

**Bubble Formation in Vegetable Oil-filled Power Transformers** 

Caesar Yudha Perkasa Bachelor of Engineering (with Honours)

A thesis submitted for the degree of Master of Engineering Science (Research) at Monash University in 2018 Department of Electrical and Computer Systems Engineering

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### Abstract

It is important to understand bubble formation during transformer overload or its initial energisation, as it can lead to the failure of the unit. This phenomenon has been investigated in a mineral oil system, but not in a vegetable oil system.

Vegetable oil is more hygroscopic than mineral oil. This means that vegetable oil is more capable of attracting and retaining water from the paper insulation, where most of the water in the insulation system resides. Owing to this property, vegetable oil is thought to be able to better resist bubble formation than mineral oil. In addition, vegetable oil is more biodegradable and has a higher fire point than mineral oil. This means that if a failure does happen, the oil is less likely to combust and contaminate the environment.

This study investigated bubble formation during overload temperatures in a vegetable oil system, and the results were then compared to a mineral oil (Shell Diala B) system which was studied previously using similar test equipment and method. The limiting hotspot temperatures for bubbles and droplets in vegetable oil with paper water content between 1 - 6 % were determined. The paper water content measurement, which is critical when setting the winding temperature limit, was evaluated using both a moisture sensor and the Karl-Fischer titration method.

## Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Signature: .....

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Date: .....

## **Publications**

### Published:

- [1] C. Y. Perkasa, N. Lelekakis, J. Wijaya, and D. Martin. "Investigating bubble formation in vegetable oil and mineral oil impregnated transformer paper insulation systems". Australasian Universities Power Engineering Conference (AUPEC), 2012, pp. 1-5.
- [2] C. Y. Perkasa, J. Wijaya, N. Lelekakis, and D. Martin. "Preliminary study of bubble formation in vegetable oil filled power transformer". Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 2013, pp. 551-554.
- [3] C. Y. Perkasa, N. Lelekakis, T. Czaszejko, J. Wijaya, and D. Martin. "A comparison of the formation of bubbles and water droplets in vegetable and mineral oil impregnated transformer paper". IEEE Transactions on Dielectrics and Electrical Insulation, vol. 21, pp. 2111-2118, Oct 2014.
- [4] C. Y. Perkasa, N. Lelekakis, T. Czaszejko, D. Martin, and T. Saha. "Moisture-bubbling of vegetable oil impregnated paper at transformer overload temperatures". International Conference on the Properties and Applications of Dielectric Materials (ICPADM), 2015, pp. 76-79.

### Acknowledgements

I would like to thank the members of the Centre for Power Transformer Monitoring, Diagnostics, and Life Management (CPTM), Dr. Daniel Martin for giving to me the opportunity to do this research project, Mr. Nick Lelekakis for helping me to prepare and conduct the experiments, Mr. Jaury Wijaya for helping me to set up the data acquisition system for the experiments, and Dr. Tadeusz Czasejko for helping me to prepare this thesis.

I would like to thank the various industry and academic experts on power transformers: Dr. Dejan Susa on power transformer operating standards, Dr. Yuriy Oderenko on power transformer design and construction, Mr. Meng Lee on power transformer field services, and Prof. Tapan Saha on power transformer research.

I would like to thank Monash University and its staff: the Department of Electrical and Computer Systems Engineering (ECSE) for the scholarship, Prof. Jamie Evans for ensuring the continuity of this project, Mr. Martin and Mr. Andrew Linzner for helping me to fabricate the components needed for the experiments, Ms. Roslyn Rimington for helping me to manage my candidature, and Dr. Alex McKnight assisted by proofreading the final draft for grammatical and stylistic errors.

I would like to thank Dr. Shawn Nielsen and Dr. Imad Khan for reviewing my thesis and suggesting improvements to it.

Finally, I would like to thank the numerous research students for their company and support.

This research was supported by an Australian Government Research Training Program (RTP) Scholarship.

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### **Chapter 1: Introduction**

The work presented in this thesis is on the bubble formation phenomenon observed in a power transformer using an oil-paper insulation system. The work focused specifically on the use of vegetable oil.

The work was done in the interest of the electrical utility and transformer manufacturer industries, in order to advance understanding of behaviour of vegetable oils as a viable medium in power transformers insulation.

### **1.1 Power Transformers**

Power transformers are key components of the electrical power infrastructure. They convert the line voltage from one level to another to enable the efficient and effective transmission and distribution of electrical power from the generation side to the consumer side. Furthermore, they are expensive elements of the electricity grid.

The reliable performance of power transformers is critical for the reliable supply of electricity. If they fail unexpectedly, they need to be replaced and service disruption may occur. A service disruption in power system operation will result in the loss of revenue and penalties being imposed on electrical utilities. A study performed by Bartley [1] derived a business loss of US\$ 9000 per Mega Volt-Amps (MVA) of transformer failure. It is therefore important to study how transformers fail in order to advise the industry on how to maintain their safe operation.

Power transformers commonly use an oil-paper insulation system. The system classically consists of mineral oil and Kraft paper. Oil is used as liquid insulation because it fills the spaces inside the transformer tank, and acts as a coolant for the windings. Paper is used as solid insulation because it can be impregnated by oil to enhance its dielectric strength. Paper is wrapped around each winding conductor in

a number of layers, and is made of cellulose. Both mineral oil and Kraft paper are abundant in supply, and hence are cost-effective for manufacturing. A common problem faced by this type of insulation system is the presence of water in the system.

Transformer-grade mineral oils are refined from predominantly naphthenic crude oils. The refining processes may include acid treatment, solvent extraction, dewaxing, hydrogen treatment, or combinations of these methods to yield mineral oil meeting the specification. These oils are mainly a mixture of hydrocarbon compounds of three classes: alkanes, naphthenes, and aromatic hydrocarbons. These molecules have little to no polarity. Polar and ionic species are a minor part of the constituents, which may greatly influence the chemical and electrical properties of the oil. "Polar compounds found in transformer oil usually contain oxygen, nitrogen, or sulphur. Ionic compounds would typically be organic salts found only in trace quantities" [2].

In addition to paper, the other cellulose-based material used in transformer construction is pressboard. Both paper and pressboard are manufactured to be electrical-grade insulation, and made from unbleached sulphate cellulose consisting of a more or less long chain of glucose rings. Pressboard is used for the structural support of the windings. Pressboard has been well known in the textile and paper processing industries for more than 100 years, and was used in the first electric machines [3].

A summary of the causes of transformer failure, the number of failure events, and the total cost associated for the particular failure type is reported by Bartley [1] in Table 1.1.

Cause of Failure	Number	Total Paid (USD)
Insulation Failure	24	149,967,277
Design / Material / Workmanship	22	64,696,051
Unknown	15	29,776,245
Oil Contamination	4	11,836,367
Overloading	5	8,568,768
Fire / Explosion	3	8,045,771
Line Surge	4	4,959,691
Improper Maintenance / Operation	5	3,518,783
Flood	2	2,240,198
Loose Connection	6	2,186,725
Lightning	3	657,935
Moisture	1	175,000
	94	286,628,811

 Table 1.1: Causes of Transformer Failure.

The failure mode of interest addressed in the present work is that during overload when the winding temperature is too high, bubbles of water are ejected from the paper into the oil, which can potentially cause dielectric failure. The overload level used was according to the Standard IEC 60076-7 [4], which sets a maximum winding and hotspot temperature of 160 °C during short-term overloads.

### **1.2 Water Presence**

Over time water accumulates in the insulation system. Water sources are either external, internal, or a combination of both. The external source is from the environment where the transformer was commissioned. The water ingresses inside the transformer via imperfections present in the seals due to imperfect manufacturing, or imperfections developed later due to the deterioration of seals due to inadequate maintenance. For free-breathing transformers, a desiccant is placed at the opening end of the air pathway and is used to dry the air coming into the transformer. Hence, if not dried regularly, the desiccant will not be able to filter out the environmental water coming into the transformer. The internal source is from the ageing by-products of cellulose, one of which results in water. Before being commissioned, the insulation system is dried, to ensure that it contains a very small amount of water.

When wet, the dielectric strength of the insulation materials is weakened. Paper in particular also loses its mechanical strength, and can break off from the conductors. The mechanical life of the paper insulation is reduced by half for each doubling in water content [5]. The rate of thermal deterioration of the paper insulation is proportional to its water content [6]. Paper insulation is very difficult to replace, because if a section of a winding paper needs to be replaced, then the entire winding must be replaced.

Water in an oil-paper insulation system is distributed very unevenly between the insulation materials, with water mostly residing in the paper insulation. Water residing in the paper insulation is held inside (absorbed) and on the surface (adsorbed) of the paper. Water resides more in the paper insulation because paper is made out of cellulose, which has polar sites for water to bind to, hence paper is

hydrophilic. Oil insulation by comparison is mainly made up of non-polar hydrocarbon chains, hence oil is hydrophobic. Furthermore, water molecules can weakly bond to other water molecules via hydrogen bonding.

Oil in general has a low affinity for water; however the water solubility increases with the temperature. Water in oil can exist in three states: dissolved, bounded, or free. In most practical cases, water is dissolved into the oil. Certain discrepancies in examining the water content using different measurement techniques suggest that water exists in the oil tightly bound to oil molecules, especially in deteriorated oil. When the water content in oil exceeds the oil's saturation limit, free water will precipitate from the oil in the form of suspensions or drops. Water in oil is measured in parts per million (ppm) using the weight of water divided by the weight of oil ( $\mu g/g$ ) [3].

Paper in general has a high affinity for water. Water in paper can exist in four states: adsorbed to surfaces, vapour, free water in capillaries, and imbibed free water. Water concentration in paper is typically expressed as a percentage of the weight of the water divided by the weight of the dry oil-free paper [3].

Water exists in insulation materials in trace amounts as moisture. From experience with mineral oil, a typical content of water is several 10s of ppm in the oil and several percent in the paper, both by weight. At room temperature, mineral oil cannot contain more than around 50 ppm [7] of water before it is saturated.

Relative humidity can be defined in terms of the moisture mixing ratio *r* versus the saturation mixing ratio  $r_s$ ,  $R.H.\% = 100 r/r_s$ , which is a dimensionless percentage. Relative humidity for air is the water vapour content of the air relative to its content at saturation. Relative humidity for oil is the dissolved water content of the oil relative to the maximum capacity of water that the oil can hold. Because the

saturation mixing ratio is a function of pressure, and especially of temperature, relative humidity is a combined index of the environment and reflects more than the water content [8].

Water vapour pressure is the partial pressure exerted by water vapour. When the system is in equilibrium with the liquid or solid form, or both, of the water, it reaches the saturation water vapour pressure. Saturation vapour pressure is a measure of the tendency of a material to change into the gaseous or vapour state, and it increases with temperature. At the boiling point of the water, the saturation water vapour pressure at the surface of water becomes equal to the atmospheric pressure.

To assess the water concentration in the insulation system, water moisture equilibrium partitioning curves are used. The usage of the equilibrium curves provides a quick way to assess the water content in paper by measuring the water content in oil. However, the water content of oil and paper are seldom in equilibrium. Hence, the use of the equilibrium curves is situational, unless appropriate considerations are taken into account [9].

When the winding temperature rises, the water absorbed and adsorbed by the paper is released towards the oil. When the winding temperature steadies or falls, the water is re-absorbed into the paper. This phenomenon is known as 'moisture dynamics'. An in-service power transformer normally experiences varying winding temperatures due to changing load demands. For this reason, the water in the insulation system constantly moves back and forth between the insulation materials, and is never in equilibrium.

Four equations that can be used to model the movement of water. They are:

$$P_v = 9.26 \times 10^9 \times C_{Paper}^{1.4959} \times e^{\frac{-7069}{T}}$$
(1.1)

$$a_w = \frac{P_v}{P_o} \approx \frac{C_{0il}}{10^{\left(A + \frac{B}{T}\right)}}$$
(1.2)

$$P_{v} = 6.1121 \times e^{\left(\frac{17.502 \times T}{240.97 + T}\right)} \times a_{w} \times 0.0009869$$
(1.3)

$$R = -D \times \frac{dP_v}{dx} \tag{1.4}$$

where *T* is temperature in Kelvin,  $P_v$  is the vapour pressure in *atm*, and  $C_{Paper}$  and  $C_{Oil}$  are the water content of the material in either % for paper or *ppm* for the oil. Equation (1.1) is from [10].

Equation (1.2) assumes that the oil water activity,  $a_w$ , which is a ratio involving vapour pressure, follows Henry's law of proportionality and can therefore be approximated by dividing the oil water content by its maximum solubility to water at that temperature. Coefficients *A* and *B* are specific to the type of oil and its quality. Once the water activity of the oil is known, the Buck equation [11] can be used to determine the vapour pressure above the oil (1.3). The term 0.0009869 is used to convert from the pressure unit of *hPa* to *atm*, so that equation (1.3) can be used to together with equation (1.1). Equation (1.4), which assumes Fickian flow, indicates that the net rate of flow *R* between two media is proportional to the vapour pressure gradient [12]. *D* is a diffusion coefficient.

The vapour pressure of a given mass of water adsorbed on the surface of the paper differs from when the same mass of water is dissolved in the oil. For instance, the water content of paper insulation is usually around several per cent by dry mass of cellulose, but the oil will have a water content of in the order of 10s of ppm.

As can be seen in Equations (1.1) - (1.3), the effect of temperature on the vapour pressure of water differs, depending on whether the water is dissolved in the oil, or adsorbed to the paper, because the equations are of different forms. A changing temperature leads to a vapour pressure gradient across the oil and

cellulose formation. When there is a pressure gradient between the surface of the paper and the adjacent oil volume, there will be a net rate of flow, with the direction being dependent on whether the paper is adsorbing or desorbing water.

When there is a net rate of water migration into the oil, if enough water migrates, the local oil volume becomes saturated, and two separate phases of water and oil then begin to form, initially creating a fine mist. Water lowers the breakdown voltage of oil, as shown in Figure 1.1, even before it has formed a precipitation in the oil.



**Figure 1.1**: Effect of water on breakdown voltage of mineral oil at room temperature, performed according to standard ASTM D1816 using brass 36 mm diameter spherically capped electrodes. An average for 20 breakdowns is shown; the error bars denote the standard deviation of the measurements. Figure redrawn from data provided by Martin [13].

Although vegetable oil dissolves more water than mineral oil, approximately 1000 ppm and 50 ppm respectively at room temperature, these concentrations are insignificant when compared to paper, which absorbs several per cent (1% = 10000 ppm). The effect of using vegetable oil may be that it takes longer to saturate because it can dissolve more water than mineral oil. However, whether or not saturation occurs depends on the volume of oil near the paper.

The direction of water migration is driven by differences in vapour pressure according to Fick's law (1.5), where *R* is the net rate of water migration, *D* is a diffusion coefficient,  $P_v$  is vapour pressure and *x* is the dimension that the vapour pressure gradient is across.

$$R = -D\frac{dP_v}{dx} \tag{1.5}$$

When Kraft paper is heated the vapour pressure of its absorbed water changes according to Equation (1.6), where *C* is water content of paper (WCP) by weight and *T* is temperature in Kelvin [3].

$$P_{v} = 9.2683 \times 10^{9} \times C^{1.4959} \times e^{-7069/T}$$
(1.6)

As the temperature increases, the rise in vapour pressure causes water to migrate out of the paper, where it then dissolves into the oil. Usually, the focus is on the insulation paper because it is wrapped around the conductors forming the windings, and therefore its temperature also rises rapidly when current is applied. The solubility of water in mineral oil is around 50 ppm at 25 °C, whereas it is nearer 1100 ppm for vegetable oil. The solubility at a given temperature is calculated using Equation (1.7), where *A* and *B* are two coefficients experimentally determined for the oil and *T* is the temperature in Kelvin. For mineral oil A = 7.0895, B = 1569 and for this vegetable oil A = 5.3318, B = 684.

$$\log S = A - \frac{B}{T} \tag{1.7}$$

A plot of solubility against temperature is given in Figure 1.2. At normal operating temperatures, around 50 to 60 °C, the solubility of water in an oil (in ppm) is very small compared to the Water Content of Paper (WCP) in per cent (1 % = 10000 ppm). Therefore, the water content of oil is sometimes ignored in calculations using WCP. However, as the oil temperature increases to levels realistic of when

bubbling occurs, 130 °C, the water solubility of these oils becomes very high, and begins to reach the same order of scale (%) as the WCP. During an overload the main bulk of oil will take a long time to heat up. However, the oil directly adjacent to the winding paper will obviously heat up far more quickly. The thermal properties of the oil also affect bubbling evolution indirectly because as the oil is a coolant, it affects the temperature reached by the paper insulation at a given load.



Figure 1.2: Solubility of water (ppm) over temperature (°C).

A limiting factor for  $P_v$  in Equation (1.6) is that once it exceeds the total pressure acting on the surface of the paper a gas bubble of water develops. This bubble expands, as explained by the Young-Laplace equation (1.8), if the internal pressure  $P_{int}$  is greater than the external pressure  $P_{ext}$  plus the surface tension  $\gamma$  and the radius of bubble *r*.

$$P_{int} = P_{ext} + \frac{2\gamma}{r} \tag{1.8}$$

The surface tension of these oils at the different temperatures studied is not a common measurement in the transformer oil industry. Most datasheets list interfacial tension rather than surface tension. One surface tension measurement for soybean oil at 30 °C is 27 mN/m, which decreases at a rate of 0.077 mN/m per °C increase

[14]. For a 0.5 mm radius bubble the  $2\gamma/r$  term of Equation (1.8) is 108 N/m<sup>2</sup>. Consequently, the magnitude of this term is fairly insignificant compared to the atmospheric pressure term, which is 101 kPa.

The external pressure  $P_{ext}$  is the sum of the atmospheric and hydrostatic pressure in Equation (1.9). The hydrostatic pressure is dependent upon the density of the fluid in Equation (1.10), where  $\rho$  is density, *g* is acceleration due to gravity (9.8 m/s<sup>2</sup>) and *h* is the depth of the oil (m). For this experiment an oil conservator was mounted 0.9 m above the top of the coil. Due to the difference in density (Table 1.2) and according to Equation (1.10), the respective hydrostatic pressure at 20 °C is 8.1 kPa for the vegetable oil and 7.7 kPa for mineral oil. Given that the atmospheric pressure is 101 kPa, the difference in hydrostatic pressure dependent on the type of oil is small.

$$\boldsymbol{P}_{ext} = \boldsymbol{P}_{atm} + \boldsymbol{P}_{hydrostatic} \tag{1.9}$$

$$\boldsymbol{P}_{hydrostatic} = \boldsymbol{\rho} \boldsymbol{g} \boldsymbol{h} \tag{1.10}$$

Table 1.2: Properties of vegetable and mineral oil affecting winding temperature	(taken from
manufacturer's data sheet [15,16]).	

Property	Vegetable oil	Shell Diala B mineral oil	
Kinematic Viscosity (mm <sup>2</sup> /s)			
@ 40 °C	33	10	
@ 100 °C	8	2	
Density (kg/m <sup>3</sup> )			
@ 20 °C	920	881	

The intention of the present study was to determine the degree of effect that differences in surface tension and water solubility of the oil have on the inception of bubbling of the oil.

Throughout their service lives, power transformers operate under varying demands. The load demands are dependent on two factors: the type of consumer (residential, commercial, or industrial) and the time of day (day or night). With regard to the time of day, the load profile can be approximated to a sine wave [9], which means that the demand peaks in the day and falls at night. On average, the winding temperature is high. The load demand directly determines the winding temperature developed, and indirectly is the driving force for moisture dynamics.

In the event of a sudden temperature rise, the water absorbed and adsorbed by the paper is released quickly towards the oil. Possible events are either initial energisation or emergency overloads during peak hours. The water released may form into bubbles. If the oil cannot dissolve the water released quickly enough, or the oil is saturated, some of the water will exist at the paper-oil interface.

### **1.3 Bubble Formation**

Bubbles form if the oil cannot dissolve the water released quickly enough, or the oil is saturated, and there is enough thermal energy for the water to build up internal pressure to overcome the external pressure exerted by the oil [17, 18, 19]. The bubbles will then float up due to the buoyancy force exerted by the oil.

It is believed that bubbles of water form on the surface of the paper, rather than actually in the oil, because the pressure required to cause a bubble to expand is very high [17]. The Young-Laplace Equation (1.11) shows that the internal pressure within a bubble acting outwards on the surface boundary,  $P_i$ , is equal to the external pressure,  $P_e$ , usually around 1 atmosphere (atm), plus a component related to the surface tension  $\sigma$  of the oil and the radius of the bubble r [20].

$$P_i = P_e + 2\frac{\delta}{r} \tag{1.11}$$

The internal pressure of a bubble must be larger than the external pressure. Therefore, when the oil becomes saturated with water, with the vapour pressure of the dissolved water equalling that of pure water at the same temperature, bubbles do not immediately form because the vapour pressure of water needs to be higher than that of the ambient atmosphere. Bubbles are therefore more likely to form in surface cracks or on imperfections of solids [17].

Bubbles will also form if the water dissolved by the oil increases the local concentration of gases in the oil [21].

As the water content of transformer insulation increases, its bubble inception temperature falls. For a system filled with mineral oil, as the WCP increases past 1 % (by mass), the bubbling inception temperature falls lower than the 160 °C maximum overload temperature limit proposed by the IEC 60076-7 [4]. Consequently, if a utility decides to operate a transformer with a WCP of higher than 1 %, they must accordingly reduce the overload limit.

The presence of bubbles in the insulation system can make way for insulation breakdown that will eventually lead to the failure of the transformer. Garton & Krasucki [22] investigated the effect of electric fields on water bubbles in oil, and the implications with regard to the dielectric failure of liquid insulation. They found that, on reaching a level in order of 1 MV/cm, an electrical field can distort the shape of a spherical bubble in the direction of the field to a prolate spheroid. When the bubble is sufficiently elongated, it is capable of causing the liquid insulation to fail by creating a conduction path which allows for flashovers to occur. Flashovers degrade the insulation materials, and hence reduce their dielectric strength.

The presence of bubbles is a hazard for safe transformer operation. The life of a transformer is dependent on the life and wellbeing of its insulation materials. It is therefore important to avoid this failure mode due to bubble formation to ensure the reliable operation of transformers. One possible way to reduce the risk of bubble formation is to use vegetable oil instead of mineral oil.

### 1.4 Vegetable Oil

Despite several researchers having investigated bubbling evolution in mineral oil insulation systems, (e.g. Heinrichs [23], Oommen [17], and Koch [18]), there is insufficient information available on other types of transformer fluid. Vegetable oil-based dielectrics are increasingly being used as the insulation of transformers, which provided the motivation to investigate how the insulation system of such a transformer behaves during overload conditions.

Natural ester-based oil, more commonly known commercially as vegetable oil, is more biodegradable, hygroscopic, and has a higher fire point than mineral-based oil. Being more biodegradable means that, should the oil spill, the contamination damage to the environment will not be as severe and the recovery effort needed for the environment will not be as great. Being more hygroscopic means that the water in the insulation system will reside more in the oil, which is the insulation that is easier to dry or be replaced. Having a higher fire point means that, should the oil spill and there is a source of ignition (e.g. electrical arcing), the oil is less likely to combust. In addition, the higher fire point means that the design of the substation's transformer deluge system can be simplified [24].

A limitation of the use of vegetable oil is that it must be used in a sealed system, limiting contact with air. Otherwise, the oil will quickly be saturated with environmental water.

It is expected that with its positive properties vegetable oil can be a good substitute for mineral oil. In general, it will perform as well as mineral oil in terms of its electrical, thermal, and chemical performances. In particular, it will be better at resisting bubble formation due to the higher hygroscopic property that allows for more water to be dissolved by the oil.

Vegetable oil is able to absorb about 20 times more water than mineral oil before becoming saturated [25], hence possibly reducing the propensity for the formation of water bubbles.

### 1.5 Overview and Aims of this Thesis

The aim of the investigation was to determine the temperatures at which bubbles form in vegetable oil with different paper water contents. The experimental set-up used was similar to that used previously at Monash University [26] to conduct bubbling experiments using mineral oil. Several thermal tests were conducted to simulate the temperature reached during overload [4] for the different paper water contents. The expected outcome was a chart of the bubble inception temperatures for vegetable oil. The chart was then compared to the chart from Monash's mineral oil experiment, to assess the suitability of vegetable oil as a substitute for mineral oil.

### **1.6 Overview of Chapters**

Chapter 1 has presented introductions to power transformers, the presence of water in insulating oil, bubble formation, and vegetable oil. This chapter also outlined the overview and aims of this thesis and the chapters in it.

Chapter 2 presents past research on bubble formation in mineral oil.

Chapter 3 presents the basic and advanced physical chemistry knowledge needed to explain surface and bubble formation phenomena.

Chapter 4 presents a study of bubble formation in mineral oil conducted by Monash University in the past.

Chapter 5 presents the results of the present study of bubble formation in vegetable oil.

## **Chapter 2: Literature Review**

A review of past research on bubble formation in mineral oil is presented in this chapter. The researchers, year of research publication, and brief summaries of their experimental set-ups, methods, and results are included.

### 2.1 T. V. Oommen & S. R. Lindgren (2001)

The authors investigated the relationship between bubble inception temperature and paper water content and oil gas content [17].

#### 2.1.1 Set-up

Two coil models were used, a three-disc model and a one-disc model. The three-disc model used thermocouple leads to measure hotspot temperature in the winding, and bubble evolution was observed visually. The one-disc model used a fibre optic temperature sensor (Luxtron Model 750) to sense hotspot temperature in the winding, and a separate winding was used to apply voltage for partial discharge (PD) detection of bubbles in addition to visual observation.

A wide range of paper water content and oil gas content was used. Water content ranged from 0.3 % to 8.0 % (dry / oil-free to wet). Gas (nitrogen) content ranged from 0.45 % to 12.3 % (fully degassed to nitrogen saturated).

The glass tank used enabled visual observation of bubble formation. The same tank was used for both types of coils, and for gas-blanketed and conservator systems.

#### 2.1.2 Method

In total 26 model tests were conducted, of which 12 used the three-disc model and the remaining used the one-disc model. Both gas-blanketed and conservator systems were tested.

A rapid temperature rise was used to simulate the conditions in a transformer winding under overload conditions.

#### 2.1.3 Results

In both fully-degassed and nitrogen-saturated systems, the results show that, as the paper water content increases, the bubble inception temperature decreases. The oil gas content starts to affect the bubble inception temperature when the paper water content is equal to, or greater than, 2 - 3 %. The results can be seen in Figure 2.1.

The implication of this finding is that the bubble inception temperatures of nitrogen-blanketed transformers may be lower than for free-breathing transformers when the insulation is wet. The authors did not conduct further investigations to confirm this.



Figure 2.1: Bubble inception temperature as a function of paper water content in both fully-degassed and nitrogen-saturated systems.

### 2.2 P. Przybylek (2010)

The author investigated the influence of degree of cellulose insulation ageing on its water sorption properties and bubble evolution. The bubble effect here is defined as the release of water from the paper insulation in the form of water steam bubbles [27].

### 2.2.1 Set-up

The measurement system included a copper tube with a controlled power heater placed inside it. The initiation temperature of the bubble effect was determined by means of a thermocouple fixed directly on the copper tube on which the investigated paper was wound. The heater with the paper wound on it was placed in a glass container filled with oil. The bubble effect was recorded using a camera.

In the investigations of the initiation temperature of the bubble effect, new paper (Degree of Polymerisation (DP) = 1357) was used and paper aged in laboratory conditions (DP = 341). Paper of different degrees of water was investigated. The water content in new paper ranged from 1.46 % to 6.98 % whereas in aged paper it varied from 0.84 % to 3.99 %. Different water contents in the investigated paper samples were obtained by heating the samples immersed in oil, for different periods. The water content in the insulation samples was determined using the Karl-Fischer titration (KFT) method. The author used Kraft paper and 10GBN Nytro mineral oil supplied by Nynas for the experiment. Investigations of initiation temperature of the bubble effect were done for total pressure equal to 767 Torr. The rate of the temperature rise was about 2 °C/min.

### 2.2.2 Results

For both new paper and aged paper, as the paper water content increases, the bubble inception temperature decreases. Furthermore, the inception temperature of the bubble effect for aged paper (DP = 341) is lower than that for new paper (DP = 1357) by about 12 %. The result can be seen in Figure 2.2.



**Figure 2.2**: Temperature of bubble effect inception as a function of water content in paper for new (DP = 1357) and aged insulation (DP = 341) [32].

### 2.3 P. Przybylek, Z. Nadolny, and H. Moscicka-Grzesiak (2010)

The authors investigated the bubble effect as a consequence of dielectric losses in cellulose insulation. The thermal effect here is defined as the temperature increase caused by the dielectric losses in the paper insulation [28].

#### 2.3.1 Set-up

To study the thermal effect the authors designed a laboratory model, with several paper layers placed between two plane electrodes. The electric field intensity in the investigated sample was uniform. Electrodes shaped from thin aluminium sheet were used to reduce the effect of sample cooling. In this way, electrodes of little thermal capacity were obtained.

The investigated sample with the electrodes was immersed in oil. The lower electrode was under voltage, while the upper was grounded. There was a circle on the upper electrode, painted matt black. The temperature of the upper electrode, heated by the investigated paper test sample, was determined by the contactless method, using an infra-red camera. The painted black circle improved the accuracy of the temperature measurement. The temperature measurement was done every 60 seconds.

In the investigation of the thermal effect, the authors used samples of Kraft paper, 14 sheets with a total thickness of 1 mm.

In order to prepare new insulation, the paper samples were dried in a vacuum drier and then they were moistened to a required water level by means of contact with air. The water content in the samples was determined on the basis of sample weight changes. Next the paper was impregnated with new oil.

The aged samples were prepared under laboratory conditions. The paper was aged in oil with a temperature of 130 °C. After ageing, the paper contained 4.28 % water. Different water contents in the samples were obtained by heating the samples immersed in oil for different times. The water content in the samples prepared in this way was determined using the KFT method.

The measurement set-up included a heating panel which enabled measurements for different values of the initial temperature of oil-paper insulation. An electromagnetic stirrer was used to equalise the temperature in the whole oil volume.

### 2.3.2 Results

There were three stages of the investigation. The details of each stage are summarised in Table 2.1.

Stages	Paper	Oil	Part	Electric field intensity, kV/mm	Paper water content, %	Initial temperature, °C
1	New (DP = 1357)	New (0.02 mgKOH/g <sub>oil</sub> )	I	8	7.5	25, 37, 62, 77
			11	8	5.5	26, 36, 52, 76
2	Aged (DP = 341)	Aged (0.18 mgKOH/g <sub>oil</sub> )	I	4, 6, 8	5.03	65
			П	4, 6, 8	5.03	80
3	Aged (DP = 341)	Aged (0.18 mgKOH/g <sub>oil</sub> ) – Oil A	I	4, 6, 8	4.28	80
	Aged (DP = 341)	Aged (0.24 mgKOH/g <sub>oil</sub> ) – Oil B	II	4, 6, 8	4.28	80

**Table 2.1**: Details of the three stages of the investigation.

### First stage

In this stage, the values of electric field intensity and paper water content were intentionally made higher in reference to values occurring in a real insulating system of a transformer, because the authors were aiming at a significant thermal effect.

The initiation temperatures of the bubble effect for new paper (DP = 1357), with paper water content of 7.5 % and 5.5 %, were about 85 °C and 98 °C, respectively.

In part I, the temperatures reached were 86, 85, 86, and 101 °C. Hence, the thermal effect occurred for all four cases.

The authors noted that the higher the initial temperature of the insulation, the more quickly the temperature reached the level corresponding to the initiation of the bubble effect. The time from the moment of applying voltage to the occurrence of the bubble effect, depending on the insulation initial temperature, is presented in Figure 2.3.



Figure 2.3: Time from the moment of applying voltage to the occurrence of the bubble effect depending on the insulation initial temperature.

In part II, the thermal effect did not occur in all four cases, because the critical temperature was not reached.

The authors concluded that the bubble effect resulting from the thermal effect should not occur in new insulation when the water content in the paper is about 5.5 %, at field intensity not exceeding 8 kV/mm and insulation temperature not exceeding 76 °C.

### Second stage

The initiation temperature of the bubble effect for aged paper (DP = 341), at paper water content of 5.03 %, was about 90 °C.

In part I, of the three cases, the bubble effect occurred only when the applied field intensity was 8 kV/mm.

In part II, the bubble effect occurred for all three applied levels of electric field intensity. In all three cases, the temperature slightly exceeded the value of 90 °C. The higher the value of the applied electric field intensity, the sooner the bubble effect appeared.

### Third stage

In this stage, the paper water content was reduced in an attempt to make this value real, whereas the field intensity and initial temperature were left unchanged.

The initiation temperature of the bubble effect for aged paper (DP = 341), at paper water content of 4.28 %, was about 95 °C.

In both parts I and II, the bubble effect occurred only for the paper impregnated with oil A and oil B, exposed to the electric field of 8 kV/mm. It is noticeable that strongly aged oil B accelerated and strengthened the thermal effect.

### 2.4 M. Koch & S. Tenbohlen (2011)

The authors investigated the influence of material quality and ageing of the oil and the paper insulation on bubble inception temperatures [18].

### 2.4.1 Set-up

An electrically-heated rod wrapped in two layers of insulation paper was placed in a vacuum-proof, 5 L capacity Duran flask. During and after filling with insulation oil, a partial vacuum of 20 – 40 mbar was applied to simulate the production process of transformers. Opto-electronic probes (Luxtron 755 multichannel fluoroptic thermometers) measured the temperature of the inner and outer side of the paper
layers. A variable transformer controlled the heating power and therefore the temperature. To emulate the static oil pressure at the hotspot of a transformer, a tube retained an oil column of 1.5 m. A digital camcorder recorded the bubble inception temperature and the process of bubbling.

The evolution of gaseous bubbles was investigated on new Kraft paper, new thermally upgraded (TU) paper, aged (thermally degraded) Kraft paper, new oil Shell Diala D, and service-aged Shell K 6 SX from 1965 [Table 2.2, Table 2.3]. Both oils were gas-saturated. The thermal degradation of the Kraft paper occurred at a temperature of 130 °C and at a relative moisture saturation of the ambient air of nearly 100 % applied for 2 weeks.

Table 2.9. Material	proportion of investigated inculation popers
Table 2.2: Material	properties of investigated insulation papers.

Property	Kraft paper	Thermally Upgraded (TU) paper
Thickness, mm	0.065 – 1	0.065 – 0.105
Density, g/cm <sup>3</sup>	0.8 ± 0.05	1.0 ± 0.05
Capillary rise, mm	> 5	> 5
Degree of Polymerisation (DP)	>1000	>1100

able 2.3: Material properties of insulation oils.
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Property	Shell Diala D [29]	Shell K 6 SX
Age	Virgin	1965
Density at 20 °C, g/cm <sup>3</sup>	0.877	0.882
Moisture saturation at 20 °C, ppm	55	153
Total acid number, mg KOH/g <sub>oil</sub>	0.016	0.48
Interfacial tension, mN/m	47	

Coloumetric Karl Fischer titration determined the paper water content relative to dry cellulose weight at a heating temperature of 160 °C. A 100  $\mu$ g scale measured the dry weight of the cellulose after oil extraction using methanol. Coloumetric Karl Fischer titration was also used to determine the oil water content in ppm relative to weight. In the case of oil, direct injection into the titration cell was used. Capacitive probes (Vaisala HMP 228) measured the relative water saturation in oil and cellulose.

#### 2.4.2 Results

#### 2.4.2.1 Influence of paper quality

The authors noted that, in new Shell Diala D oil, new Kraft paper has the lowest inception temperature, and new TU paper has the highest inception temperature. The results can be seen in Figure 2.4. They claimed that this was due to the microstructure of the new TU paper that contains fillers that increase the ageing durability and decrease the number and diameter of capillaries, where the water molecules can reside. They also noted that the water molecules are bound more strongly in TU paper than in Kraft paper, according to [30]. The authors did not comment further on the specifics of these filters, and the mechanism by which they influence bubble formation.



Figure 2.4: Bubble inception temperature for new Kraft paper and new thermally upgraded paper in new Shell Diala D.

The authors also noted that, in new Shell Diala D oil, the inception temperature of aged (thermally degraded) Kraft paper surpasses that of new Kraft paper. The result can also be seen in Figure 2.4. They claimed that this phenomenon was due to the effect termed 'hornification', which is well known in the paper industry [31]. In the case of paper ageing at high temperatures, the OH-groups of the cellulose chains saturate one another. The connected microfibrils of the dried cellulose do not react any longer even if they are moistened once again. The number, diameter, and volume of the pores and capillaries decrease, resulting in a higher bubble inception temperature.

#### 2.4.2.2 Influence of oil ageing

The authors noted that, with new Kraft paper, the inception temperature in service-aged Shell Diala K 6 SX was lower than that in new Shell Diala D. The result can be seen in Figure 2.5. They claimed that this was due to the surface-active substances of the service-aged Shell Diala K 6 SX that decrease the surface tension, resulting in a decreased inception temperature.



Figure 2.5: Bubble inception temperature for new Kraft paper in new oil and in aged oil.

The authors also noted that, for aged (thermally degraded) Kraft paper in service-aged Shell Diala K 6 SX, the inception temperature increases again to the value obtained by new oil and new paper. They claimed that the hornification of microfibrils in cellulose results in a positive impact on the inception temperature, although on the other hand it decreases the flexibility of the fibres.

#### 2.4.2.3 Influence of temperature rise

The authors showed in Figure 2.6 the temperature gradient that is necessary to release the water in the form of bubbles. From the figure, the critical temperature gradient is around 3 K/min; below this value, the water only diffuses into the oil without forming gaseous cavities.



Figure 2.6: Bubble inception temperature as a function of temperature rise for new Kraft paper in aged Shell Diala K 6 SX.

## 2.5 S. M. Korobeynikov, A. L. Bychkov, A. Yu. Ryzhkina, M. V.

# Sviridenko, L. A. Darian, and A. V. Melekhov (2013)

The authors investigated microbubbling in transformer oil due to vibration [33].

#### 2.5.1 Set-up

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

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

#### 2.5.2 Results

Non-degassed transformer oil GK was used at room temperature  $20 \pm 2$  °C. The cell volume was fully filled. In case of a gap of  $100 - 200 \ \mu m$  (the gap was oil filled or partially fulled-board), bubbles do not appear. Intense gassing was

registered both at the gap absence and slackening of the frame tension. Because the microgap plane was oriented along the buoyancy force, nucleating bubbles moved along the gap line. About 10 - 20 microbubbles were registered simultaneously in the microscopic field. Voltage inception was 60 V; bubble quantity slightly increased when the voltage increased. Bubble formation frequency was approximately one per second. Bubble radius varied from 40 to 60 µm, lifting the vertical speed to 0.3 - 0.4 mm/s due to buoyancy force. The authors noted that the horizontal bubble speed (moving away from the gap) was approximately the same as the vertical speed. The vibration spectrum at voltages of more than 70 V had higher frequencies up to 1 kHz in addition to the basic frequency of 100 Hz. The authors noted that these facts point to microbubble oscillation. It should be noted that transformer oil degassing suppressed bubble formation. However, gas generation in the form of dissolved gas also took place in this case.

# 2.6 P. Przybylek (2013)

The author compared the bubble evolution temperature in aramid and cellulose paper. The bubble effect here is defined as the release of water from the paper insulation in the form of water steam bubbles [34].

### 2.6.1 Set-up

Two types of new winding papers were used in the study: Kraft cellulose paper and aramid paper. The Kraft paper had a thickness of 0.055 mm, a grammage of  $47.6 \text{ g/m}^2$ , and the degree of polymerisation was equal to 1360. The aramid paper was 0.05 mm thick and had a grammage of 40.4 g/m<sup>2</sup>.

A total of fifteen strips each of Kraft paper and aramid paper were prepared, and each strip was 300 mm long and 33 mm wide. The samples were divided into five sets. Each set included three strips of both cellulose paper and aramid paper, and was placed in a separate weighting bottle.

The strips of paper were then dried in a vacuum dryer for 8 hours at 90 °C and at a reduced pressure equal to 0.35 mbar. The dried samples were placed in an environmental chamber. The purpose of conditioning the samples in an environmental chamber was to prepare paper samples with different water content levels. The paper samples were conditioned at 70 °C, in air with a relative humidity (RH) of 5, 15, 27, 40, and 54 %. The conditioning times for different sample sets are presented in Table 2.4.

Set	RH, %	Conditioning time, hours
I	5	t <sub>5%</sub> = 24
Ш	15	$t_{15\%} = t_{5\%} + 24 = 48$
Ш	27	$t_{27\%} = t_{5\%} + t_{15\%} + 24 = 72$
IV	40	$t_{40\%} = t_{5\%} + t_{15\%} + t_{27\%} + 24 = 96$
V	54	$t_{54\%} = t_{5\%} + t_{15\%} + t_{27\%} + t_{40\%} + 24 = 120$

 Table 2.4: Conditioning times for different sample sets.

Immediately after removing each set from the environmental chamber, the samples were impregnated with mineral oil conditioned in the same manner as the paper. The samples were immersed in oil, sealed in weighting bottles and conditioned at a temperature of about 23 °C for 30 days. The samples were then wound around aluminium tubes. In total, 15 aluminium tubes were used; two strips of papers conditioned in the same manner were wound around each tube (one cellulose paper strip and one aramid paper strip).

After winding the paper strips around the tubes, the tubes were immediately placed in glass containers filled with oil.

In total five sets were used in the study, each containing three tubes. In each set, two tubes were used to determine the bubble initiation temperature and one was used to determine the water content of the paper strips. The KFT method was applied to determine the water content. The results of the KFT tests are given in Figure 2.7.



Figure 2.7: Water sorption isotherms for cellulose and aramid paper determined at 70 °C. The curves presented in Figure 2.7 indicate that aramid paper adsorbs much less water than cellulose paper.

### 2.6.2 Method

The measurement set-up consisted of a glass container filled with mineral oil that had an immersion heater inside. The tubes, wrapped in cellulose and aramid paper samples that had been pre-conditioned for different water content levels, were slid onto the heater. A thermocouple was inserted into the tube. The thermocouple was connected to a multi-channel temperature sensor. The rate of the temperature rise in the tube was changed by modifying the heater supply voltage over time, which was achieved by means of an autotransformer. The temperature of the tube was increased by approximately 6 °C/min. The bubble effect was recorded with a camera, and the bubble effect initiation temperature was determined based on observation (i.e. the moment when the water vapour bubbles first started to appear) and by measuring the temperature in the tube.

#### 2.6.3 Results

In both cellulose and aramid paper set-ups, the higher the water content in the paper, the lower the bubble effect initiation temperature. The result can be seen in Figure 2.8.



Figure 2.8: Bubble effect initiation temperature for cellulose and aramid paper as a function of paper water content.

Assuming the same water level in both types of paper, the author concluded that the bubble effect initiation temperature is lower for aramid paper than it is for cellulose paper. On average, the bubble effect initiation temperature for aramid paper is lower by about 18 °C compared to cellulose paper.

In both cellulose and aramid paper set-ups, the bubble effect initiation temperature depends to a large extent on the environmental conditioning parameters; in this case it was air humidity, where an increase in air humidity led to a lowering of the bubble effect initiation temperature. The result can be seen in Figure 2.9.



Figure 2.9: Bubble effect initiation temperature for cellulose and aramid paper as a function of the relative humidity of air in which both papers were conditioned.

If cellulose and aramid papers are conditioned under the same environmental conditions, their bubble effect initiation temperature is very similar.

## 2.7 Summary and Areas Identified for Investigation

From this review of the past research on bubble formation in mineral oil, factors that influenced the bubble inception temperature were identified. They are as follows:

- 1. The paper water content [17, 18, 27, 28, 34].
- 2. The oil gas content [17].
- 3. The paper ageing [18, 27].
- 4. The paper dielectric losses [28].

- 5. The type of paper [18].
- 6. The oil ageing [18].
- 7. The temperature rise [18].
- 8. The mechanical vibration [33].
- 9. The material of paper [34].

# **Chapter 3: The Physics of Bubble Formation**

This chapter presents the basic and advanced physics concepts and theories needed to explain the process of bubble formation in the context of an oil-paper insulation system.

# 3.1 Basic – The Liquid-Vapour Interface

#### 3.1.1 Introduction

This section covers the concepts and theories of surface tension, curved surfaces, capillary action, and condensation. The source for this section is [20].

#### 3.1.2 Surface Tension

Liquids tend to adopt shapes that minimise their surface area, for then the maximum number of molecules is in the bulk and hence surrounded by and interacting with neighbours. Droplets of liquids therefore tend to be spherical, because a sphere is the shape with the smallest surface-to-volume ratio.

In the context of an oil-paper insulation system, the oil surface tension will influence the likelihood that bubble will form based on how well the oil surface will deform in response to the build-up of released water from the paper. In this case, the greater the oil surface tension, the better it should be at resisting bubble formation.

Scala [19] noted that bubble formation is more likely to form on paper because the interfacial tension of a liquid is often reduced at solid surfaces, whereas in oil there is an increase of surface tension on the bubble. This statement reinforces the importance of oil surface tension in resisting bubble formation. The work needed to change the surface area,  $\sigma$ , of a sample by an infinitesimal amount  $d\sigma$  is proportional to dw, expressed as

$$dw = \gamma d\sigma \tag{3.1}$$

The constant of proportionality,  $\gamma$ , is called the **surface tension**; its dimensions are energy/area and its units are typically joules per metre squared (J m<sup>-2</sup>). However, values of  $\gamma$  are also usually reported in newtons per metre (N m<sup>-1</sup>, because 1 J = 1 N m).

#### 3.1.3 Curved Surfaces

The minimisation of the surface area of a liquid may result in the formation of a curved surface. A **bubble** is a region in which vapour (and other gaseous contaminant) is trapped by a thin film. A **cavity** is a vapour-filled hole in a liquid. What are widely called 'bubbles' in liquids are therefore strictly cavities. True bubbles have two surfaces (one on each side of the film), and cavities have only one. A **droplet** is a small volume of liquid at equilibrium surrounded by its vapour (and other gaseous contaminant).

In the context of an oil-paper insulation system, the formation of bubbles in the insulation system is then really the formation of cavities filled with the water released from the paper in vapour form.

The pressure on the concave side of an interface,  $P_{in}$ , is always greater than the pressure on the convex side,  $P_{out}$ . This relation is expressed by the **Young-Laplace equation**, expressed as

$$\boldsymbol{P}_{in} = \boldsymbol{P}_{out} + \frac{2\gamma}{r} \tag{3.2}$$

In the context of an oil-paper insulation system, the internal pressure is the sum of the dissolved gas and water vapour pressures, and the external pressure is the sum of atmospheric (for free breathing systems) / gas space (for gas-blanketed systems) and hydrostatic (due to oil) pressures, as noted by Scala [19].

The equation shows that the difference in pressure decreases to zero as the radius of curvature becomes infinite (i.e. when the surface is flat). Since small cavities have small radii of curvature, the pressure difference across their surface is quite large.

In the context of an oil-paper insulation system, small cavities form due to the total internal pressure of the substance(s) that make up the cavities. The internal pressure can increase by either the addition of dissolved gas and / or water vapour, and / or the addition of thermal energy to increase the temperature of the substance(s), which in turn increases its pressure. This relation is expressed by the ideal gas law, expressed as

$$PV = nRT \tag{3.3}$$

where, *P* is the pressure of the gas in *Pa*, *V* is the volume of the gas in  $m^3$ , *n* is the amount of substance of gas in *mole*, *R* is the ideal, or universal, gas constant, equal to the product of the Boltzmann constant and the Avogadro constant with the value 8.314 J/(K mol) ~ 2 cal/(K mol) or 0.08206 L atm/(mol K), and *T* is the absolute temperature of the gas in *Kelvin*.

#### 3.1.4 Capillary Action

The tendency of liquids to rise up capillary tubes (tubes of narrow bore), which is called **capillary action**, is a consequence of surface tension. Consider what happens when a glass capillary tube is first immersed in water or any liquid that has a tendency to adhere to the walls. The energy is lowest when a thin film covers as much of the glass as possible. As this film creeps up the inside wall it has the effect of curving the surface of the liquid inside the tube. This curvature implies that the pressure just beneath the curving meniscus is less than the atmospheric pressure by approximately  $2\gamma/r$ , where *r* is the radius of the tube and assuming a hemispherical surface. The pressure immediately under the flat surface outside the tube is *p*, the atmospheric pressure, but inside the tube under the curved surface it is only  $p - 2\gamma/r$ . The excess external pressure presses the liquid up the tube until hydrostatic equilibrium (equal pressures at equal depths) is reached.

To calculate the height to which the liquid rises, we note that the pressure exerted by a column of liquid of mass density  $\rho$  and height *h* is

$$\boldsymbol{p} = \boldsymbol{\rho} \boldsymbol{g} \boldsymbol{h} \tag{3.4}$$

This hydrostatic pressure matches the pressure difference  $2\gamma/r$  at equilibrium. Therefore, the height of the column at equilibrium is obtained by equating  $2\gamma/r$  and  $\rho gh$  which gives

$$h = \frac{2\gamma}{\rho g r} \tag{3.5}$$

This expression provides a reasonably accurate way of measuring the surface tension of liquids. However, note that surface tension decreases with increasing temperature.

In the context of an oil-paper insulation system, Equation (3.4) can also be used to determine the hydrostatic pressure exerted by the oil on each of the windings, which will then contribute to the external pressure resisting bubble formation. It is then of importance to know the oil density, as it will determine how well the oil resists bubble formation. The denser the oil, the more it should be able to resist bubble formation.

When the adhesive forces between the liquid and the material of the capillary wall are weaker than the cohesive forces within the liquid (e.g. mercury in glass), the liquid in the tube retracts from the walls. This retraction curves the surface with the concave, high-pressure side downwards. To equalise the pressure at the same depth throughout the liquid, the surface must fall to compensate for the heightened pressure arising from its curvature. This compensation results in a capillary depression.

In many cases there is a non-zero angle between the edge of the meniscus and the wall. If this contact angle is  $\theta_c$ , Equation (3.5) should be modified by multiplying the right-hand side by  $\cos \theta_c$ . The origin of the contact angle can be traced to the balance of forces at the line of contact between the liquid and the solid. If the solidgas, solid-liquid, and liquid-gas surface tensions (essentially the energy needed to create unit areas of each of the interfaces) are denoted  $\gamma_{sg}$ ,  $\gamma_{sl}$ ,  $\gamma_{lg}$  respectively, then the vertical forces are in balance if

$$\gamma_{sg} = \gamma_{sl} + \gamma_{lg} \cos \theta_c \tag{3.6}$$

This expression solves to

$$\cos\theta_c = \frac{\gamma_{sg} - \gamma_{sl}}{\gamma_{lg}} \tag{3.7}$$

If the superficial work of adhesion of the liquid to the solid (the work of adhesion divided by the area of contact) is

$$w_{ad} = \gamma_{sg} + \gamma_{lg} - \gamma_{sl} \tag{3.8}$$

Equation (3.7) can be written

$$\cos\theta_c = \frac{w_{ad}}{\gamma_{lg}} - 1 \tag{3.9}$$

The liquid 'wets' (spreads over) the surface, corresponding to  $0 < \theta_c < 90^\circ$ , when  $1 < w_{ad}/\gamma_{lg} < 2$ . The liquid does not wet the surface corresponding to  $90^\circ < \theta_c < 180^\circ$ , when  $0 < w_{ad}/\gamma_{lg} < 1$ .

In the context of an oil-paper insulation system, given that the liquid is the oil and the solid surface is the paper which is hydrophilic, the contact angle of the oil should be in the range of  $90^{\circ} < \theta_c < 180^{\circ}$ . This is because oil does not adhere to paper as well as water does, and it is therefore the released water that spreads on the paper surface instead.

#### 3.1.5 Condensation

Saturated vapour pressure is defined as the pressure exerted by a vapour in thermodynamic equilibrium with its condensed phases (solid or liquid) at a given temperature in a closed system.

The vapour pressure of a liquid depends on the pressure applied to the liquid. Because curving a surface gives rise to a pressure differential of  $\Delta P = 2\gamma/r$ , it can be expected that the vapour pressure above a curved surface to be different from that above a flat surface.

The quantitative relation between the vapour pressure, p, when a pressure  $\Delta P$  is applied and the vapour pressure,  $p^*$ , of the liquid in the absence of additional pressure is

$$\boldsymbol{p} = \boldsymbol{p}^* \boldsymbol{e}^{V_m \Delta \boldsymbol{P}/RT} \tag{3.10}$$

where  $V_m$  is the molar volume in  $m^3 \mod^1$ , R is the ideal, or universal, gas constant, equal to the product of the Boltzmann constant and the Avogadro constant with the value 8.314 J/(K mol) ~ 2 cal/(K mol) or 0.08206 L atm/(mol K), and T is the absolute temperature of the gas in *Kelvin*. This equation shows how the vapour pressure increases when the pressure acting on the condensed phase is increased.

By substituting this value of the pressure difference into Equation (3.10), where  $p^*$  is the vapour pressure when the pressure difference is zero, what is obtained is

the **Kelvin equation** for the vapour pressure of a liquid when it is dispersed as droplets of radius *r*.

$$\boldsymbol{p} = \boldsymbol{p}^* \boldsymbol{e}^{2\gamma \boldsymbol{V}_m/\boldsymbol{r} \boldsymbol{R} \boldsymbol{T}} \tag{3.11}$$

The analogous expression for the vapour pressure inside a cavity can be written at once. Since the pressure of the liquid outside the cavity is less than the pressure inside, the only change is in the sign of the exponent in the last expression.

In the context of an oil-paper insulation system, the modified Kelvin equation can be used to determine the external pressure exerted on the water vapour bubble as a function of oil surface tension.

Consider the formation of a cloud. Warm, moist air rises into the cooler regions higher in the atmosphere. At some altitude the temperature is so low that the vapour becomes thermodynamically unstable with respect to the liquid and we expect it to condense into a cloud of liquid droplets. The initial step can be imagined as a swarm of water molecules congregating into a microscopic droplet. Because the initial droplet is so small, it has an enhanced vapour pressure. Therefore, instead of growing it evaporates. This effect stabilises the vapour because an initial tendency to condense is overcome by a heightened tendency to evaporate. The vapour phase is then said to be **supersaturated**. It is thermodynamically unstable with respect to the liquid but not unstable with respect to the small droplets that need to form before the bulk liquid phase can appear, so the formation of the latter by a simple, direct mechanism is hindered.

Clouds do form, so there must be a mechanism. Two processes are responsible. The first is that a sufficiently large number of molecules might congregate into a droplet so big that the enhanced evaporative effect is unimportant. The chance of one of these **spontaneous nucleation centres** forming is low, and in

rain formation it is not a dominant mechanism. The more important process depends on the presence of minute dust particles or other kinds of foreign matter. These **nucleate** the condensation (that is, provide centres at which it can occur) by providing surfaces to which the water molecules can attach.

In the context of an oil-paper insulation system, cellulose fibres from the paper, or even a piece of the paper itself, may break off from the bulk of the paper and exist in the oil. These particular oil impurities can act as nucleation sites for bubble formation.

Liquids may be **superheated** above their boiling temperatures and **supercooled** below their freezing temperatures. In each case the thermodynamically stable phase is not achieved on account of the kinetic stabilisation that occurs in the absence of nucleation centres. For example, superheating occurs because the vapour pressure inside a cavity is artificially low, so any cavity that does form tends to collapse. This instability is encountered when an unstirred beaker of water is heated, for its temperature may be raised above its boiling point. Violent bumping often ensues as spontaneous nucleation leads to bubbles big enough to survive. To ensure smooth boiling at the true bubbling temperature, nucleation centres, such as small pieces of sharp-edged glass or bubbles (cavities) of air, should be introduced.

### 3.2 Advanced – Phase Change, Nucleation, and Cavitation

### 3.2.1 Introduction

This section covers the concepts and theories of the liquid state, fluidity and elasticity, cavitation and boiling, types of nucleation, homogeneous nucleation theory, heterogeneous nucleation, effect of contaminant gas, nucleation in flowing liquids, and viscous effects in cavitation inception. The source for this section is [35].

This section focuses on the mechanisms of formation of two-phase mixtures of vapour and liquid. Particular attention is given to the process of the creation of vapour bubbles in a liquid.

The studies reported here deal largely with very pure liquids and clean environments in order to isolate the behaviour of pure liquids. On the other hand, most engineering systems are impure or contaminated in ways that have important effects on the process of nucleation.

In the context of an oil-paper insulation system, the impurities that are most likely able to induce nucleation are cellulose fibres and insulation paper pieces.

The physics of nucleation in such engineering environments tends to be divided into two separate fields of interest, cavitation and boiling. **Cavitation** is defined as the process of nucleation in a liquid when the pressure falls below the vapour pressure. **Boiling** is defined as the process of nucleation that occurs when the temperature is raised above the saturated vapour / liquid temperature.

In the context of an oil-paper insulation system, the process of nucleation is via cavitation, but the fall in oil pressure is due to the increasing pressure exerted by the released water which is driven by thermal energy / heat from the increasingly heated windings during overload.

In the context of an oil-paper insulation system, and given that water resides mostly in the paper insulation – a solid, the process of nucleation here is then due to the drying of the paper insulation.

From a basic physical point of view, there is little difference between the two processes. The differences in the two processes occur because of the different

complicating factors that occur in cavitating flow on the one hand, and in the temperature gradients and wall effects that occur in boiling on the other hand.

#### 3.2.2 The Liquid State

Typical, though idealised, phase diagrams can be seen in Figure 3.1, where *p* is pressure, *T* is temperature, and *V* is specific volume. The **triple point** is that point in the phase diagram at which the solid, liquid, and vapour states coexist; that is to say, the substance has three alternative stable states. The saturated liquid / vapour line (or bimodal) extends from this point to the critical point. Thermodynamically it is defined by the fact that the chemical potentials of the two co-existing phases must be equal. On this line the vapour and liquid states represent two limiting forms of a single "amorphous" state, one of which can be obtained from the other by isothermal volumetric changes, leading through intermediate but unstable states. To quote Frenkel [36], "Owing to this instability, the actual transition from the liquid state to the gaseous one and vice versa takes place **not** along a **theoretical** isotherm (dashed line, right, Figure 3.1), but along a horizontal isotherm (solid line), corresponding to the splitting up of the original homogeneous substance into two different coexisting phases...". The critical point is that point at which the maxima and minima in the theoretical isotherm vanish and the discontinuity disappears.



Figure 3.1: Typical phase diagrams.

The line joining the maxima in the theoretical isotherms is called the **vapour spinodal line**; the line joining the minima is called the **liquid spinodal line**. Clearly, both spinodals end at the critical point. The two regions between the spinodal lines and the saturated (or binodal) lines are of particular interest, because the conditions represented by the theoretical isotherm within these regions can be realised in practice under certain special conditions.

#### 3.2.3 Fluidity and Elasticity

It is valuable to point out several qualitative features of the liquid state and to remark on its comparison with the simpler crystalline solid or gaseous states.

The first difference between the saturated liquid and saturated vapour states is that the density of the liquid remains relatively constant and similar to that of the solid, except close to the critical point. On the other hand, the density of the vapour is different by at least 2 and up to 5 or more orders of magnitude, changing radically with temperature.

Second, an examination of the measured specific heat of the saturated liquid reveals that this is of the same order as the specific heat of the solid, except at high temperatures close to the critical point. Specific heat is defined as the amount of heat needed to raise the temperature of one kilogram of mass by one Kelvin, and its units are typically joules per kilogram Kelvin (J kg<sup>-1</sup> K<sup>-1</sup>).

The above two features of liquids imply that the thermal motion of the liquid molecules is similar to that of the solid and involves small amplitude vibrations about a quasi-equilibrium position within the liquid. Therefore, the arrangement of the molecules has greater similarity with a solid than with a gas. This similarity with a solid is stressed to counteract the tendency to think of the liquid state as more akin to the gaseous state than to the solid state, because in many observed processes it possesses a dominant fluidity rather than a dominant elasticity.

In the context of an oil-paper insulation system, the oil being liquid possesses the property of 'elasticity' due to surface tension. This elasticity resists bubble formation, until there is sufficient pressure built up in the released water to 'rupture' the oil. From the point of rupture the water expands in an omnidirectional way, increasing the oil surface area. The oil in response then curves its surface to minimise water expansion, thus forming a bubble of water.

Since in many cases the process of nucleation is also controlled by stochastic events, the observation time plays a significant role in determining this process. Over a longer period of time there is a greater probability that vacancies will coalesce to form a finite vapour pocket, leading to nucleation. Conversely, it is also possible to visualise that a liquid could be placed in a state of tension (negative pressure) for a significant period of time before a vapour bubble would form in it. Such a scenario was visualised in 1850, when Berthelot [37] subjected purified water to tensions of up to 50 atm before it yielded. This ability of liquids to withstand tension, that is its tensile strength, is very similar to the more familiar property exhibited by solids and is a manifestation of the elasticity of a liquid.

### 3.2.4 Cavitation and Boiling

The tensile strength of a liquid can be manifest in at least two ways:

1. A liquid at constant temperature could be subjected to a decreasing pressure, p, which falls below the saturated vapour pressure,  $p_v$ . The value of  $(p_v - p)$  is called the **tension**,  $\Delta p$ , and the magnitude at which rupture occurs is the **tensile strength** of the liquid,  $\Delta p_c$ . The process of rupturing a liquid by

decrease in pressure at roughly constant liquid temperature is often called **cavitation**.

2. A liquid at constant pressure may be subjected to a temperature, *T*, in excess of the normal saturation temperature / boiling point temperature, *T*<sub>S</sub>. The value of  $\Delta T = T - T_S$  is the **superheat**, and the point at which vapour is formed,  $\Delta T_C$ , is called the **critical superheat**. The process of rupturing a liquid by increasing the temperature at roughly constant pressure is often called **boiling**.

In the context of an oil-paper insulation system, the process of bubble formation is via cavitation. The oil ruptures due to it experiencing a decreasing pressure as a consequence of an increasing pressure exerted by the released water which is driven by thermal energy / heat from the increasingly heated windings during overload.

Tensile strength is determined by weaknesses at points within the liquid. Such weaknesses are probably ephemeral and difficult to quantify, since they could be caused by minute impurities. This difficulty and the dependence on the time of application of the tension greatly complicate any theoretical evaluation of the tensile strength.

Although the basic mechanics of cavitation and boiling must clearly be similar, it is important to differentiate between the thermodynamic paths that precede the formation of vapour. There are differences in the practical manifestations of the two paths because, although it is fairly easy to cause uniform changes in pressure in a body of liquid, it is very difficult to uniformly change the temperature. Note that the

critical values of the tension and superheat may be related when the magnitudes of these quantities are small. By the Clausius-Clapeyron relation,

$$\left(\frac{dp}{dT}\right)_{saturation \ conditions} = \frac{L}{T[\rho_V^{-1} - \rho_L^{-1}]}$$
(3.12)

where  $\rho_L$ ,  $\rho_V$  are the saturated liquid and vapour densities and *L* is the latent heat of evaporation. Except close to the critical point, we have  $\rho_L \gg \rho_V$  and hence  $dp/dT \approx \rho_V L/T$ . Therefore

$$\Delta T_{c} \approx \Delta P_{c} \frac{T}{L_{\rho\nu}}$$
(3.13)

It is important to emphasize that Equation (3.13) is limited to small values of the tension and superheat but provides a useful relation under those circumstances. When  $\Delta p_c$  and  $\Delta T_c$  are larger, it is necessary to use an appropriate equation of state for the substance in order to establish a numerical relationship.

#### 3.2.5 Types of Nucleation

In any practical experiment or application, weaknesses can typically occur in two forms. The thermal motions within the liquid form temporary microscopic voids that can constitute the nuclei necessary for rupture and growth to macroscopic bubbles. This is termed **homogeneous nucleation**. In practical engineering situations, it is much commoner to find that the major weaknesses occur at the boundary between the liquid and the solid or between the liquid and small particles suspended in the liquid. When rupture occurs at such sites, it is termed **heterogeneous nucleation**.

In the context of an oil-paper insulation system, the process of nucleation / bubble formation is classified as heterogeneous nucleation. The major weakness that exists at the boundary between the liquid and the solid, that is the oil and the

paper, is due to the pores of the paper surface. The minor weakness that can exist suspended in the liquid, that is the oil, is due to impurities. The most likely impurity is cellulose fibres that were broken off from the paper due to paper ageing.

In covering the subject of homogeneous nucleation, the classical treatment using the kinetic theory of liquids allows only weaknesses of one type: the ephemeral voids that happen to occur because of the thermal motions of the molecules. In any real system several other types of weakness are possible. First, it is possible for nucleation to occur at the junction of the liquid and a solid boundary. Kinetic theories have also been developed to cover such heterogeneous nucleation and allow the evaluation of whether the chance that this will occur is larger or smaller than the chance of homogeneous nucleation. Heterogeneous nucleation could also occur on very small, sub-micron-sized contaminant particles in the liquid; experimentally this would be hard to distinguish from homogeneous nucleation.

Another form of weaknesses are micron-sized bubbles (micro-bubbles) of contaminant gas, which could be present in crevices within the solid boundary or within suspended particles, or could simply be freely suspended within the liquid. In water, micro-bubbles of air seem to persist almost indefinitely and are almost impossible to remove completely, perhaps because of contamination of the interface. While it may be possible to remove most of these nuclei from a small research laboratory sample, their presence dominates most engineering applications. In liquids other than water, the kinds of contamination which can occur in practice have not received the same attention.

In the context of an oil-paper insulation system, bubbles of contaminant gas could be present in the pores of the paper surface. The contaminant gas would most likely be the dissolved gases in, and from, the oil and / or the by-product of paper

ageing. The bubbles of contaminant gas by themselves would not be able to induce transformer failure, as contaminant gases are normally found in low quantities, but would be able to contribute to the released water by adding to its internal pressure.

Another important form of contamination is cosmic radiation. A collision between a high energy particle and a molecule of the liquid can deposit sufficient energy to initiate nucleation when it would otherwise have little chance of occurring. Such is the principle of the bubble chamber [38].

#### 3.2.6 Homogeneous Nucleation Theory

In a pure liquid, surface tension is the macroscopic manifestation of the intermolecular forces that tend to hold molecules together and prevent the formation of large holes. The liquid pressure, p, exterior to a bubble of radius R, is related to the interior pressure,  $p_B$ , by

$$p_B - p = \frac{2S}{R} \tag{3.14}$$

where, *S* is the surface tension. In this section, it is assumed that the concept of surface tension (or, rather, surface energy) can be extended to bubbles or vacancies a few intermolecular distances in size. Such an approximation is accurate [38].

If the temperature, *T*, is uniform and the bubble contains only vapour, then the interior pressure  $p_B$  will be the saturated vapour pressure  $p_V(T)$ . However, the exterior liquid pressure,  $p = p_V - 2S/R$ , must be less than  $p_V$  in order to produce equilibrium conditions. Consequently, if the exterior liquid pressure is maintained at a constant value just slightly less than  $p_V - 2S/R$ , the bubble will grow, *R* will increase, the excess pressure causing growth will increase, and rupture will occur.

It follows that if the maximum size of vacancy present is  $R_C$  (termed the critical radius or cluster radius), then the tensile strength of the liquid,  $\Delta p_C$ , will be given by

$$\Delta p_c = 2S/R_c \tag{3.15}$$

In the case of ephemeral vacancies such as those created by random molecular motions, this simple expression,  $\Delta p_c = 2S/R_c$ , must be couched in terms of the probability that a vacancy,  $R_c$ , will occur during the time for which the tension is applied or the time of observation. This would then yield a probability that the liquid would rupture under a given tension during the available time.

Equation (3.15) is the first of three basic relations that constitute homogeneous nucleation theory. The second expression which needs to be identified is that giving the increment of energy that must be deposited in the body of the pure liquid in order to create a nucleus or microbubble of the critical size,  $R_{\rm C}$ . Assuming that the critical nucleus is in thermodynamic equilibrium with its surroundings after its creation, then the increment of energy that must be deposited consists of two parts. First, energy must be deposited to account for that stored in the surface of the bubble. By definition of the surface tension, S, that amount is S per unit surface area for a total of  $4\pi R_c^2 S$ . However, in addition, the liquid has to be displaced outward in order to create the bubble, and this implies work done on or by the system. The pressure difference involved in this energy increment is the difference between the pressure inside and outside the bubble (which, in this evaluation, is  $\Delta p_{C}$ , given by Equation (3.14). The work done is the volume of the bubble multiplied by this pressure difference, or  $4\pi R_c^3 \Delta_{p_c}$ ,/3, and this is the work done by the liquid to achieve the displacement implied by the creation of the bubble. Therefore, the net energy,  $W_{CR}$ , that must be deposited to form the bubble is

$$W_{CR} = 4\pi R_c^2 S - \frac{4}{3}\pi R_c^3 \Delta_{p_c} = \frac{4}{3}\pi R_c^2 S$$
(3.16)

It can also be useful to eliminate  $R_c$  from equation (3.15) and (3.16) to write the expression for the critical deposition energy as

$$W_{CR} = 16\pi S^3 / 3 (\Delta_{p_c})^2$$
(3.17)

Gibbs [39] in 1961 first formulated this expression.

The final step in homogeneous nucleation theory is the evaluation of the mechanisms by which energy deposition could occur and the probability of that energy reaching the magnitude,  $W_{CR}$ , in the available time. Then Equation (3.17) yields the probability of the liquid being able to sustain a tension of  $\Delta p_C$  during that time. In the body of a pure liquid completely isolated from any external radiation, the issue is reduced to the evaluation of the probability that the stochastic nature of the thermal motions of the molecules would lead to a local energy perturbation of magnitude  $W_{CR}$ . Most homogeneous nucleation theories therefore relate  $W_{CR}$  to the typical kinetic energy of the molecules, namely kT (k is Boltzmann's constant), and the relationship is couched in terms of a Gibbs number,

$$Gb = W_{CR}/kT \tag{3.18}$$

It follows that a given Gibbs number will correspond to a certain probability of a nucleation event in a given volume during a given available time. For later use it is wise to point out that other basic relations for  $W_{CR}$  have been proposed. For example, Lienhard and Karimi [40] in 1981 found that a value of  $W_{CR}$  related to  $kT_C$  (where  $T_C$  is the critical temperature) rather than kT led to a better correlation with experimental observations.

A number of expressions have been proposed for the precise form of the relationship between the nucleation rate, *J*, defined as the number of nucleation events occurring in a unit volume per unit time and the Gibbs number, *Gb*, but all take the general form

$$\boldsymbol{J} = \boldsymbol{J}_{\boldsymbol{\theta}} \boldsymbol{e}^{-\boldsymbol{G}\boldsymbol{b}} \tag{3.19}$$

where,  $J_o$  is some factor of proportionality. Various functional forms have been suggested for  $J_o$ . A typical form is given by Blander and Katz [41] in 1975, namely

$$J_o = N \left(\frac{2S}{\pi m}\right)^{\frac{1}{2}} \tag{3.20}$$

where, *N* is the number density of the liquid (molecules/ $m^3$ ) and *m* is the mass of a molecule. Although  $J_o$  may be a function of temperature, the effect of an error in  $J_o$  is small compared with the effect on the exponent, *Gb*, in Equation (3.19).

#### 3.2.7 Heterogeneous Nucleation

In the case of homogeneous nucleation, microscopic voids of radius *R* were considered, which grow causing rupture when the pressure on the liquid, *p*, is reduced below the critical value  $p_V - 2S/R$ . Therefore the tensile strength was 2S/R.

Now consider a number of analogous situations at a solid / liquid interface as indicated in Figure 3.2.



CASE (C) CONICAL CAVITY



Figure 3.2: Various modes of heterogeneous nucleation.

The contact angle at the liquid / vapour / solid intersection is denoted by  $\theta$ . It follows that the tensile strength in the case of the flat hydrophobic surface is given by  $2S \sin \theta/R$ , where *R* is the typical maximum dimension of the void. Hence, in theory, the tensile strength could be zero in the limit as  $\theta \rightarrow \pi$ . On the other hand, the tensile strength for a hydrophilic surface is comparable with that for homogeneous nucleation, since the maximum dimensions of the voids are comparable, in that the voids are sphere-like. It is possible to conclude that the presence of a hydrophobic surface would cause heterogeneous nucleation and much reduced tensile strength.

In the context of an oil-paper insulation system, here the surface is the paper which is hydrophilic, and the liquid is the oil which is not attracted to the surface. Hence, the bubble should be closer in shape to that shown in case (A), because the oil would like to minimise its surface area and so spreads the bubble across the paper surface. Again, the oil in this context resists bubble formation and how well it

resists is dependent on the oil tensile strength, which is determined by the oil surface tension.

At the microscopic scale, since surfaces are not flat, we must consider the effects of other local surface geometries. The conical cavity of case (C) is usually considered in order to exemplify the effect of surface geometry. If the half angle at the vertex of this cavity is denoted by  $\alpha$ , then it is clear that zero tensile strength occurs at the more realisable value of  $\theta = \alpha + \pi/2$  rather than  $\theta \to \pi$ . Moreover, if  $\theta > \alpha + \pi/2$ , it is clear that the vapour bubble would grow to fill the cavity at pressures above the vapour pressure.

Hence, considering the range of microscopic surface geometries, then it is not surprising that vapour pockets would grow within some particular surface cavities at pressures in the neighbourhood of the vapour pressure, particularly when the surface is hydrophobic.

In the context of an oil-paper insulation system, the paper is porous in order to allow for it to be impregnated with the oil. The surface pores of the paper give the released water and contaminant gases the space for them to accumulate.

Two matters still need to be considered. First, how might such a vapour pocket first be created? In most experiments it is quite plausible to conceive of minute pockets of contaminant gas absorbed in the solid surface. This is perhaps least likely with freshly-formed glass capillary tubes, a fact that may help explain the larger tensions measured in Berthelot tube experiments. The second issue concerns the expansion of these vapour pockets beyond the envelope of the solid surface and into the body of the liquid. It can be argued that dramatic rupture requires the appearance of large voids in the body of the liquid and hence that the flat surface configurations should still be applicable on a larger scale. The answer clearly lies

with the detailed topology of the surface. If the opening of the cavity has dimensions of the order of  $10^{-5}$  *m*, the subsequent tension required to expand the bubble beyond the envelope of the surface is only of the order of a tenth of an atmosphere and hence quite within the realm of experimental observation.

Some specific sites on a solid surface have the optimum geometry to promote the growth and macroscopic appearance of vapour bubbles. Such locations are called **nucleation sites**. As the pressure is reduced more and more, sites become capable of generating and releasing bubbles to the body of the liquid. Hence, the density of nucleation sites as a function of superheating is an important component in the quantification of nucleate boiling.

In the context of an oil-paper insulation system, the paper property of nucleation site density is dependent on the paper type, which in turn is dependent on its composition and manufacturing process.

#### 3.2.8 Effect of Contaminant Gas

Virtually all liquids contain some dissolved gas, and it is virtually impossible to eliminate this gas from any substantial liquid volume. If the nucleation bubble contains some gas, then the pressure in the bubble is the sum of the partial pressure of this gas,  $p_G$ , and the vapour pressure. Hence the equilibrium pressure in the liquid is  $p = p_V + p_G - 2S/R$  and the critical tension is  $2S/R - p_G$ . Thus dissolved gas decreases the potential tensile strength. If the concentration of gas leads to sufficiently large values of  $p_G$ , the tensile strength is negative and the bubble will grow at liquid pressures greater than the vapour pressure.

In the context of an oil-paper insulation system, the efficacy of dissolved gas in decreasing the potential tensile strength of the oil and helping promote the formation and growth of bubbles can be confirmed in the work of Oommen and Lindgren [17].

In the above context, the liquid is **not** saturated with gas at the pressure at which it has been stored. In theory, no gas bubbles can exist in equilibrium in a liquid unsaturated with gas but otherwise pure if the pressure is maintained above  $p_V + p_G$  where  $p_G$  is the equilibrium gas pressure. They should dissolve and disappear, thus causing a dramatic increase in the tensile strength of the liquid.

In the context of an oil-paper insulation system, the oil and paper used would have been dried and degassed before the transformer is put into service.

Degassing or high-pressure treatment does cause some increase in tensile strength [42], but the effect is not as great as one would expect. At least three plausible explanations have been advanced to explain this lack of efficacy. First is the Harvey nucleus [43] in which the bubble exists in a crevice in a particle or surface and persists because its geometry is such that the free surface has a highly convex curvature viewed from the fluid so that surface tension supports the high liquid pressure. Second is the possibility of the continuous production of nuclei by cosmic radiation. The third possibility was proposed by Fox and Herzfeld [44] of an 'organic skin' that gives the free surface of the bubble sufficient elasticity to withstand high pressure. Although originally less plausible than the first two possibilities, this explanation is now more widely accepted because of recent advances in surface rheology, which show that quite small amounts of contaminant in the liquid can generate large elastic surface effects. Such contamination of the surface has also been detected by electron microscopy.

#### 3.2.9 Nucleation in Flowing Liquids

The most common occurrence of cavitation is in flowing liquid systems where hydrodynamic effects result in regions of the flow where the pressure falls below the vapour pressure.

In the context of an oil-paper insulation system, bubble formation may occur if the transformer uses either an oil-forced (OF) or oil-directed (OD) cooling system. When used, both systems may potentially create such low pressure regions near the windings as they are being cooled. The bubbles generated may then gather and coalesce into bubbles of sufficient size to induce transformer failure.

Consider a steady, single-phase flow of a Newtonian liquid of constant density,  $\rho_L$ , velocity field,  $u_i(x_i)$ , and pressure,  $p(x_i)$ . In all such flows it is convenient to define a reference velocity,  $U_{\infty}$ , and reference pressure,  $p_{\infty}$ . In external flows around solid bodies,  $U_{\infty}$  and  $p_{\infty}$  are conventionally the velocity and pressure of the uniform, upstream flow. The equations of motion are such that changing the reference pressure results in the same uniform change to the pressure throughout the flow field. Therefore, the pressure coefficient

$$C_p(x_i) = \frac{p(x_i) - p_{\infty}}{\frac{1}{2}\rho U_{\infty}^2}$$
(3.21)

is independent of  $p_{\infty}$  for a given geometry of the macroscopic flow boundaries. Furthermore, there will be some location,  $x_i^*$ , within the flow where  $C_p$  and p are minimum, and that value of  $C_p(x_i^*)$  will be denoted for convenience by  $C_{pmin}$ . Note that this is a **negative** number.

Viscous effects within the flow are characterised by the Reynolds number,  $Re = \rho_L U_{\infty} l/\mu_L = U_{\infty} l/\nu_L$  where  $\mu_L$  and  $\nu_L$  are the dynamic and kinematic viscosities of the liquid and *l* is the characterised length scale. For a given geometry,  $C_p(x_i)$  and  $C_{pmin}$ 

are functions only of *Re* in steady flows. In the idealised case of an inviscid, frictionless liquid, Bernoulli's equation applies and  $Cp(x_i)$  and  $C_{pmin}$  become dependent only on the geometry of the flow boundaries and not on any other parameters. Suppose that for the flow geometry under consideration, the value of  $C_{pmin}$  for the single-phase flow is known either from experimental measurement or theoretical calculation.

The stage is therefore set to consider what happens in a given flow when either the overall pressure is decreased or the flow velocity is increased so that the pressure at some point in the flow approaches the vapour pressure,  $p_V$ , of the liquid at the reference temperature,  $T_{\infty}$ . In order to characterise this relationship, it is conventional to define the **cavitation number**,  $\sigma$  as

$$\sigma = \frac{p_{\infty} - p_V(T_{\infty})}{\frac{1}{2}\rho_L U_{\infty}^2}$$
(3.22)

Any flow, whether cavitating or not, has some value of  $\sigma$ . If  $\sigma$  is sufficiently large ( $p_{\infty}$  sufficiently large compared with  $p_V(T_{\infty})$  or  $U_{\infty}$  sufficiently small), single-phase liquid flow will occur. However, as  $\sigma$  is reduced, nucleation will first occur at some particular value of  $\sigma$  called the incipient cavitation number and denoted by  $\sigma_i$ . Further reduction in  $\sigma$  below  $\sigma_i$  causes an increase in the number and extent of vapour bubbles.

In the hypothetical flow of a liquid that cannot withstand any tension and in which vapour bubbles appear instantaneously when p reaches  $p_V$ , it is clear that

$$\boldsymbol{\sigma}_i = -\boldsymbol{\mathcal{C}}_{pmin} \tag{3.23}$$

and hence the incipient cavitation number could be ascertained from observations or measurements of the single-phase flow.
#### **3.2.10 Viscous Effects in Cavitation Inception**

The discussion in the previous section was deliberately confined to ideal, steady flows. When the flow is also assumed to be inviscid, the value of  $-C_{pmin}$  is a simple positive constant for a given flow geometry. However, when the effects of viscosity are included,  $C_{pmin}$  will be a function of the Reynolds number, *Re*, and even in a steady flow one would therefore expect to observe a dependence of the incipient cavitation number,  $\sigma_i$ , on the Reynolds number. For convenience, this is referred to here as the **steady viscous effect**.

In the context of an oil-paper insulation system, the oil viscosity partly determines its capability to act as a coolant for the windings. The oil viscosity indirectly influences bubble formation by determining how well the oil can cycle the hot and wet oil away from the windings for the cold and dry oil to replace it. In doing so, the thermal energy and the released water are removed to prevent bubble formation at the interface of the oil and paper.

Up to this point it has been assumed that the flow and the pressure are laminar and steady. However, most of the flows with which engineers must deal are not only turbulent but also unsteady. Vortices occur, not only because they are inherent in turbulence, but also because of both free and forced shedding of vortices. This has important consequences for cavitation inception because the pressure in the centre of a vortex may be significantly lower than the mean pressure in the flow. The measurement or calculation of  $-C_{pmin}$  would elicit the value of the lowest mean pressure, while cavitation might first occur in a transient vortex the core pressure of which was much lower than the lowest mean pressure. Unlike the residence time factor, this would tend to cause higher values of  $\sigma_i$  than would otherwise be expected. It would also cause  $\sigma_i$  to change with the Reynolds number, *Re.* Note that

this would be separate from the effect of Re on  $C_{pmin}$  and, to distinguish it, we refer to it here as the **turbulence effect**.

In summary, there are a number of reasons for  $\sigma_i$  to be different from the value of  $-C_{pmin}$  that might be calculated from knowledge of the pressures in the single-phase liquid flow:

- 1. Existence of a tensile strength can cause a reduction in  $\sigma_i$ .
- 2. Residence time effects can cause a reduction in  $\sigma_i$ .
- 3. Existence of contaminant gas can cause an increase in  $\sigma_i$ .
- 4. Steady viscous effect due to dependence of  $C_{pmin}$  on Re can cause  $\sigma_i$  to be a function of Re.
- 5. Turbulence effects can cause an increase in  $\sigma_i$ .

If it were not for these effects, the prediction of cavitation would be a straightforward matter of determining  $C_{pmin}$ . Unfortunately, these effects can cause large departures from the criterion,  $\sigma_i = -C_{pmin}$ , with important engineering consequences in many applications.

Furthermore, the above discussion identifies the parameters that must be controlled, or at least measured, in systematic experiments on cavitation inception:

- 1. The cavitation number,  $\sigma$ .
- 2. The Reynolds number, Re.
- 3. The liquid temperature,  $T_{\infty}$ .
- 4. The liquid quality, including the number and nature of the free stream nuclei, the amount of dissolved gas, and the free stream turbulence.
- 5. The quality of the solid, bounding surfaces, including the roughness (since this may affect the hydrodynamics) and the porosity or pit population.

Since many factors are involved, and many of the effects such as the interaction of turbulence and cavitation inception have only recently been identified, it is not surprising that the individual effects are not readily isolated from many of the experiments performed in the past. Nevertheless, some discussion of these experiments is important for practical reasons.

## **Chapter 4: Bubble Formation in Mineral Oil – Previous**

## Study by Monash University

A study funded by the Electric Power Research Institute (EPRI) USA of bubble evolution in mineral oil took place in the mid-1990s at Monash University. The results of this investigation were reported in [26].

Since the intention of the present study is to compare the bubble formation tendency of cellulosic insulation impregnated with different fluids, a similar set-up using the same test equipment and method are used. The new results will then be compared to the previous findings for mineral oil. This section presents a summary of the key findings of the previously reported work.

### 4.1 Rig Design

A rig was specifically designed to simulate the winding of a transformer, in particular, the effect of sudden changes in temperature on the movement of water between the insulation materials. The goal of the experiment was to establish the foundations of water movement dynamics in a transformer, as a basis for a practical tool for use by electrical power utilities. The tool could assess the state of the insulation, and the risk of a transformer failing during either initial energisation or emergency overloads due to bubble formation.

The test rig used two concentric copper coils wrapped in Kraft paper similar to one disc of a transformer winding (Figure 4.1). The coils were impregnated with mineral oil before use (Figure 4.2). A key advantage of this rig was that it used a glass vessel made using borosilicate glass, such that bubble evolution could be observed and video-recorded for later use.



Figure 4.1: Coils used in the investigation.



Figure 4.2: Test rig on standby.

The rig was designed to heat up and cool down in a manner similar to that of an actual in-service transformer. The coils were heated by passing a current through them. This is similar to an operating transformer which may have areas within the windings hotter than the top oil. The one winding used was to represent the top-most winding of an in-service transformer, where the hottest hotspot will develop.

The temperatures within the rig were measured at various points. A Harley water sensor monitored the oil water content and the oil temperature at the top of the tank. A total of eight fibre optic temperature sensors were inserted into the gaps between the copper and Kraft paper sections of the coils, allowing the winding temperatures to be measured. The fibre optic sensor sensing the highest temperature was designated as the one measuring the hotspot temperature.

#### 4.2 Set-up

The cellulosic and mineral oil insulation was conditioned to three set levels of water. These levels were: 0.9 % - realistic of a new transformer, 2.1 % - for a midlife transformer, and 4.1 % - for an older transformer. To achieve the 0.9 % cellulose wetness, the process was vacuum drying of both the paper and mineral oil to a very dry level. To achieve the 2.1 % cellulose wetness, the process was heating the mineral oil up to 60 °C while exposing it to atmospheric water, and then cooling it back to room temperature. Mineral oil dissolves more water at high temperatures. To achieve the 4.1 % cellulose wetness, the process was syringing a known volume of water into the oil and mixing it with a stirrer bar.

#### 4.3 Method

The winding conductor current was raised in steps to give the desired hotspot temperature profile, shown in Table 4.1. The duration of the steps was as follows: 10 minutes of partial load, 10 - 30 minutes of rated load, and 30 minutes of overload. After 20 minutes of overload, the current was reduced by about 10 % to maintain the hotspot temperature constant. An example of the stepped current sequence is shown in Figure 4.3.

As the current was stepped up and the temperature increased, the rig was carefully inspected for the presence of bubbles. As soon as bubbles were detected the hotspot temperature was recorded.

Loading type	Hotspot temperature (°C)	Current (A)
Partial	60	46
Rated	98	160
Over 1	120	210
Over 2	140	240
Over 3	160	260
Over 4	180	290

Table 4.1: Winding conductor current used, and resulting hotspot temperatures.



Figure 4.3: Winding conductor current profile of a test.

## 4.4 Results

In Figure 4.4, two events were noted during water movement. The first event was bubble emission when water precipitation was observed. The second event was when the precipitation formed droplets which fell to the bottom of the tank. In both of these events, as the paper water content increases, their inception temperature decreases. Droplets form at higher temperatures may be due to the need of the droplets to gain enough liquid water mass first, to then be released from the winding.



Figure 4.4: Bubble and droplet inception temperatures as a function of paper water content.

As these droplets appeared to be liquid water, the interfacial tension of the oil may have had an effect on their growth. In addition, their being of liquid water is important in an operating transformer because if a droplet did drop, the electric field of the winding where it came from and the one next below it will hold the droplet between them where it then may continually grow in water quantity due to the bubbles coming up from the windings below. The suspended droplet will then be distorted by the electric field of the windings, and eventually bridge them, as in the experiment by Garton & Krasucki [22].

Bubbling can occur minutes after the temperature has been raised. This is because some amount of time is required for the local oil volume to saturate and a two- phase medium to form. The implication is that bubbles of water do not appear to be forming because the water is desorbing from the paper quicker than it can be dissolved by the oil, rather bubbles are forming because the oil is already saturated.

Figure 4.5 shows the temperature profile of the coil, and it can be seen that not all bubbling was observed on a rising temperature. Occasionally, the temperature had settled. The end temperature reached by the coil is also shown on the graph. This indicates that, in this circumstance, it is likely that the mineral oil was becoming saturated before bubbling was observed, rather than the paper releasing water so fast that the oil was unable to dissolve this water. The thermal properties of the oil,

such as viscosity, may therefore affect bubbling, because this will have an impact on the speed at which water migrates around the vessel. Figure 4.6 shows the relationship between the temperature when bubbling was observed, and the initial water content of paper.



Figure 4.5: Duration of overload when bubble emission was noted, showing the hotspot temperature of the winding when bubbling was observed as a function of the current used to heat the winding.



Figure 4.6: Relationship between the temperature when bubbling was observed, and the initial water content of paper.

## 4.5 Summary

Since paper absorbs far more water than oil, it may be that the ability of vegetable oil to dissolve more water than mineral oil results in more time being required until bubbling commences. If the temperature is increasing, then this time extension effect may result in a higher bubbling temperature being reached. The thermal properties of the vegetable oil, which may affect the migration of water away from the surface of the paper, may have an effect.

# Chapter 5: Bubble Formation in Vegetable Oil – Current Study by Monash University

The formation of bubbles and droplets in degassed vegetable oil (FR3) was investigated using a similar set-up with the same test equipment and method used previously for mineral oil [26].

## 5.1 Set-up

The experiment was conducted in a glass vessel (Figure 5.1) to allow visual observation of bubbles and droplets. The vessel consisted of a winding made up of two copper coils, each with four layers of Kraft paper. The two coils were tightly wound around a Teflon former creating a disc with 16 turns (Figure 5.2). The ends of the coils were connected to brass rods on the inner side of the Teflon flange, and a current transformer was used to supply current to the coils via copper conductors that were connected to the very same brass rods on the outer side of the Teflon flange. The coils were connected in parallel.



Figure 5.1: Setup used for the bubble formation in vegetable oil experiment.



Figure 5.2: A close-up of the winding showing the thermocouples and paper samples embedded into the winding.

Four disc-shaped type-K thermocouples were embedded into the coil between turns 7 - 8, 8 - 9, 9 - 10, and 10 - 11 to measure the hotspot temperature (Figure 5.2). The turns were numbered starting from the centre of the coil (i.e. the innermost turn is turn 1 and the outermost turn is turn 16).

A length of type-K pressboard (830 cm length x 30 mm width x 1 mm thickness) was included into the vessel below the winding. The purpose of the pressboard was to regulate the water content in the system, by acting as a water sink and source. A length of copper wire was coiled around the pressboard to create gaps and allow oil to flow through it. A fifth thermocouple was placed near the pressboard to measure the bottom oil temperature. The mass of paper, pressboard, and vegetable oil used are summarised in Table 5.1.

Total mass of paper	58.91 g
Total mass of pressboard	292.99 g
Total mass of vegetable oil	12.5 kg
Total mass of paper and pressboard	351.9 g

Table 5.1: Mass of paper, pressboard, and vegetable oil used.

Pressboard to paper ratio	5:1
Oil to pressboard and paper ratio	36:1

New vegetable oil (FR3) was dried and degassed using vacuum at 60 °C for 72 hours, and then transferred to the test tank. The test tank was filled, such that there was no gas space between the oil and the lid of the vessel. The paper and pressboard were not pre-dried.

The experimental set-up (Figure 5.1) was heated in a large oven set to 55 °C continuously to equilibrate water between the oil and the paper.

A water activity and temperature sensor (Vaisala HMP 228) was fixed onto the tank and positioned above the coil to estimate the paper water content (Figure 5.1). The paper water content (WCP), expressed as a percentage, was calculated using the water activity and temperature from the sensor and Equations (5.1) - (5.3) [9, 10, 45].

$$WCP = 2.173 \times 10^{-7} \times P_w^{0.6685} \times e^{4725.6/(T+273)} \times 100\%$$
(5.1)

$$\boldsymbol{P}_{\boldsymbol{W}} = \boldsymbol{A}_{\boldsymbol{W}} \times \boldsymbol{P'}_{\boldsymbol{W}} \tag{5.2}$$

$$P'_{w} = 0.6112e^{\left(\frac{17.67T}{243.5+T}\right)} \times 9.869 \times 10^{-3}$$
 (5.3)

where,  $P_w$  is the water vapour pressure of the water dissolved on the surface of the paper (atm),  $P'_w$  is the water vapour pressure of pure water at the same temperature (atm), T is the temperature of the oil (°C), and  $A_w$  is the water activity of the oil between 0 to 1.

Samples of Kraft paper (2 cm length x 1.5 cm width x 0.13 mm thickness) were embedded into the winding between turns 15 - 16 (Figure 5.2), and were used for direct Karl-Fischer measurements according to ASTM 1767.2.8 – 2008 [46]. The paper samples were washed in hexane and acetone after Karl-Fisher titration to completely remove vegetable oil residue from the paper. The paper was then dried in the oven to determine the dry mass of the sample. The water content of a paper sample was tested before each experiment once the water activity of the oil had stabilised, which was usually after 4 - 5 days.

#### 5.2 Method

A variac was used to supply voltage to the current transformer, which in turn produced the current needed for the bubble formation experiment. The load profile shown in Figure 5.3, consisted of 10 minutes of partial load, 10 minutes of rated load, and 10 minutes of overload. This profile was chosen to allow comparison with the mineral oil investigated previously by Monash University [26]. The overload was extended for a further 10 minutes if bubbles were not observed in the first 10 minutes of overload. The applied voltage, duration, hotspot temperature reached, and the measured current in the winding (measured using a clamp-on ammeter) are summarised in Table 5.2. The rated load was designed to give a hotspot temperature of ~98 °C, which is defined in the loading guide [4] as producing normal ageing of non-upgraded paper insulation.



Figure 5.3: Current profile used for each experiment. The overload was extended for a further 10 minutes if bubbles were not observed in the first 10 minutes of overload.

Time (minutes)	Load	Applied Voltage (V)	Measured Current (A)	Hotspot Temp (°C) at the end of each load
0	None	0	0	55
0 – 10	Partial	40	56	60
10 – 20	Rated	120	163	98
20 – 30	Over	210	267	160
30 - 40	Over (cont.)	210	267	170

**Table 5.2**: Summary of loading parameters used during bubble formation experiments using vegetable oil.

A 2-litre conical flask with a 1-litre rubber bag was used as a conservator for oil expansion. The conservator was placed outside and above the oven with the oil height being 90 cm above the winding.

The time and hotspot temperature were recorded when bubbles and droplets were observed. The measurements from the thermocouples and the water activity sensor were recorded using a data acquisition program running on a PC.

Vacuum was applied immediately to the system after each experiment to dry the oil and thus lower the paper water content in the winding, as otherwise the released water during the experiment would return to the winding. The duration of the vacuuming process varied depending on the paper water content, but generally it increased the drier the paper (i.e. the drier the paper, the longer the vacuuming process).

### 5.3 Results

#### 5.3.1 Hotspot Temperature

The temperatures of the winding in vegetable oil measured by the thermocouples positioned between turns 7 - 8, 8 - 9, 9 - 10, and 10 - 11 are shown in Figure 5.4. The hottest location on the winding, referred to as the 'hotspot' temperature of winding was found to be between turns 10 - 11.





The rapid temperature rise during overload was to simulate an overload condition in a transformer. The initial rate of temperature rise in the first minute of overload was 25 °C/min and gradually decreased to an average value of 2 °C/min (Figure 5.5).



Figure 5.5: Rate of temperature rise between turns 10-11 during overload using 267 A (i.e. an overload of 160 °C).

In practise the winding temperature is usually measured using a fibre optic sensor placed between the winding disc and a pressboard spacer. The temperature measured by fibre optic has been found to be very close to the winding temperature modelled using computational fluid dynamics (CFD) [47].

#### 5.3.2 Bubbles and Droplets

The hotspot temperatures measured between turns 10 - 11 at the moment when a stream of bubbles were first formed above the winding and when droplets were released from below the winding are shown in Figure 5.6.



**Figure 5.6**: Hotspot temperatures between turns 10 – 11 at which bubbles and droplets form in FR3 oil for different water content of Kraft paper measured by Karl-Fischer.

Many streams of bubbles formed at high water content of paper at almost the same time and across the entire coil. Fewer bubble streams formed when the paper water content was less than 2 %. The streams of bubbles shown in Figure 5.7 appeared to be dispersing or dissolving into the oil, as there was very little accumulation of bubbles on the glass lid at the top of vessel during overload.



Figure 5.7: Streams of bubbles taken during overload.

There was a steeper rise in the bubble formation temperature below 2 % water content in paper. This pattern was also observed in mineral oil (Figure 5.8) using a similar experiment set-up and procedure [48].



Figure 5.8: Hotspot temperature of paper at which gas bubbles and droplets were formed in degassed Shell Diala B for different water contents of Kraft paper.

Bubbles were also formed on the bottom side of the coil which could not escape compared to the bubbles formed above the coil. As the bubbles accumulated under the coil they merged to form larger bubbles which eventually released small droplets (<1 mm diameter) falling downwards. This 'rain' of droplets onto lower coils is particularly dangerous in a transformer. Droplets were formed between 9 – 19 °C higher than the bubble formation temperature. It is not known if droplets would form in a multi-disc system if the oil under a disc is heated by the coil below. If they were formed, it is possible that vibration in a real transformer could cause the droplets to dislodge from beneath the coil sooner than in these experiments, which were conducted with no mechanical stirring.

Droplets were not observed within 20 minutes of overload at 260 A (i.e. and overload of 160 °C) when the water content of the paper was below 2 %. There is a chance that droplets may form after a longer period or when using a higher load (e.g. 290 A – an overload of 180 °C). However, the experiment was not extended since 160 °C is the hotspot temperature limit of the winding recommended in IEC 60076-7 [4].

#### 5.4 Comparisons

## 5.4.1 Paper Water Content Determined Using Water Activity Sensor and Karl-

#### **Fischer Titration Method**

The paper water content in a transformer must be evaluated accurately before being able to apply a bubble evolution temperature chart. It is more practical to use a water activity sensor and then to calculate the water content of paper in a transformer, but any difference to a true reading using the KFT method should be known in order to select the correct limiting temperature to prevent bubble formation [9].

The paper water content calculated using the water activity sensor and equations (5.1) - (5.3) compared to direct Karl-Fischer measurements are given in Table 5.3. The average difference between the water activity sensor and Karl-Fischer measured before each test at equilibrium and 55 °C was ~1.0 %. One

possible explanation is that the water activity sensor calculates the average surface water content on paper and pressboard in the system, whereas the KFT method measures the water content of only the paper. Since there is five times more pressboard in this system, the water activity sensor calculation will represent the water content on the surface of the pressboard more closely. Hence, the paper water content estimate made using the water activity sensor will depend on its proximity to the paper and the ratio of paper to pressboard. In a transformer with multiple cellulosic materials the estimate will depend on the ratio of paper, pressboard, and wood.

Experiment	Paper water content, %		
	Water activity sensor	Karl-Fischer	Difference
1	6.8	5.0	1.8
2	5.2	4.3	0.9
3	5.3	3.7	1.6
4	4.6	3.7	0.9
5	3.9	2.9	1.0
6	3.0	2.0	1.0
7	2.3	1.7	0.6
8	2.1	1.2	0.9

**Table 5.3**: Difference between measured and calculated paper water content.

If the paper water content is overestimated by 1 % in a transformer by using a water activity sensor, the temperature limit of the winding will be set lower in order to prevent bubble formation, which is actually safer for the operation of the transformer. However, an over-estimation of the paper water content will under-estimate the remaining life of the paper insulation, meaning the transformer could be retired sooner than required [49, 50].

#### 5.4.2 Bubble and Droplet Formation in Vegetable and Mineral Oil

#### 5.4.2.1 Inception Temperatures

The hotspot temperatures for bubble formation in mineral and vegetable oil are compared using straight trends in Figure 5.9. The results for the mineral oil were previously reported in [26]. The mineral oil had also been degassed using the same equipment and method. The temperatures are based on the hottest temperature of the winding at that instance.



Figure 5.9: Comparison of bubble formation temperatures in mineral oil (Shell Diala B) and vegetable oil (FR3).

The temperature difference between bubble formation in mineral and vegetable oil ranges from 6 – 13 °C for paper with water content between 1 – 6 %. The experiments below 1.9 % paper water content in mineral oil were conducted using 290 A (i.e. an overload of 180 °C) but were plotted on the same curve. No bubbles were formed below 1.9 % water content of paper using a 260 A load (i.e. an overload of 160 °C).

The hotspot temperatures at which droplets are formed in mineral and vegetable oil are compared in Figure 5.10. The experiments for 1.4 % and 1.6 % paper water content in mineral oil were conducted using 290 A (i.e. an overload of 180 °C) but were plotted on the same curve.



Figure 5.10: Comparison of droplet inception temperatures in mineral oil (Shell Diala B) and vegetable oil (FR3).

Droplets were formed between 5 – 16 °C higher in vegetable oil compared to in mineral oil for paper water content between 1.5 - 6 %.

The higher inception temperatures in vegetable oil are initially explained by comparing the hotspot winding temperature in both oils. The hotspot winding temperatures in mineral and vegetable oil under the same load are compared in Figure 5.11. We found that the hotspot temperature was 2 °C higher in vegetable oil after 20 minutes (rated load) and the difference increased to 20 °C after 40 minutes (i.e. 20 minutes of overload).



Figure 5.11: Difference in hotspot temperature of winding in mineral and vegetable oil under the same load.

The hotspot temperature in mineral oil did not exceed 160 °C after 30 minutes of overload using 260 A (i.e. an overload of 160 °C). This explains why there was no bubble formation observed in mineral oil when the paper water content was 1.3 %, but bubbles were formed in vegetable oil because the temperature reached 163.5 °C after 13.27 minutes when the paper water content was 1.2 %. In the case of dry paper, bubbles are more likely to form in vegetable oil because the necessary inception temperature can be reached during an overload situation.

#### 5.4.2.2 Inception Times

The times at which a stream of bubbles was formed after applying a 267 A (i.e. an overload of 160 °C) overload to the winding in mineral and vegetable oil are shown in Figure 5.12. The inception times in mineral oil using 290 A (i.e. an overload of 180 °C) cannot be compared to those using 260 A (i.e. an overload of 160 °C) load and have therefore not been included in this figure. There is a large increase in bubble inception times in vegetable oil below 2 % paper water content, which is consistent with the increase in the bubble inception temperatures.



Figure 5.12: Time at which a stream of bubbles is observed in mineral and vegetable oil for different paper water content after applying 260 A (i.e. an overload of 160 °C).

Bubble formation occurs at approximately the same time in mineral and vegetable oil between 3 - 6 % paper water content under the same load, but the winding temperature is higher in the vegetable oil.

The most likely explanation for this is the higher viscosity of vegetable oil compared to mineral oil. If the convective flow near the surface of the winding is not as smooth in vegetable oil as that in mineral oil, more heat will build up in that area. In a separate study of two transformers sharing the same load, one filled with mineral oil and the other with vegetable oil, it was found that the transformer filled with vegetable oil showed a 5 °C higher top oil temperature and a similar difference in calculated hotspot temperature under normal operation [51, 52]. The winding hotspot temperature in vegetable oil (BIOTEMP) and mineral oil were also compared in a 50 MVA transformer [53]. The study found that the winding hotspot temperatures of paper-wrapped conductors were 8 °C and 20 °C higher in vegetable oil compared to mineral oil at steady state for oil-natural, air-natural (ONAN) and oil-natural, air-forced (ONAF) systems respectively.

The higher temperatures observed in vegetable oil are more likely due to the thermal and chemical properties of the oil. The three factors which determine the

usefulness of a liquid as a coolant are: thermal conductivity, specific heat, and viscosity [13]. However, the author could not find data on these factors at temperatures other than at 25 °C. This makes it difficult to explain the temperature difference in terms of the oil's thermal performance at high temperature levels. The viscosity of vegetable oil is 3 - 4 times higher than that of mineral oil, creating a higher temperature on the winding (Table 5.4). The viscosity of vegetable oil decreases with temperature but still remains several times higher than that of mineral oil; therefore there will always be a difference in bubble emission temperatures.

manufacturer's da	ita sheet)	
Property	FR3	Shell Diala B

33

8

920

10

2

881

Kinematic Viscosity (mm<sup>2</sup>/s) At 40 °C

At 100 °C

Density (kg/m<sup>3</sup>) At 20 °C

 Table 5.4: Properties of vegetable and mineral oil affecting winding temperature (taken from manufacturer's data sheet).

The higher density of vegetable oil may also affect the bubble formation temperature. The density of vegetable oil is higher than that of mineral oil at the same temperature (Table 5.4) [13]. This means that the oil hydrostatic pressure (P) on the paper will be higher in vegetable oil and therefore bubble formation will be more difficult and require higher temperature. The hydrostatic pressure is a function of density and oil depth, according to Equation (5.4). Given that the coil is at the same length in both oils, the only difference is the density of the oil.

$$\boldsymbol{P} = \boldsymbol{\rho} \times \boldsymbol{g} \times \boldsymbol{h} \tag{5.4}$$

where,  $\rho$  is the density in kg/m<sup>3</sup>, *g* is the acceleration due to gravity equal to 9.8 m/s<sup>2</sup> and *h* is the oil depth from the topmost surface of the oil in meters.

The height of oil above the winding used in this set-up was 90 cm. If the height difference between the top windings and the top oil level in an actual transformer is greater (i.e. there is a greater pressure exerted) the bubble inception temperature will be higher than the values reported here. Therefore, the reported values can still be used as a safe limit. If lower pressure is exerted, the bubble inception temperature temperature will be lower than the values reported here.

Although the bubble inception temperature when using vegetable oil is relatively higher, the time to bubble formation is similar. Hence, the higher water solubility of vegetable oil did not seem to delay or prevent bubble formation. Therefore, there is no reason to believe that the higher water solubility of vegetable oil is attributed to shifting the bubble formation temperature in vegetable oil higher. The time to bubble formation is another way to assess the likelihood of bubble formation with regard to the paper water content of a wet system.

## 5.5 Discussion

Despite the bubble inception temperature of vegetable oil being approximately 10 °C higher than that for mineral oil, at the same WCP, the bubbling inception time for these two oils is very similar. This indicates that it is not solely temperature which defines when bubbles will form.

Oommen and Lindgren [17] computed the water vapour pressure using Equation (5.5), where P is pressure in mmHg, W is WCP in % and T is temperature in Kelvin. A conversion factor of 0.13 has been used to convert the pressure units into kPa. Oommen and Lindgren also added the pressure of a dissolved gas.

However, since the oil used in the present investigation was degassed, this has been omitted. The water vapour pressure (in kPa) calculated using Equation (5.5) is shown in Table 5.5. When comparing the bubbling temperature of mineral oil in Figure 5.9 to the vapour pressure, the approximate relationship is that bubbling occurs once the vapour pressure exceeds that of the external pressure, ~ 110 kPa, as described in the Young-Laplace Equation (3.2).

$$\ln P = 22.454 + 1.4495 \times \ln W - \frac{6996.7}{T}$$
(5.5)

WCP (%)	Temperature (°C)					
	120	125	130	135	140	145
1	15	19	24	30	36	45
2	42	53	65	81	99	122
3	76	95	118	145	179	219
4	115	144	178	221	272	333
5	159	198	247	305	375	460

**Table 5.5**: Water vapour pressure (kPA) calculated for different WCPs and temperatures.

Since the bubbling inception temperature of vegetable oil is 5 – 10 °C higher than that of mineral oil, the vapour pressure of water must also be higher to cause bubbling. However, differences in the other terms, surface tension and hydrostatic pressure, due to the differing properties of the oil, do not appear significant when compared with the atmospheric pressure.

Oommen and Lindgren [17] wrote that a free bubble is not formed in a fluid, but is generated in a cavity on the surface of a solid because the external pressure exerted on the bubble by the fluid is too large for it to form in the fluid. Since the type of oil did not seem to affect the time for bubbling to occur (Figure 5.12), despite a different temperature being reached, this supports this hypothesis, because the generation of the bubble is dependent on the surface of the paper. Equation (5.5) was used to calculate the water vapour pressure at the temperature and the WCP when bubbles were observed, and the results are shown in Figure 5.13. Bubbling seems to occur in mineral oil at a vapour pressure less than atmospheric + hydrostatic (~ 110 kPa). This is consistent with Oommen and Lindgren's comment that bubbling tends to form on the surface of a solid in a cavity, and not in the fluid where the pressure may be too great.



Figure 5.13: Bubble inception temperature to moisture vapour pressure.

The vapour pressure of water reaches the external pressure at between 2 to 3 % in the mineral oil system (Figure 5.13). This may explain the change in the gradient of the trend-line for mineral oil around 2 % (Figure 5.9). For instance, at WCP below 2 % bubbles of water are generated on the surface of the paper but they do not have sufficient vapour pressure to overcome the external pressure. However, once the WCP exceeds 2 % the vapour pressure of the bubble is high enough to overcome the external pressure and thus the bubble can grow. Small bubbles are therefore more likely to grow.

It is of interest in Figure 5.13 that the vapour pressure of water in the vegetable oil system is higher at a given WCP than for the mineral oil, yet the bubbling inception temperature is also higher. This implies that more water can dissolve into the vegetable oil. At the high temperatures when bubbling occurs the solubility of water in vegetable oil is very high, at nearly 1 %. The temperature of the system immersed in vegetable oil reaches higher levels than when mineral oil is used, caused by the poorer thermal performance of the vegetable oil. However, as the vegetable oil becomes hotter it becomes better at dissolving water.

#### 5.6 Summary

The type of oil did not seem to have had a significant effect on the nucleation of bubbles on the paper, because the time to bubble was very similar for both vegetable and mineral oil-filled systems, despite the temperature being different. This is consistent with previous work where it was believed bubbles form on the paper and in cavities, and not in the fluid.

The vegetable oil system reaches a higher temperature than the mineral oil due to differing coolant properties. This increases the solubility of water in the vegetable oil.

The vapour pressure of water that can be dissolved in the vegetable oil before bubbling occurs is significantly higher than that in the mineral oil system. This may be due to the very high solubility of the vegetable oil. One explanation could be that the oil itself does not significantly affect bubble nucleation, but the high solubility of water helps dissolve the water away from the nucleation site, preventing bubbles from actually forming.

## **Chapter 6: Summary and Conclusions**

A bubble and droplet evolution temperature chart was developed for new FR3 oil.

There was a large increase in bubble inception time and bubble emission temperatures in vegetable oil below 2 % paper water content.

Water droplets were observed in vegetable oil some time after bubble formation, as observed in mineral oil.

The temperature difference between bubble formation in mineral and vegetable oil ranges from 6 - 13 °C for water content of paper between 1 - 6 %.

Water droplets were formed between 5 – 16 °C higher in vegetable oil compared to in mineral oil for paper water content between 1.5 - 6 %.

For a dry paper system, bubbles are more likely to form in vegetable oil than in mineral oil for the same water content of paper due to the higher hot spot temperatures which are reached.

For a wet system, the likelihood of bubble formation in vegetable oil seems to be lower than in mineral oil due to the higher bubble inception temperatures.

The hot spot temperature of winding in vegetable oil was 20 °C higher than that in mineral oil after 20 minutes of overload. However, the hot spot temperature during overload in a real transformer also depends upon its thermal design. A transformer can be designed such that the hot spot is the same for mineral oil using the same load.

The higher emission temperatures observed in vegetable oil are due to the thermal and chemical properties of the oil (thermal conductivity, heat capacity, and viscosity).

The density of the oil and the height difference between the top windings and top oil level determines the hydrostatic pressure exerted on the winding surfaces that will determine bubble formation.

Since the water activity sensor calculates the average surface water content of all cellulosic materials in the system, the ratio of paper, pressboard, and wood used in a system is an important factor to consider when using an indirect measurement device. The average difference between Vaisala and Karl-Fischer values measured before each test at equilibrium and 55 °C was 1.0 % for a system with an oil-to-cellulose (paper and pressboard) ratio of 36:1.

## **Appendix: Tabulated Data**

No.	Water content of paper (%)	Temperature when bubble evolution was recorded (°C)	Time on overload when bubble evolution was observed (min)	Current (A)
1	6.3	114	1.2	260
2	0.9	*167		260
3	4.9	124	1.3	260
4	3.3	137	2.2	260
5	1.4	160	1.2	290
6	1.6	155	1.6	290
7	0.9	180	27.5	290
8	2.1	142	5.5	240
9	2.2	*153		240
10	2.3	143	17.3	240
11	2.2	142	7	260
12	2.2	145	27.3	240
13	2.1	146	15.3	240
14	4.8	124	1.2	260
15	4.1	131	1.9	260
16	4.2	130	3.2	260
17	4.4	128	1.5	260
18	1.2	*130		210
19	1.3	*167		260

**Table A.1**: Results of bubbling investigation for mineral oil.

20	1.2	*153		240
21	1.3	172	7.1	290

\* denotes the end winding hotspot temperature and no bubble formation

Water content of paper (%)	Bubble formation (°C)		Droplet for	mation (°C)
	290 A	260 A	290 A	260 A
6.3		108		115
4.9		117		
4.8		117		124
4.4		120		
4.2		122		
4.1		123		132
3.3		128		131
2.2		134		
1.6	145		154	
1.4	149		163	
1.3	160			
0.9	167			

 Table A.3: Time to bubble formation during overload in mineral oil (Shell Diala B).

Water content of paper (%)	Bubble formation (minutes) at 260 A
6.3	1.2
4.8	1.2
3.3	2.2

Water content of paper (Karl Fischer, %)	Bubble formation (°C)	Droplet formation (°C)
5	125.6	135.2
4.3	127.4	143.7
3.7	131.2	140.4
3.7	133.2	143.3
2.9	137.3	149.3
2	140.9	160.3
1.7	155.5	
1.2	163.5	

Table A.4: Hot spot temperature of bubble and droplet formation in vegetable oil (Envirotemp FR3).

Table A.5: Time to bubble formation during overload in vegetable oil (Envirotemp FR3).

Water content of paper (Karl Fischer, %)	Bubble formation (minutes)
5	1.27
4.3	1.38
3.7	1.72
3.7	1.92
2.9	2.28
2	2.98
1.7	9.57
1.2	13.27

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