{BIT} = \frac{10880}{30.544+3.156\times .ln(\text{WCP})-ln(P)}$ Aged paper: $\text{BIT} = \frac{1.621\times 10^{7}}{3.747+4497\times ln(\text{WCP})+ln(P)}$
Koch and Tenbohlen [22]	New oil, new kraft paper: $\text{BIT} = 195.5\, e^{-0.11186\text{WCP}}$ New oil, new thermally upgraded paper: $\text{BIT} = 273.7\, e^{-0.13718\text{WCP}}$ Aged oil, thermally degraded paper: $\text{BIT} = 178\, e^{-0.07338\text{WCP}}$
Hill et al. [6]	$\text{BIT} = \frac{7064.8}{1.495 ln\left(\frac{1}{9.3\times 10^{-5}\, e^{-\frac{339.1}{DP}}}\right)+1.4959 ln(\text{WCP})-ln(P)}$

The majority of the equations reported in [18,22,80] were developed through a series of laboratory experiments using the experimental mechanisms covered in the previous section. Some models [82,83] were just generated mathematically without any experimental validation. Nevertheless, all the researchers have agreed that the BIT depends mainly on the moisture content of the paper. Several researchers have distinguished between the new and aged papers [22,80]. The BIT as a function of water content in papers reported by various researchers is shown in Figure 6.

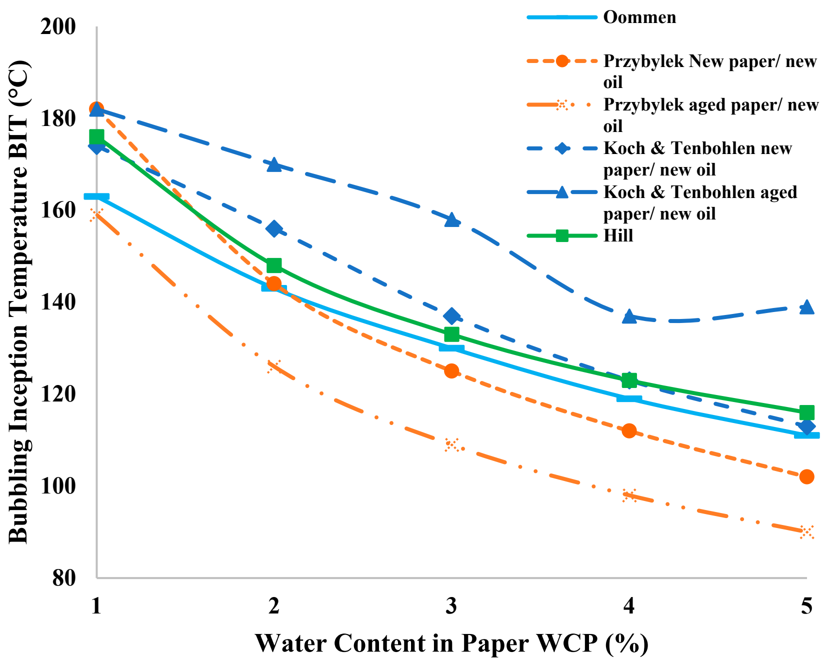

Figure 6. The temperature of bubble effect initiation for different water contents in paper as estimated by various investigators.

For the drawing of the curves presented in Figure 6, the values of "g", "P", and "DP" were taken directly from the cited references. Specifically, for Oommen et al. [18], g was 1% and P was 926 torr. For Przybylek et al. [80], P was 767 torr. For Hill et al. [6], the values of P and DP were not explicitly specified. For that, P and DP were assumed to be 926 torr and 1200, respectively.

Other than water content in paper and oil/paper's degradation, it is also important to note that the BIT depends on many other factors, as discussed in the next section. Additionally, the BIT differs from one study to another, and this is due to the difference in the pressure, the conditions, the type of the investigated materials (paper/oil), and even the methodology of the experiment. Thus, there is no all-case formula to use; it depends on several factors and conditions.

5. Influencing Factors of Bubbling

There are many other parameters to consider than simply the amount of moisture within the solid and fluid insulation. This section reports several key factors that might greatly influence the BIT.

5.1. Temperature

Temperature is one of the most significant parameters that may trigger bubbles in the insulation system. In fact, overloading the transformer increases the temperature inside the insulation system. During an overload, the temperature rise of the paper insulation over the conductor leads to a quick moisture migration into the oil. At a certain temperature, the migrated moisture can be vaporized in the paper or at the paper surface, and water vapor is present in the form of gas bubbles in the mixed phase [84,85]. The impact of temperature on the BIT has been examined in numerous studies. In fact, Oommen et al. [18] found that for a paper moistened at a rate above 2.5%, a temperature of 140 °C can produce bubbles. Przybylek [80] has proven that, for an aged paper (DP_v = 341), a temperature increase of the insulation up to 120 °C can lead to bubble generation. Recall that the IEC standard 60076-7 [78] sets an operational temperature limit of 140 °C. The transformer operates safely without bubbling below 140 °C for 2% of the water content in the paper. This was also suggested by Heinrichs [73].

The temperature rise rate is another important factor in the bubbling phenomenon, as reported in [20,22]. Under the tested conditions, a minimum rate of 3 K/min increase in temperature is necessary to produce bubbles [22]. Furthermore, Gao et al. [20] reported that the BIT inversely correlates to the rate of temperature rise. It is the same finding as in [75]. This is explained by the fact that a temperature rise leads to moisture evaporation in the paper. Hence, several microbubbles aggregate in the pores of the solid insulation when the pressure of some pores on its surface increases and reaches a certain level to overcome the external pressure. This is because the temperature rise increases the energy required to expel bubbles [76]. Thus, the bubbles escape from the surface of the paper. So, the higher the temperature rise rate, the lower the number of bubbles escaping into oil and the BIT.

5.2. Moisture

The research showed that the water content in the paper significantly impacts the bubble initiation temperature. Due to the low moisture affinity of insulating oil, in in-service transformers, moisture mainly resides in their cellulosic insulation, so water in the paper is more impactful on the BIT than water in oil. It increases the capillary internal pressure, which forces the bubble into the oil [22]. This is consistent with extensive experimental results [82]. In fact, Oommen et al. [18] proved that a risk of bubble generation could be present only at high moisture levels. Moreover, Gao et al. [20] and Przybylek [46,81] have studied the effect of water content in the paper on the BIT and noted that an increase in the WCP leads to a decrease in BIT. Recently, a study was done by Wilhelm et al. [21] to evaluate bubbles' evolution under rapid temperature changes, and it was observed that the temperature at which bubbles first appeared dropped as the water content decreased, reaching 55 °C at a WCP of 2.5% and 120 °C at 0.3%. Another point of concern is that the influence of moisture content on BIT is stronger when it is between 2% and 3%. This is the result of saturated vapor pressure, which limits how much water can evaporate in a given amount of time. Higher moisture content causes the vapor to saturate more quickly and has less impact on the BIT [82].

5.3. Insulation Degradation

The paper ageing is characterized by the (DP_v) value, which describes the average number of cellulose monomers per chain in the solid insulation. Ageing is a chemical process that occurs over time due to exposure to various environmental factors, such as humidity, temperature, etc. The breakdown of the bond 1,4-β-glycosidic linkages of cellulose, which are responsible for the structural integrity of the paper, reduces the

DPv [86]. The degradation has an impact on the quantity and distribution of capillaries and pores on the paper surface as well as the paper's hydrophilicity. This significantly influences the BIT. The presence of impurities and degradation by-products can lower the energy needed for bubble inception and supply nucleation sites. In fact, the decomposition of the paper itself produces moisture [76]. Only a few studies have examined the impact of paper ageing [22,75,80]. These experiments have not yielded a clear conclusion. Studies [22,80] tested fresh and used paper and found contrasting BIT results. BIT was reported to decrease with ageing in [80], whereas [22] revealed the opposite, presumably as a result of hornification. During hornification, the OH groups in cellulose chains saturate each other as the paper ages and is exposed to high temperatures, and even after being re-moisturized, the linked microfibrils of dry cellulose no longer react [22]. This reduces the number, diameter, and volume of pores and capillaries, resulting in a higher bubble inception temperature. This is generally referred to as the hornification phenomenon and is illustrated in Figure 7.

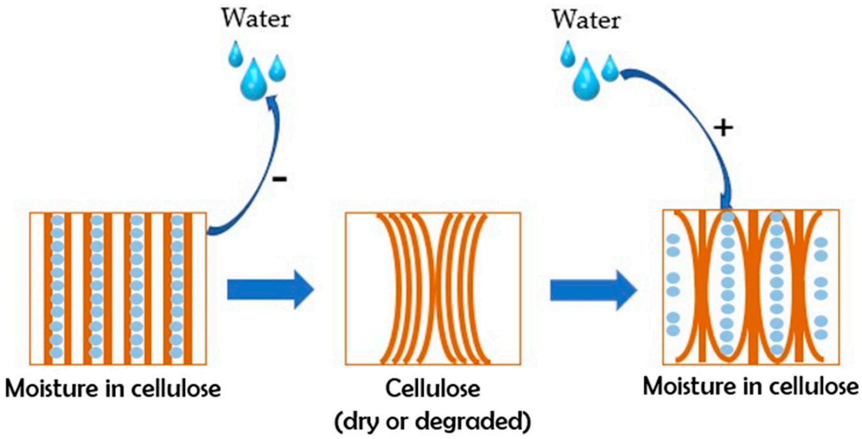

Figure 7. Illustration of the hornification phenomenon of microfibrils during thermal ageing of the paper.

According to [80], with a drop of 50% in the DP_v, the BIT for kraft paper falls below 140 °C. Reference [22] reported that BIT of TUK paper is higher than that of new kraft paper. Zhao et al. [75] have studied the ageing effect on the BIT by observing the generation of the bubble in 3 types of pressboard samples ageing (0, 10, and 25 days). The number of bubbles and their intensity have decreased as thermal ageing days rise. This work makes it abundantly evident that for samples with the same moisture content, the BIT increases with ageing time. For these pressboard samples, scanning electron microscopy was performed. This demonstrated that thermal ageing causes the paper fibers to get saturated and polymerized with one another, which reduces the number and diameter of capillaries and pores between the fibers, thus preventing the bubbles from escaping. Therefore, the bubble effect is inhibited by thermal ageing, which is aligned with Koch and Tenbohlen's study [22]. Recently, [87] has numerically studied the inception temperature of bubbles for aged and new insulating systems (paper/oil). It has been reported that the BIT in aged paper is lower than that of the new paper. After these contrasting findings, the relationship between paper degradation and temperature is still ambiguous.

Not only the age of the paper insulation but also the age of the liquid insulation is assessed in [22]. In these investigations, a new mineral oil (total acid number (TAN) = 0.016 mg KOH/g) is compared to a service-aged mineral oil (TAN = 0.48 mg KOH/g). It is to be recalled that the degradation of the liquid insulation may be monitored through its acidity value, dielectric dissipation factor, or interfacial or surface tension value, among others [88,89]. The literature indicates that the BIT decreases as acidity increases [76]. This can be explained by the fact that some of the acids from the oil is likely to have migrated into the paper. This may have reduced the energy needed to desorb moisture from the paper.

It is also crucial to note that the presence of acids decreased the surface tension of the oil, which decreased the energy needed to produce a bubble [76]. It is interesting to note that the moisture saturation limit of oil increases with ageing. As more moisture may transfer from paper to oil, it would be expected that this would raise the BIT [76]. So oil ageing also has an impact on BIT and they are inversely proportional, as mentioned in some references such as [22,87]. However, in [90], it is reported that the difference between the BIT in fresh oil and aged oil is not too drastic compared to the effect of paper ageing. Despite that, very little is known about the influence of oil degradation on the bubble inception temperature. Further research is needed to understand the impact of the paper-oil degradation on the bubbling inception temperature.

5.4. Thickness of the Paper

The thickness of the solid insulation is also important in the generation of bubbles in the transformer's solid insulation. For instance, Garcia et al. [66] performed experimental tests and proposed mathematical equations to analyze the correlation between cellulose, water content, and thickness.

Recently, Zhao et al. [75] investigated the thickness of paper or multi-layering solid insulation. This work considered four test samples (with one, two, three, and four layers). They reported that the BIT for four insulation paper layers is 8.1 °C lower than that for one layer at a temperature rise rate of 3.3 K/min. Thus, bubbles tend to form at a lower temperature for a monolayer sample than for a multilayer sample. So generally, it is more difficult for moisture to migrate to the surface and produce a bubble in thicker layers [17].

In the study of the effect of layering on bubble formation, Zhao [75] emphasized a delamination phenomenon. A difference in the color of the paper is observed before the bubbles appear on the surface of the paper. During a sudden temperature increase, a lot of water vapor concentrates between the layers of insulating paper, gradually expanding the delamination area and causing a large number of bubbles to pop out of the paper edge.

Apart from the thickness, the quality of the paper also impacts the formation of the bubble. The surface roughness of the solid insulation could decrease the energy needed to overcome the free energy barrier for bubble formation by increasing the contact angle [68].

5.5. Type of Oil

As previously stated, the oil type has an impact on the bubbling temperature. This is explained by the difference in the microstructure of mineral oils and esters (natural and synthetic). In fact, many factors can contribute to this difference, such as the fluid's thermochemical properties (thermal conductivity, viscosity, heat capacity, and density) and the effects of ageing, such as surface tension and acidity. Indeed, it has been reported [82] that the effect of oil parameters such as surface tension and density has an impact on the bubble formation temperature. The surface tension is a crucial factor in determining the energy needed to create and maintain a bubble. Consequently, some researchers provided another justification that would explain the difference in BIT when the liquid insulation quality changes. According to literature, the most significant properties that determine the cooling capability of the liquid insulation are thermal conductivity, specific heat, viscosity, and density [11].

These parameters are worthy of consideration because they affect the cooling performance of the transformer. However, a limited number of studies have analyzed the influence of the above-mentioned factors on the BIT. Perkasa et al. [11,78] have evaluated the impact of the oil density on the BIT. Since the density of vegetable oil is higher than that of mineral oil, it was found that the bubbling temperature in vegetable oil is higher by 6–13 °C for a water content ranging from 1 to 6%. Esters have a higher oil hydrostatic pressure on the paper, thus making bubble formation more challenging and requiring a higher temperature [11]. Therefore, the hydrostatic pressure exerted on the winding surfaces affects bubble formation.

Esters are hygroscopic, meaning they can absorb considerably more moisture than petroleum-derived oils. So, under the same ambient conditions and with the same total amount of water, the water content in paper impregnated with esters is slightly lower than that in mineral oil. This increases the BIT for esters compared to mineral oil.

The diameter of the bubbles is a function of material density and can vary from 0.01 to 7 mm [22]. As the temperature rises, water and gases flow into the bubble germ, expanding it. A stable bubble forms if the internal pressure can overcome all opposing forces present in the material, including the capillary force, the interfacial tension, the friction in the fibers, and the external pressure of the liquid. After that, the temperature must rise quickly to allow the water to evaporate and generate bubbles filled with water vapor [22].

Liu et al. [82] reported that the surface tension, density, and oil depth all have an impact on the bubbling temperature. The oil pressure on the bubble surface, which is defined by oil depth and density, and the atmospheric pressure make up the external pressure exerted on the bubble. Therefore, the larger the external pressure, the lower the initial radius of the bubble and the higher the BIT. The BIT rises by around 1 °C for every 0.5 m increase in oil depth. This is similar to how the increased density or surface tension of the insulating oil causes higher pressure and therefore BIT [82].

In addition, Zhao et al. [75] investigated the bubble effect temperature in natural esters while taking into account several factors such as the number of paper layers, temperature rise rate, and paper ageing. The higher BIT value for esters is justified by the fact that vegetable oils are more hygroscopic than mineral oils, so they dissolve much more water from paper and resist more bubble formation. Furthermore, the higher viscosity of ester fluids would probably cause a transformer to operate at a temperature slightly higher than that at which it would operate if filled with mineral oil [90].

5.6. Type of Paper

In addition to these variables, the paper type also has an impact on the BIT. Investigations have mostly concentrated on kraft paper. Therefore, one would expect that different types of solid insulation would have different BIT performance. Two studies [10,22] have looked at different types of solid insulation. Reference [10] addressed the aramid insulation, whereas [23] used TUK. Both studies found substantial differences in the BIT compared to kraft paper when assessing them at the same moisture level. This is typically explained by the hygroscopicity of aramid (meta-aramid) and the thermostabilization done on TUK. The addition of nitrogen stabilizing agents by the Insuldur process was pointed out as the reason for the reduction in hydrophilicity of the insulation [76,90]. The literature lacks information about the impact of paper type on the bubbling initiation temperature. Further research into the solid-insulating influence on BIT is therefore necessary.

6. Challenges and Perspectives

Despite the significant progress made in the understanding of bubbling phenomena in liquid-filled transformers, there are still numerous challenges and perspectives for further research in this area. The following are some of the key challenges and perspectives that require attention:

- Development of accurate and reliable methods for moisture assessment in operational transformers: current methods for determining moisture in paper rely on equilibrium curves, or KFT, and assume an equilibrium state of moisture and temperature inside the transformer. However, the actual service conditions of transformers involve continuous fluctuations in loading, temperature, and other factors. Therefore, the development of accurate and reliable methods for monitoring moisture in operational transformers is critical for the effective management of transformer insulation systems;
- Investigation of the impact of transformer design on bubbling phenomena: transformer design features, such as winding type, winding arrangement, and core type, can affect the thermal and moisture behavior of the insulation system, which in turn can impact the bubbling phenomenon. Further research is necessary to explore the

relationship between transformer design and the occurrence of bubbling phenomena in insulation systems;
- Investigation of the effects of insulation materials: while the effect of paper aging on bubbling has been studied to some extent, the impact of various insulation materials on bubbling phenomena is still largely unknown. Further research on the effects of different insulation materials, taking into account the moisture content, transformer temperatures, and loading profiles, is necessary to gain a more comprehensive understanding of the bubbling phenomenon;
- Exploration of alternative fluids: most of the existing research on bubbling phenomena has been focused on mineral oil. There is a need for further investigation into bubbling phenomena in mixed oils, silicon oils, and natural esters (regenerated or reclaimed oil). These fluids are less expensive than ester fluids and have superior electrical, dielectric, and operational characteristics than mineral oil [90–94]. Furthermore, exploring ester admixtures in mineral oil for the bubbling phenomenon could lead to better insulation system performance at higher temperatures;
- Mathematical modeling of bubbling inception temperature in alternative fluids: theoretically, no research has reported an exact equation for bubbling inception temperature in esters. All the developed equations were for mineral oil. Therefore, generating a mathematical formula for BIT in alternative fluids and examining the effects of pressure on BIT could provide a more accurate and comprehensive understanding of the bubbling phenomenon;
- Investigation of nanoparticle-enhanced insulation systems: nanoparticles have been investigated with regard to the improvement of the dielectric properties of transformer insulation systems [95]. Further research on the use of nanoparticles to enhance insulation paper dielectric characteristics, moisture behavior, and thermal performance could prove useful in mitigating the effects of bubbling in transformer insulation systems;
- Development of advanced monitoring and diagnosis techniques: advanced monitoring and diagnosis techniques were used to detect and diagnose transformer faults. Further research is necessary to explore the potential of these techniques for early detection and diagnosis of bubbling phenomena, as well as the development of new techniques that can provide more accurate and reliable information on the condition of transformer insulation systems;
- Assessment of the impact of bubbling on transformer performance and reliability: bubbling phenomena can impact transformer performance and reliability by causing insulation degradation, overheating, and reduced lifetime. Further research is necessary to quantitatively assess the impact of bubbling on transformer performance and reliability, as well as to develop models that can predict the lifetime of transformers under different bubbling scenarios.

Overall, these challenges and perspectives demonstrate the need for continued research in the area of bubbling phenomena in transformer insulation systems. By addressing these challenges and exploring these perspectives, researchers can gain a more comprehensive understanding of the bubbling phenomenon and develop effective mitigation strategies that can improve transformer performance and reliability.

7. Conclusions

The bubbling phenomenon in liquid-filled transformers is a critical issue that can significantly impact the performance and reliability of this equipment. The presence of moisture in transformer insulation systems is a primary cause of bubbling, and various assessment methods were developed to detect and quantify this moisture accurately.

The present paper provides a comprehensive overview of the state of the art on the bubbling phenomenon in liquid-filled transformers. Throughout the discussion on the various influencing factors of bubbling, the timeline of experimental and numerical studies, and the challenges and discussions surrounding this issue, we highlighted the interest in pursuing research and development in this area.

Indeed, further research is essential to gain a deeper understanding of the mechanisms behind bubbling and develop more accurate and reliable assessment methods for detecting and quantifying moisture in transformer insulation systems. With the ongoing advancements in this area, we can ensure the safe and reliable operation of liquid-filled transformers, a crucial component in many electrical systems.

Overall, the present paper emphasizes the importance of understanding the bubbling phenomenon in liquid-filled transformers and serves as a valuable resource for researchers.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

BIT	Bubbling inception temperature (°C)
d	Thickness of the solid insulation (mm)
D	Diffusion coefficient ($m^2 \cdot s^{-1}$)
D_G	Preexponential factor ($m^2 \cdot s^{-1}$)
DP_v	Degree of polymerization
E	Required energy to break chemical bonds (kJ/mol)
g	Gas content of oil (%)
P	Pressure (kPa)
NTUK	Non-thermally upgraded kraft-paper
T	Actual temperature (K)
TUK	Thermally upgraded kraft-paper
WCP	Water content in paper (%)
τ	Diffusion time constant (s)

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