Zhao, SC, Zhang, X, Liu, Q, Wilkinson, M, Negro, M and Daghrah, M (2021) Development of an experimental setup to study temperature distribution of liquid natural cooled power transformers. In: 22nd International Symposium on High Voltage Engineering (ISH 2021), 21 November 2021 - 26 November 2021, Hybrid Conference, Xi'an, China.

DOI: https://doi.org/10.1049/icp.2022.0222

Publisher: Institution of Engineering and Technology

Version: Accepted Version

Development of an Experimental Setup to Study Temperature Distribution of Liquid Natural Cooled Power Transformers

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Keywords: Power transformer, Complete-cooling-loop, ON, Disc-type winding, Transformer liquid

Abstract

Knowing the temperature profile of a transformer is of great interest because the expected thermal lifetime of the transformer is mainly determined by the hotspot temperature in windings. Understanding the thermal behaviours of the transformer in different conditions facilitates better utilizing and managing transformer assets for a utility in the most optimum manner. Thermosiphon-driven liquid natural (ON/KN) cooled transformers are widely used in the electric grid as they generally require less maintenance compared to pump-driven liquid forced and directed (OD/KD) cooled transformers. Therefore, a complete-cooling-loop experimental setup is developed to study the parameters affecting the thermal behaviour of an ON/KN cooled transformer. The affecting parameters can be categorized into three categories: geometric characteristics, operational conditions and material properties. Geometric parameters include the transformer thermal head and the number of discs per pass for the winding model studied. Operational conditions are considered by different loading scenarios. The material properties refer to alternative insulating liquids. In this paper, the design and implementation of an experimental setup is presented which is used to study the effects of these parameters on the thermal behaviour of liquid natural cooled transformers.

1 Introduction

Understanding the temperature profiles within a power transformer for different operating conditions gives advantages in transformer utilization as the ageing rate of the cellulose based insulation paper increases exponentially with the hottest temperature in the transformer windings, and this ageing is generally taken to determine the expected lifetime of a transformer [1]. Such an understanding could also improve future transformer design, especially when alternative insulating liquids are used to replace conventional mineral oil for a greener and safer transformer.

Experimentally, studying the thermal profile of a liquid-immersed transformer has been carried out by many researchers, and the work can be categorized by the transformer cooling mode, i.e. liquid natural air natural (ONAN/KNAN), liquid natural air forced (ONAF/KNAF), liquid forced air forced (OFAF/KFAF) and liquid directed air forced (ODAF/KDAF) cooling modes. In [2], both a laboratory-scale experimental setup and dimensionless Computation Fluid Dynamics (CFD) simulations were adopted to study the temperature and liquid flow distributions within a disc-type winding in the OD/KD cooling mode. The work has covered different operating conditions, winding geometries and alternative liquids. The same experimental setup was used to study the transformer thermal behaviour in ON cooling modes in [3] and [4], by controlling liquid temperatures and velocities at the winding inlet in representative ranges using a pump. It is worth mentioning that the controlled velocities when studying the thermal behaviour of different insulating liquids were based on an analytical calculation in [4], which assumes the total liquid flow rate is approximately proportional to the square root of the total heat loss in the winding and to the square root of physical thermal head, as reported in [5]. However, some uncertainties will be brought in due to the above assumptions, especially for transformer retro-filling scenarios.

The studies of alternative transformer liquids in ON/KN cooling modes have also been conducted using real transformers. A 154/22.9 kV transformer was used to compare the thermal performance between the conventional mineral oil and a natural ester in [6]. Another retro-filling study was carried out in [7] using a 141/13 kV transformer, and it was found that the hot-spot temperature was 8 °C higher for natural ester filled case comparing to the mineral oil one under rated condition in an ONAN/KNAN cooling mode. The experiments using real transformers were mainly conducted at the rated loading conditions, and there was less information of thermal profile under different loading scenarios and their comparisons with corresponding experiments.

In this paper, a laboratory-scale experimental setup was designed to study the transformer thermal behaviours in

ONAN/KNAN cooling modes, by achieving spontaneous flows in the setup and measuring a complete winding temperature profile within a representative winding design. The geometric characteristics, loading conditions and alternative liquids are all considered in the experiments. The key components of the setup are presented in Section 2. One set of experimental results under the rated loading condition was given in Section 3 to demonstrate how the key parameters, i.e. top, bottom liquid temperatures, hot-spot temperature, winding temperatures and radiator surface temperatures, are measured and analysed. A conclusion is given in Section 4.

2 Experimental Setup

The transformer complete-cooling-loop experimental setup aims to study the winding liquid flow rate and the temperature profile under different operating conditions and in different thermal designs, e.g. thermal heads, as well as the applications of alternative insulating liquids, e.g. gas-to-liquids and ester liquids. It consists of a disc-type winding model, a 4-panel transformer radiator, pipework, a temperature measurement system and a particle image velocimetry (PIV) system, as shown in Fig.1. The winding model housing and the transparent box at the top of the winding model are made of transparent Polycarbonate, which allow the liquid flow velocity between parallel winding discs and total liquid flow rate at the transparent box to be measured by the PIV system. In the temperature-rise tests, the power loss is injected through the winding model. Both the winding model and the pipework are wrapped with thermal insulation to direct the heat being dissipated by the 4-panel transformer radiator.

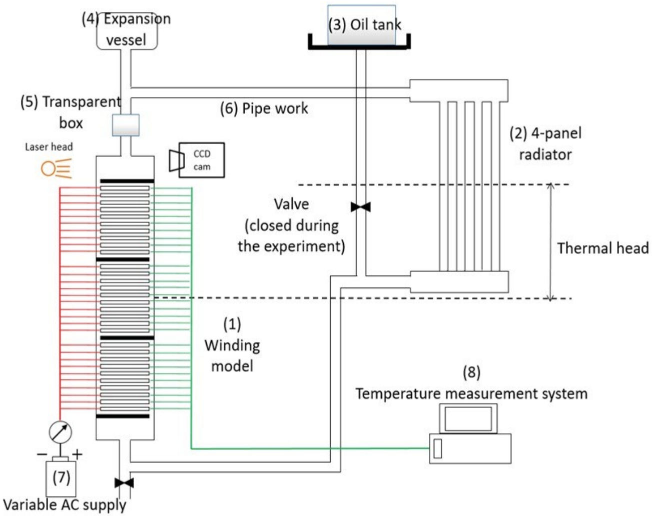


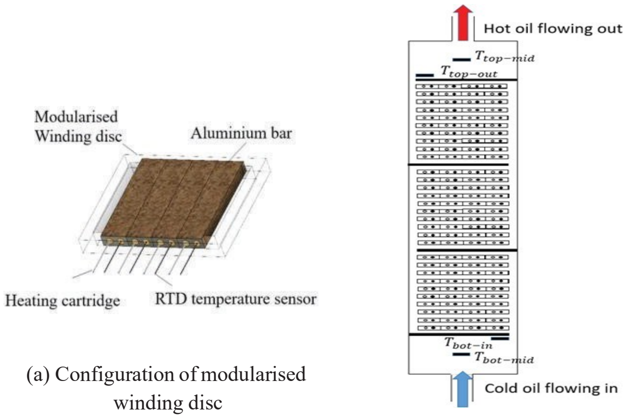
Fig. 1 Configuration of complete-cooling-loop experimental setup

2.1 Modularised Winding Model

The winding model is made to replicate a typical disc-type winding segment between two sets of adjacent spacers. The disc-type winding model is constructed by the modularised winding discs, each of which consists of four aluminium bars representing the winding turns and polycarbonate housing. Each aluminium bar is wrapped with Kraft paper insulation. One heating cartridge and one Resistance Temperature Detector (RTD) are installed in each aluminium bar, to simulate the heat losses in each winding turn and to measure the temperature, respectively. The configuration of one modularised winding disc is shown in Fig. 2 (a).

The design of the modularised winding disc enables injecting both uniform and non-uniform power loss profiles, and studying the effect of different winding geometries on the winding thermal profile, e.g. different number of winding discs in different passes. There are in total 30 modularised winding discs constructed, and to the present test condition, all 30 modularised winding discs are equally arranged in three passes, as shown in Fig. 2 (b), segregated by 2 mm washers. The width of liquid vertical duct and height of liquid horizontal duct are 10 mm and 4 mm, respectively.

The winding temperatures are measured by RTD temperature sensors, as shown in Fig. 2. The liquid temperatures are measured by 4 RTD sensors, locating at the top and bottom buffer zones, as depicted in Fig. 2 (b). The top liquid temperatures are measured by two RTD temperature sensors, one placed at the middle of top buffer zone ($T_{top\text{-}mid}$) and the other at the winding outlet ($T_{top\text{-}out}$). The bottom liquid temperatures are also measured by two RTD temperature sensors, one placed at the middle of bottom buffer zone, and the other at the winding inlet, named as $T_{bot\text{-}mid}$ and $T_{bot\text{-}in}$, respectively.



(a) Configuration of modularised winding disc

(b) Configuration of winding model

Fig. 2 Configuration of modularised winding disc (a) and winding model (b)

The power losses of the winding model are referred from [8]. The current density for transformer windings is in the range from 2 to 5 A/mm². Therefore, the total power injection for the present winding model is designed from 200 W to 1400 W in compliance with the current density range. The power losses and corresponding heat flux densities are listed in

Table 1. There have been seven heat losses for each complete-cooling-loop setup geometry, from 200 W to 1400 W with a power injection interval of 200 W. The 800 W condition, corresponding to 3.9 A/mm^2, is treated as the rated loading condition.

Table 1 Power injection conditions for complete-cooling loop temperature-rise tests

Power injection (W)	200	400	600	800	1000	1200	1400
Current density (A/mm^2)	2.0	2.8	3.5	3.9	4.5	4.9	5.3
Heat flux (W/m^2))	303	607	910	1213	1517	1820	2123
Loading condition (p.u.)	0.5	0.7	0.9	1.0	1.1	1.3	1.4

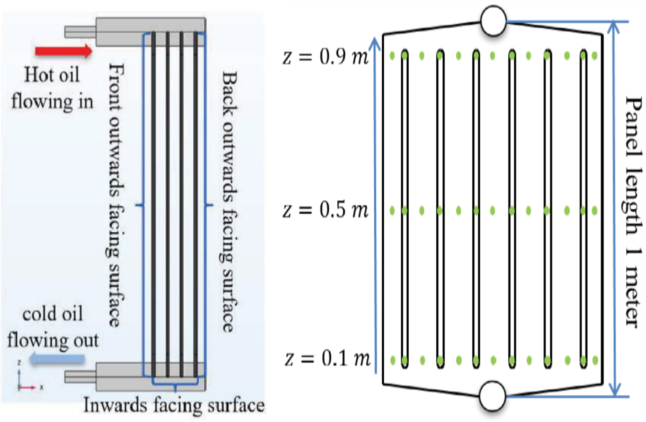
2.2 4-panel Transformer Radiator

The power loss generated in the transformer active parts is mainly dissipated by the radiators. Therefore, a 4-panel 1-meter long stamped plate transformer radiator, as shown in Fig. 3 (a), is implemented in the setup to ensure that the key parameters are all in a representative range, as given in Table 2.

Table 2 Key parameters and their ranges in complete-cooling-loop temperature-rise tests

Key parameters in temperature-rise tests	Range
Top liquid temperature	32.8 - 76.2 °C
Bottom liquid temperature	24.3 - 56.3 °C
Top liquid temperature rise over bottom liquid temperature	8.5 - 20.0 K
Hot-spot Temperature	38.7-104.4 °C
Liquid velocity at winding bottom	0.02-0.05 m/s

To the complete-cooling-loop thermal studies of transformers in the ONAN/KNAN cooling mode, the liquid temperature distribution along the radiator height is of huge importance in determining the total liquid flow rate. However, the liquid temperature within in the radiator cannot be measured directly due to the thin liquid channel structure of the radiator. Therefore, instead of measuring liquid temperatures in the transformer radiator, the radiator surface temperatures are measured on two radiator outwards facing surfaces, namely 'front outwards facing surface' and 'back outwards facing surface', by using an infrared thermometer (Fluke 572), with accuracy of ±0.8 °C in the measurement range from 10 to 80 °C. Each surface was marked with eleven horizontal points under nine different vertical heights from radiator bottom to top, namely from 0.1 meter to 0.9 meter with an interval of 0.1 meter. The back outwards facing surface is taken as an example to depict the measurement positions, three out of nine vertical heights are shown in Fig. 3 (b). There are, in total, 198 positions measured.



(a) Configuration of the transformer radiator

(b) Radiator surface measurements on back outwards facing surface (shown as green points)

Fig. 3 Configuration of radiator and measurements on radiator surface

2.3 Ambient Temperature

The ambient temperature is another key parameter, which is requested in the temperature-rise test in [1]. To the experimental setup, four RTD sensors are used to measure the ambient temperature, three of which are placed at a level about halfway up of radiator surfaces and 1 meter away from the radiator outwards facing surfaces, and the other one is placed at 1 meter away from the radiator bottom surface.

3 Measurement Results

All the temperature measurements can be categorized into 4 groups: winding temperature, liquid temperature, ambient temperature and radiator surface temperature measurements. The number of sensors for each kind of measurement and the relevant accuracy are listed in Table 3.

The temperatures of all the 128 RTD sensors are recorded every minute during the temperature-rise tests using a multiplexer 'Keithley T 3700AS-901-01D'. The radiator surface temperature has been measured using an infrared thermometer (Fluke 572) three times, with a time interval of 10 minutes, after the system reaches its steady-state condition.

Table 3 Measurement objects and sensor accuracy in the temperature-rise test

Measurement objects	No. of sensors	Accuracy
Winding temperature	120 RTD sensors	±0.35 °C
Top liquid temperature	2 RTD sensors	±0.35 °C
Bottom liquid temperature	2 RTD sensors	±0.35 °C
Ambient temperature	4 RTD sensors	±0.15 °C
Radiator surface temperature	Infrared thermometer	±0.8 °C

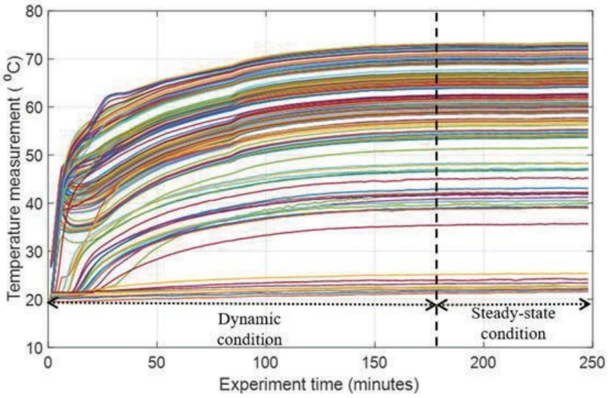
3.1 Temperature Profile

As introduced, the winding temperatures, liquid temperatures and ambient temperatures are measured every minute from a cold start. The rated loading condition, the 800 W total power injection condition with 0.5 meter thermal head filled with a mineral oil, is taken as an example to depict the dynamic temperature profiles, shown in Fig. 4. As documented in IEC60076-2 [1], the criterion of steady-state condition in a temperature-rise test is that the change of temperature within 1 hour is less than 1 K. In each temperature-rise test, the temperature measurements of all sensors in the last hour have been checked to ensure that the temperature fluctuation in the last hour is within 1 K. Moreover, to avoid the uncertainties caused by power injection and ambient temperature fluctuations, the temperatures measured in the last hour are averaged to represent the steady-state condition.

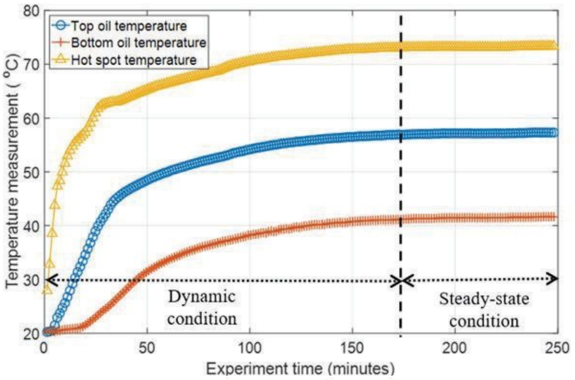
The key parameters in the temperature-rise test are hot-spot temperature, top and bottom liquid temperatures, and the dynamic temperature profiles of which are shown in Fig. 4 (b). The top oil temperature has a faster increase than the bottom oil temperature from the beginning of the temperature-rise test until the thermosyphonic oil flow is fully established. The dynamic temperature profiles provide steady state temperatures and make possible the study of transformer dynamic thermal behaviours.

3.3 Winding Temperature Distribution

The hot-spot temperature (HST) in the transformer windings is the dominating parameter to the transformer ageing and its asset management. However, the HST may not necessarily be at the topmost winding disc due to the non-uniform liquid flow distribution inside the winding, especially when reverse flow occurs [3]. Therefore, the winding temperature profiles under different conditions help understanding the liquid flow distribution and improving transformer thermal design.



(a) All RTD temperature measurements in temperature-rise tests



(b) Key parameter measurements in temperature-rise tests

Fig. 4 Temperature measurements in the temperature-rise tests

For the disc-type winding model, each winding disc consists of 4 metal bars, named from 'bar 1' to 'bar 4' along the nominal liquid flow direction. The complete temperature profile, consisting of all the temperature measurements in 120 bars, in the steady-state condition, under the rated loading condition, are shown in Fig. 5.

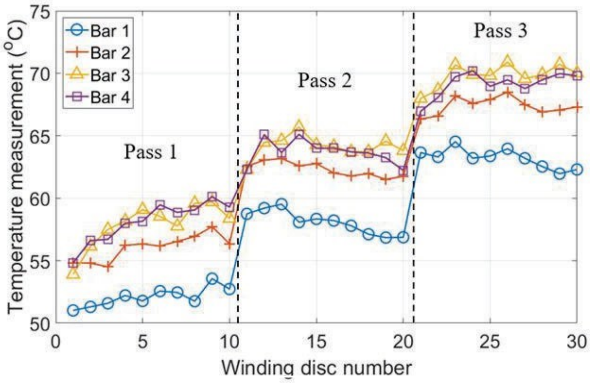


Fig. 5 Winding temperature profile under rated loading condition

The winding temperature distribution in each winding disc helps understanding the localised liquid flow phenomena, especially for the reverse flow condition. A decreasing trend of temperature distribution from 'Bar 1' to 'Bar 4' in a winding disc, indicates the presence of the reverse flow in the corresponding horizontal duct, whereas an increasing trend of temperature distribution in a winding disc indicates the expected nominal liquid flow.

Moreover, the mean and maximum temperature of the 4 bars of a winding disc, have been shown in Fig. 6, which helps understanding the overall liquid flow distribution and HST location within a pass under different conditions.

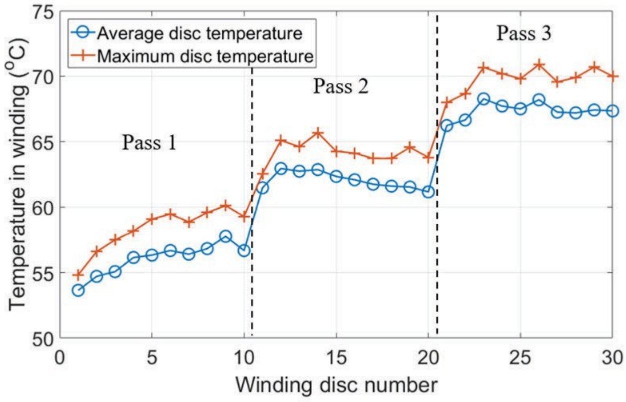


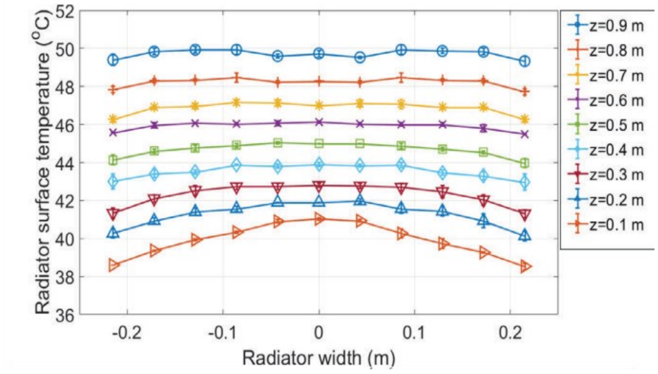
Fig. 6 Winding temperature profile (maximum and mean winding disc temperatures)

3.2 Radiator Temperature Measurements

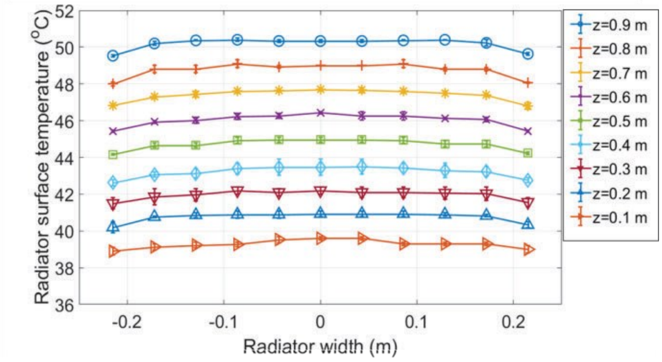
The radiator surface temperatures were measured to study the liquid temperature distribution in the transformer radiator to help understanding the total liquid flow rate under different loading conditions, in different geometries and of different alternative insulating liquids.

The rated loading condition, 800 W total power injection with a mineral oil and a thermal head of 0.5 meter, is taken as an example to show the radiator surface temperature results, as in Fig. 7. All the 198 points for outwards facing surfaces, i.e. radiator front and back outwards facing surfaces, are shown in Fig. 7 (a) and Fig. 7 (b), respectively. The error bar represents the standard deviation among the three sets of measurements. The maximum value of the error bars is 0.6 K.

Two analytical calculations of total liquid flow rates for ON/KN cooled transformers were performed in [9]. The difference of these two calculation methods is the assumption of the liquid temperature distribution along the transformer radiator height, either being linear or exponential. Therefore, the radiator surface temperature measurements at the same vertical height are averaged to represent the liquid temperature distribution, as shown in Fig. 8, which is approximately in a linear relationship under the tested condition. More tests will be conducted under different loading conditions with different thermal heads and alternative liquids to further investigate the liquid temperature distribution pattern in the radiator, and how different patterns will affect the total liquid flow rate in ON/KN cooled transformers.



(a) Radiator surface temperature measurement on front outwards facing surface



(b) Radiator surface temperature measurement on back outwards facing surface

Fig. 7 Radiator surface temperature measurements

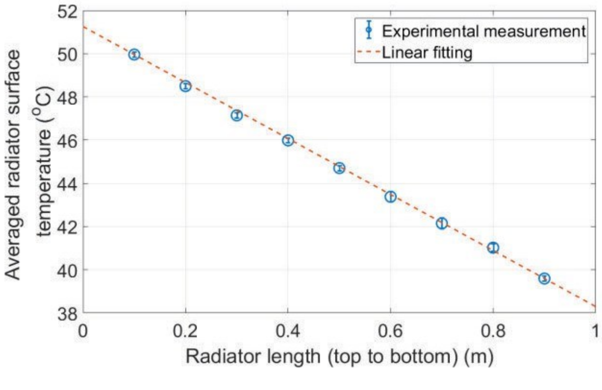


Fig. 8 Radiator surface temperature distribution along the radiator height

4 Conclusion

A transformer complete-cooling-loop experimental setup was developed to investigate the thermal behaviour of power transformers in ONAN/KNAN cooling modes. The rated loading scenario was conducted to verify the functionality of the designed test system, in terms of liquid temperature, winding temperature, ambient temperature and radiator surface temperature measurements.

The designed system will be used in the future to conduct extensive temperature-rise tests to study the effects of geometric parameters, e.g. transformer thermal head, different operating conditions, e.g. different loading scenarios, and the thermal performance of alternative liquids, e.g. gas-to-liquids and synthetic esters. The implementation of PIV to measure the liquid flow distribution inside the winding passes will be considered if needed.

5 Acknowledgements

The authors would like to express their gratitude to EPRI, M&I Materials, National Grid, Scottish Power, SGB-SMIT, Shell and Weidmann for their financial and technical contributions to the Transformer Research Consortium.

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