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Bubble Formation in Power Transformers – a Potential Risk for the Future Network Reliability?

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SUMMARY

Achieving the UKs ambitious Net-Zero targets by 2050 will depend mostly on the integration of low-carbon technologies which will affect both generation and consumption of electricity. Electrification of heat and transport which are currently mainly relying on fossil fuels is inevitable. Those changes in generation and demand are likely to cause less predictable and highly fluctuant load patterns and require flexible operating strategies in the power network, which could also put additional stress on the already aged fleet of network assets.

The reliability of the system is strongly connected to the dependable operation of transformers and failures could be catastrophic and severely affect the network resulting in huge financial losses. Bubble formation from winding insulation is one of the transformer failure mechanisms which is related to rapid temperature rise due to severe short-term over-loading conditions. It could cause transformer failure from flash over when they are moving into an area of high electrical field strength. The risk of bubble formation is one of the main loading constraints for transformers and understanding the fundamentals behind bubble formation mechanisms will help to utilise short-term overloading, if necessary, with minimum risks.

The well-known constraint of a hot-spot temperature of 140 °C with a respective water content of around 2% in the winding insulation paper is based on the bubble formation risk linked to a formula provided in IEC and IEEE standards. However, results in the literature provide a wide range of bubble formation temperature even for same water content in paper. This could be caused by a variety of possible impact parameters such as the temperature rise, material condition, the test setups/procedures and measurement techniques. Due to lack of information about the test conditions and the setups, a comparison of the different results is hardly possible even for the same material combination. This shows the limitation of available data to be applied for future loading scenarios or alternative insulating materials when minimising the risk of transformer failure. A coherent study with a thermally validated test setup would be beneficial to study the impact of different parameters and future energy scenarios on bubble formation of transformer insulation systems.

This paper introduces the development of a small-scale test setup along with a testing procedure to investigate the bubble formation of transformer insulation systems. The system design and test procedure has been verified through multiple studies on the temperature and water content in the system. Furthermore, initial tests have confirmed that results are in line with literature and the system is suitable to perform a coherent study on the impact of various parameters such as the temperature rise, material type or condition. Those results will help to answer the question if bubble formation is a potential risk for power transformers under future energy scenarios.

KEYWORDS

Transformer, Overload, Temperature, Failure, Bubble, Water, Paper, Ageing, Winding, Insulation

1. Introduction

The UK has set an ambitious target to reduce its greenhouse gas emissions to net zero by 2050. This goal requires the integration of multiple low carbon technologies such as wind, solar and other renewable energy sources into the grid to fulfil the required electricity demand. Another area, which is currently relying mainly on fossil fuels and hence awaiting major changes is the electrification/decarbonisation of heat and transportation. These changes in generation and demand are likely to create less predictable and highly fluctuating load patterns in the power network, which could also put stress on the already aged fleet of network assets. Furthermore, meeting such a demand may also require flexible operating strategies.

Transformers are an essential part in the electricity network and the reliability of the system is strongly connected to their dependable operation. Failures could be catastrophic and severely affect the network reliability resulting in huge financial losses. Bubble formation from winding insulation is one of the transformer failure mechanisms which is related to rapid temperature rise due to severe short-term over-loading conditions. These bubbles, if moving into an area of a high electric field, can cause transformer failure through flash over. Therefore, risk of bubble formation is one of the main loading constraints for transformers and understanding the fundamentals behind bubble formation mechanisms will help to utilise short-term overloading of transformers, if necessary, with minimum risks.

This paper summarises the current understanding on bubble formation from transformer insulation systems and discuss the knowledge gaps which needs to be filled to study the impact of future energy scenarios on the bubble formation process. Next, it introduces a small-scale test tube based setup which has been developed to perform a coherent study on possible future impact parameters such as the temperature rise and the influence of different alternative insulating materials and their condition. The suitability of the setup will be validated according to the two main impact parameters on bubble formation which are the temperature and water content in paper. Furthermore, initial tests with mineral oil and non-thermally upgraded Kraft paper have been performed to validate the suitability of the test setup to study impact parameters on the bubble formation process.

2. Bubble formation temperature and operating limitations

Bubble formation from winding insulation in transformer is a random process depending on loading and insulation conditions which could lead to failure of the unit. In consequence, the outage of the asset strongly impacts the grid reliability and can lead to greater financial losses.

To prevent such scenarios, IEC and IEEE standards [1, 2] provide guidelines on transformer loading conditions under both normal and emergency operating conditions. A maximum hot-spot temperature of 140 °C is mentioned in these guidelines as the temperature limitation which could lead to bubble formation in transformer winding insulation. In addition, an empirically determined formula [2-4] is provided to calculate the bubble formation temperature according to the water content in paper, system pressure and dissolved gas for an insulation combination of mineral oil and non-thermally upgraded Kraft paper. Various studies have shown that among the others, water content to be the main impact parameter on bubble formation [4-9].

Applying the formula on the provided temperature limitation of 140 °C, it is resulting in a water content of paper of around 2%. This value is considered as representative for an aged transformer insulation. The closely linked temperature and water content in paper limit is a well-known benchmark in the field of bubble formation of transformer insulation systems and emphasises the importance of a thorough understanding of both parameters in a transformer to prevent it from fatal consequences.

A transformer is a highly dynamic system where the temperature is continuously changing depending on the loading conditions. Such temperature variations also impact material parameters and dynamics of chemicals between liquid and solid insulation. Furthermore, windings have a non-uniform temperature distribution with hot-spot being typically at the top part of the windings.

Focusing on the water content in paper as one of the main impact parameters on bubble formation, its content in paper is highly affected from the local temperature within the system. The temperature and water content in paper are negatively correlated, and hence paper at a higher temperature will contain less water and vice versa. In addition, a chemical equilibrium is hardly reached in a transformer and water continuously migrate between paper and liquid. All these factors hinder the ability to obtain a bubble formation risk factor based on the equation provided in standards. In addition to constant loading, future scenarios could include much more fluctuations and it is yet not fully clear what the impact of such fluctuating loading conditions on the risk of bubble formation is. This questions the global applicability of such an equation for future scenarios where rapid loading conditions, new insulation materials, and aged insulation systems will also need to be considered.

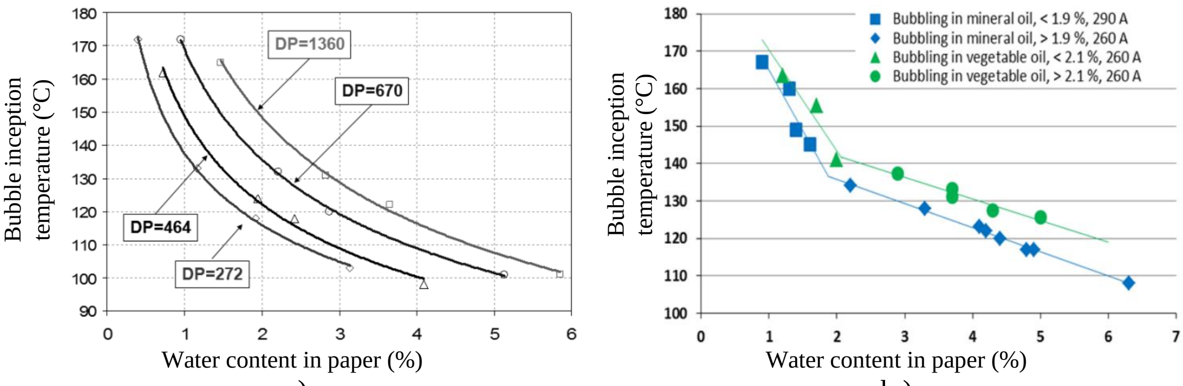
3. Bubble formation impact parameters

For several decades, researchers have studied the bubble inception phenomenon from liquid-paper insulation systems of transformers. According to findings from [8, 10] the development of bubbles depends on the existence of bubble germs, which originate from dissolved particles, exist in microcapillaries or are stable microbubbles. With an increasing temperature gasses and water diffuse into the bubble germ, leading to an increase in volume. In consequence, when the internal bubble pressure overcomes the external pressure and hampering forces inside the material, a stable bubble could arise. This process requires a rapid temperature increase leading to the evaporation of water in a short time where the volume of the water vapour exceeds that of liquid water by 1700 times [8]. In consequence, the bubbles are leading to voids in the insulating material and could cause harm due to partial discharges or flash over, when occurring or moving into an area of high electric field strength.

Most of the available studies have been performed with the most common insulating material combination of non-thermally upgraded Kraft paper and mineral oil. Studies proposed several impact parameters such as [8]:

- Amount of evaporable water in paper
- Microstructure of the paper
- Surface tension
- Gradient of temperature rise
- Extrinsic pressure, static pressure in the liquid
- Dissolved gasses in oil

Figure 1 shows two examples of parameters with a possible impact on the bubble formation temperature depending on the water content in paper. In a.) the condition of Kraft paper is varied with respect to the degree of polymerisation (DP) in combination with mineral oil. The impact of mineral and vegetable oil in combination with Kraft paper is compared in b.). Furthermore, a thorough analysis on investigated parameters and current limitations of data has been carried out in [11, 12].



a.) b.)

Figure 1: a.) Impact of the degree of polymerisation (DP) and b.) alternative insulating liquids on the bubble formation temperature, adapted from [6, 7].

Focusing on the constraint of a hot-spot temperature of 140 °C and 2% water content in paper, as considered critically for bubble formation, the literature results vary from nearly 140 °C to 155 °C. This range emphasises the possible impact of other parameters within the same insulating material combination and could be representative for the differences in a transformer fleet. Hence, the applicability of a single temperature value based on the water content in paper can be already questioned for the most common insulating material combination.

An additional and often overlooked factor is the difference between the test setups and procedures used in the literature such as the insulation thickness, observation method or measurement techniques which are likely to contribute to the temperature difference and hasn't fully understood yet. The rate of temperature rise is another important parameter that could be vital in future energy scenarios. The lack of information on such crucial parameters challenges the comparability between literatures to propose updated models to evaluate the potential risk of bubble formation.

Consequently, a coherent study of the impact from different parameters on the bubble formation of transformer insulation systems, such as the loading or alternative insulating materials seem to be necessary to evaluate possible future scenarios. Ideally it is performed with at validated conditions with the same test setup to guarantee the comparability and draw a meaningful conclusion regarding the potential risk of bubble formation for the network reliability.

4. Small-scale test tube setup

A small-scale test setup has been developed to study bubble formation of transformer insulation systems inspired by a similar experiment from Heinrichs [13] in the late 1970s. The proposed test system, as shown in Figure 2, is based on a glass test tube with a diameter of 25 mm and a length of 150 mm. It is filled with 40 ml of insulating liquid and a 90 mm long cartridge heater (220 V, 100 W) is immersed and kept centred from washers on top (85 mm) and bottom (0 mm). The system has therefore an axis-symmetric design with respect to the cartridge heater centre and it provides similar heating conditions around the surface circumference. A hollow silicone stopper attached on top of the glass tube ensures the fixation of the wires to provide further support while maintaining the headspace at ambient pressure during the test. The cartridge heater itself is wrapped with insulating paper in the designated bubble observation area (25-80 mm). In addition, a thermocouple is attached at 15 mm which will be used for reference temperature measurements. The test system is heated by applying a voltage step to the cartridge heater through a variac. Two video cameras placed in opposite directions are used to record any bubbles formed during tests. This small-scale test tube setup provides even conditions around the circumference and allows a quick and easy change of the test conditions.

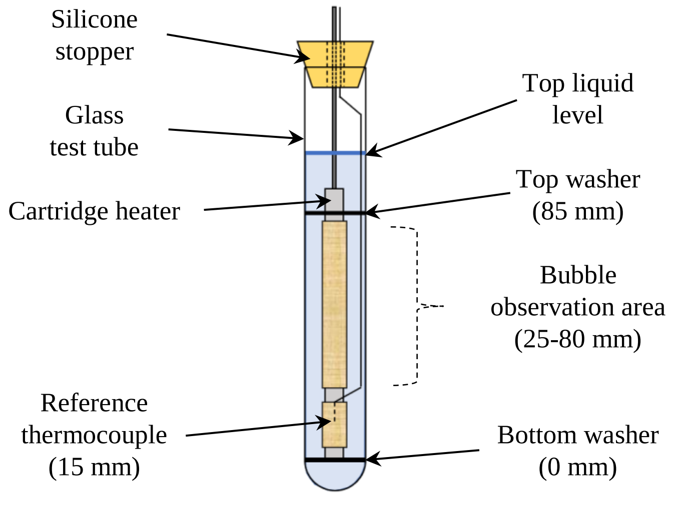


Figure 2: Test setup sketch.

5. Thermal validation of the small-scale test tube setup

Temperature is one of the key parameters in the bubble formation process. Therefore, it is important to know the thermal profile of both cartridge heater and liquid. The thermal profile of the test setup has been obtained from multiple measurements within the tests tube as it is shown in Figure 3. Temperature on the cartridge heater surface (below the paper layers), on the paper surface, in-between paper surface and glass surface, and on the glass surface was measured at seven levels of height along the test tube, resulting in 28 locations. Each of the measurements has been performed individually to reduce any impact of the immersed thermocouples (rod type with a diameter of 0.5 mm) on the liquid flow or cartridge heater surface. This procedure was possible due to the high repeatability of the individual heating cycles which is shown in Section 6.

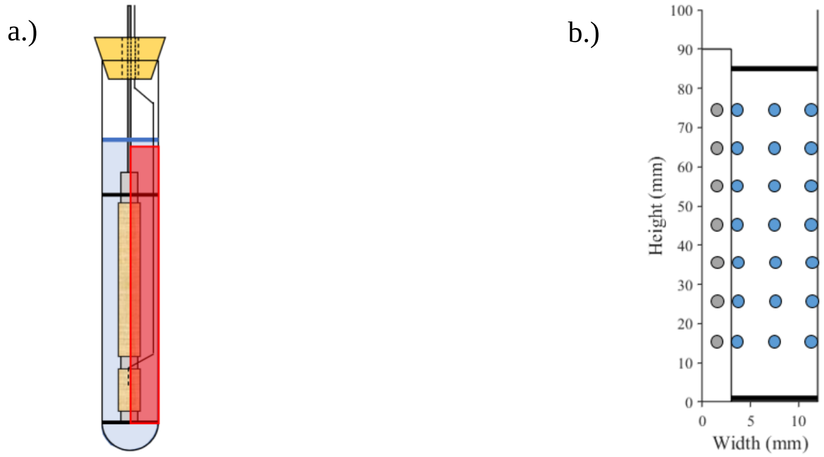


Figure 3: a.) Sketch of the test setup with highlighted area for the illustration b.) of the individual locations from the thermocouples.

A heat map, created from the measurements, in Figure 4 shows the time development of the temperature distribution within the sample. The cartridge heater shows a non-uniform temperature profile with a distinct hottest area between 45 mm and 60 mm, which could be the most likely area for bubble inception. This non-uniform temperature profile of the heater hinders the possibility of a direct temperature measurement during the bubble inception process. Therefore, a two-step procedure as shown in Section 6 was used to obtain the temperature at the location of bubble formation in a separate test.

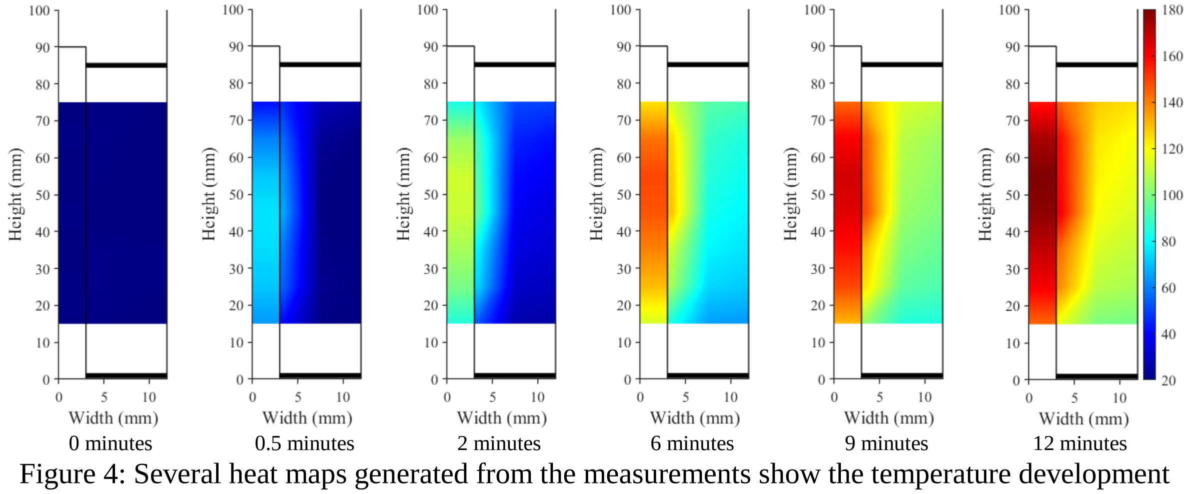


Figure 4: Several heat maps generated from the measurements show the temperature development within the sample during a heating cycle.

6. Test procedure to obtain the bubble formation temperature

The non-uniform thermal profile along cartridge heater has led to the introduction of an indirect temperature measurement method in which the bubble formation temperature is obtained in two steps. The bubble formation time and the location are observed during the first step and the temperature at the location where the bubble was formed is measured during the second step. In addition, a reference thermocouple attached at 15 mm is used to validate repeatability of the thermal profile between two tests. Details of the steps are as below.

<u>Step1: Bubble formation observation</u>
A voltage step will be applied to cause the first heating cycle where bubble formation will be observed with support of the video cameras and the temperature at the reference location (15 mm) is recorded with a data logger. The power supply will be switched off as soon as the initial bubble formation is observed, and a paper sample will be removed for water content measurement in paper at the time of bubble formation. The exact time and location of bubble formation is then obtained from the video recordings.

<u>Transition:</u>
When the system is cooled down a thermocouple will be attached to the cartridge heater surface, under the paper layers which have been replaced from the initial ones, at the location where initial bubble formation has been spotted in step one.

<u>Step 2: Temperature measurement</u>
The sample is heated using the same voltage step while recording the temperature at the location of bubble formation and the reference point (15 mm), for a duration higher than the one for bubble formation in step one.

<u>Correlation of the results from each individual step:</u>
The temperature profiles, recorded at the reference location (15 mm), will be used to validate the repeatability between the two steps as in Figure 5. Once validated, time to bubble formation obtained from step one is used to estimate the bubble formation temperature from the temperature measurement in step two as in Figure 6.

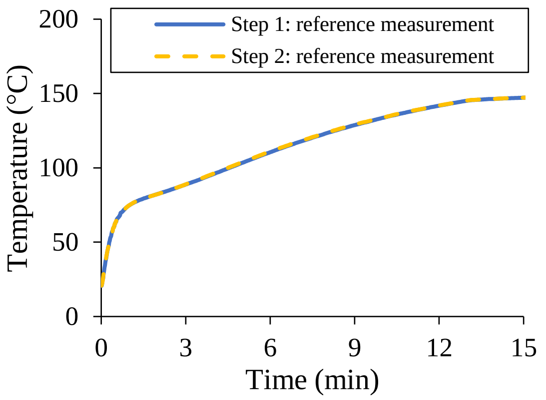


Figure 5: Comparison of the reference measurements from step one and step two to highlight the repeatability.

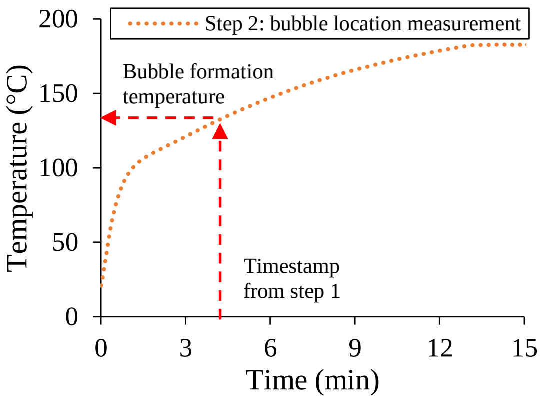


Figure 6: Correlation of measurement step one and step two to obtain the temperature at the bubble formation location.

The thermal profile of each cartridge heater is obtained prior to the tests and any heater with deviations were discarded. Furthermore, multiple measurements from single cartridge heaters were conducted to validate the repeatability of individual heater. Figure 7 shows the temperature profile at 15 mm and 50 mm of those measurements at different days and indicates a maximum standard deviation of 1 °C. In addition, tests were conducted with different heaters where a maximum standard deviation of 2 °C could be obtained.

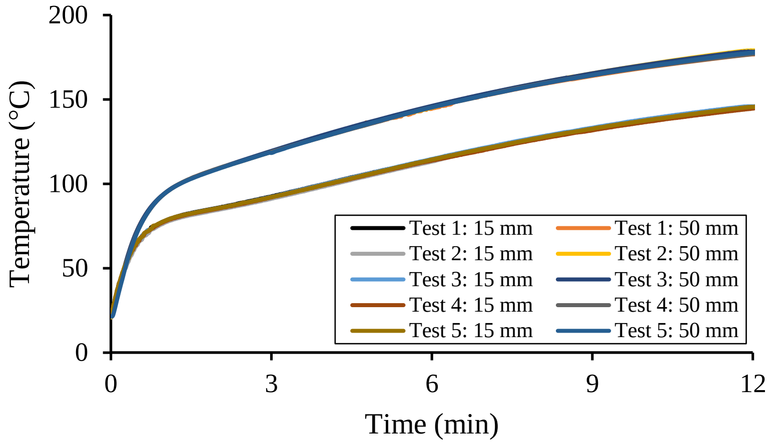


Figure 7: Temperature profiles measured at different days and locations show the high repeatability.

7. Moisture measurement technique and validation

Apart from the temperature, water content in paper is a key influence factor on the bubble formation process. Similar to the thermal profile of the test setup, a thorough understanding and measurement procedure is required to optimise the outcome of the study. Most literature ignore the dynamics of water in the system and assume that the water content at the time of bubble formation to be same as the initial water content [4, 6]. However, preliminary studies with the current system indicate a considerable moisture migration during the heating process and hence water content right after bubble formation in step one was selected for the water content measurement in paper.

Therefore, the paper sample will be taken immediately after the bubble formation has been detected and the power supply was switched off. The paper sample for water content measurement will be taken from the innermost layer as the bubbles are formed in this layer. This process is done as fast as possible to avoid any impact from ambient conditions. Moisture measurement conducted with multiple samples just before and after bubble formation confirmed that the bubble formation process has a negligible impact on the water content of paper, which could be due to the avoidance of excessive bubble formation by terminating the test at the first observation of a bubble. In addition, the volume of water in the gaseous phase is around 1700 times higher than in the liquid phase [8] and hence multiple bubbles could be a result of much smaller volume of liquid water.

Similar to the impact of the location of temperature measurement, the location of the sample obtained for water content was studied by measuring the water content at multiple locations along the cartridge heater height. Figure 8 shows the water content in paper at seven locations along the cartridge height, measured from a sample underwent heating. The hottest area (45 mm to 60 mm) has the lowest water content and is constant in the region. This confirms that the water content measurement from any paper sample obtained from the hottest region will be representative of the water content in the hottest area. Therefore, a single large sample obtained from this region was used for the water content measurement. Samples where bubble formation happens outside this area will be discarded.

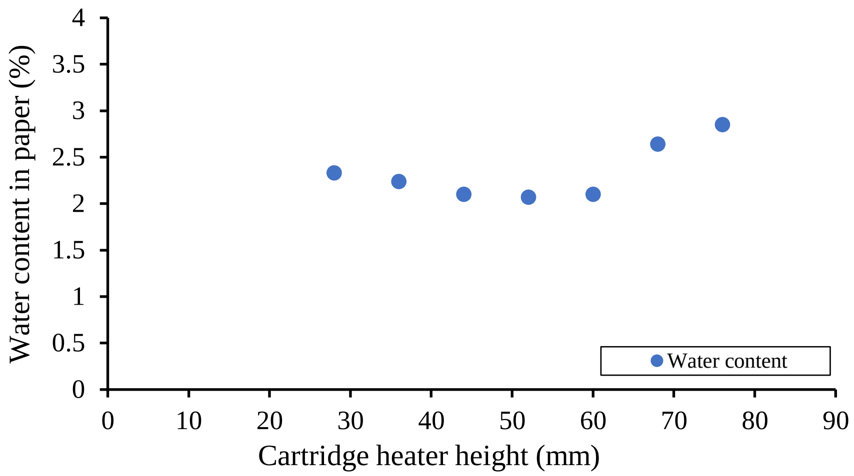


Figure 8: Water content in paper of the observation area after being heated.

8. Preliminary tests

Preliminary tests aim to verify the suitability of the test setup for the measurement of the bubble formation temperature according to the proposed test setup design, procedure, and measurement method.

For the preliminary bubble formation tests, five samples have been prepared according to the described design with non-thermally upgraded Kraft paper [14] and mineral oil [15]. They have been conditioned with a high initial water content above 5% to increase the chance to observe bubble formation. Two of the samples were used to verify the even distribution of the water content along the paper. The remaining three samples were used for the bubble formation tests by following the procedure described Section 6 and 7. The results of the tests can be seen in Table 1.

Table 1: Results from preliminary tests.

Sample number	Location on cartridge heater (mm)	Time to bubble inception (min)	Bubble inception temperature (°C)	Water content in paper (%)
1.	60	5.9	153	2.30
2.	53	3.5	132	3.86
3.	56	8.7	175	1.45

The results show that the bubble inception locations are within the hottest area of the cartridge heater, which would justify the assumption of the prime inception location. The time of bubble formation varies widely and hence the bubble inception temperature. Water content measured at bubble inception was lower than the initial water content in all three samples, which further confirms the moisture dynamics in the system. However, all three results follow the general trend of an increase in bubble inception temperature with a decrease in water content in paper. Results indicate that there could be still additional factors such as the surface structure of paper which could impact the randomness in the bubble formation process.

Figure 9 shows the results from the preliminary tests plotted together with results from literature. The results match well with the available data and prove the suitability of the developed test setup and measurement method for further studies.

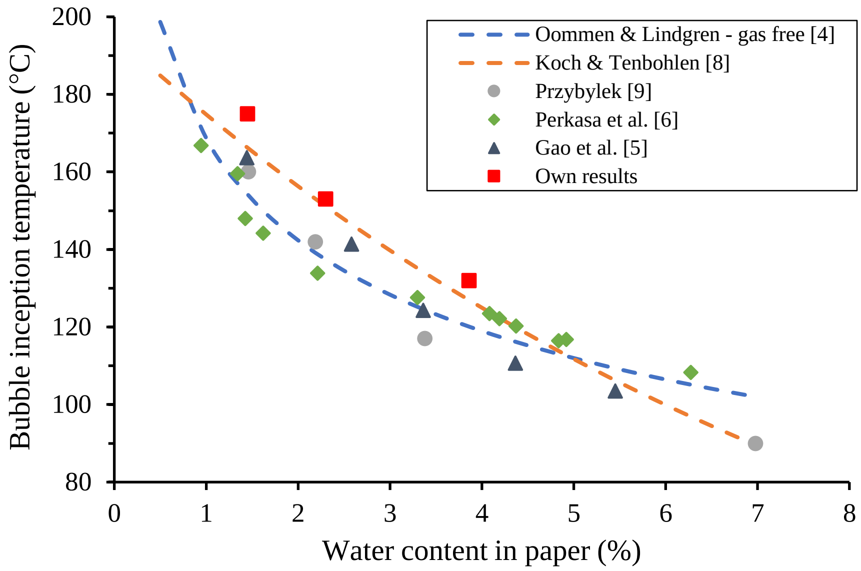


Figure 9: Comparison of the obtained results from own tests with the available data from the literature for a combination of non-thermally upgraded Kraft paper and mineral oil.

9. Conclusion

Changes to the electrical grid are inevitable for the UK to reach the ambitious Net-Zero targets by 2050. This includes the integration of various low carbon technologies and renewable energy resources into the grid. In consequence, the grid is likely to change in terms of supply and demand which could lead to less predictable and highly fluctuating load patterns. Assets, such as transformers, might suffer from this additional stress and could be prone to failure due to their already aged condition. A potential failure cause, when rapidly overloaded, could be bubble formation from winding insulation. The current constraint for bubble formation is related to a hot-spot temperature of 140 °C with a respective water content in the winding insulating of around 2%. However, available results regarding this water content in paper vary widely and are hardly comparable due to different test setups and a lack of applied test parameters. Consequently, the applicability of a single temperature value to cover potential future scenarios, such as the impact of load changes or insulating material type and condition, is questionable. A coherent study, performed with a validated test setup, is therefore key to investigate the impact of different future scenarios to shed light in this research field.

This paper introduces the development of a small-scale test tube based setup with a cartridge heater to study bubble formation of transformer insulation systems. It has been validated for the two most critical impact parameters on bubble formation which are temperature and water content in paper. First, a detailed temperature mapping was conducted on the setup which indicated a non-uniform thermal profile with a distinct hottest area along the cartridge heater. Based on those results an indirect temperature measurement has been introduced to avoid any impact during the test until bubble formation is observed. In addition, a new water content in paper measurement strategy has been introduced by measuring the water content shortly after the bubble observation to account for moisture dynamics in the system during the heating process.

Preliminary results have matched well with the available literature which validates the suitability of the test setup to investigate the bubble formation of transformer insulation systems. The system will be used to study impact parameters on bubble formation such as the temperature rise, insulation material type, thickness and ageing condition which will help to answer the question if bubble formation is a potential risk for the future network reliability.

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