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Experimental Study of the Influence of Different Liquids on the Transformer Cooling Performance

Muhammad Daghrhah, Zhongdong Wang, *Member, IEEE*, and Qiang Liu, *Member, IEEE*, Andree Hilker, Attila Gyore, *Member, IEEE*

Abstract—Mineral oil is traditionally used in liquid immersed transformers to act as a coolant, an information carrier, and as an electrical insulator. Emerging alternative transformer liquids provide advantages, such as improved fire safety and better biodegradability, of which transformer operators would like to utilize. In this paper, an experimental study is conducted to compare the thermal performance of a mineral hydrocarbon transformer oil, a gas-to-liquid hydrocarbon transformer oil, and a synthetic ester transformer liquid as coolants in a zig-zag disc type winding model. Comparisons are made under liquid directed cooling modes and under liquid natural cooling modes. It was found that under both cooling modes, the mineral based transformer oil and the gas-to-liquid based transformer oil behaved almost with comparable liquid flow and temperature distributions. Under liquid directed cooling modes, the synthetic ester gave more uniform flow distribution and delayed the occurrence of liquid reverse flow compared to the other oils. Under liquid natural cooling modes and using the zig-zag disc type winding model, synthetic ester due to its higher viscosity caused lower inlet flow rate to develop under the specific tested retrofilling conditions which resulted in less uniform oil flow distribution within the pass and higher hot spot temperature.

Index Terms—Transformer, Experiment, Particle Image Velocimetry, Mineral Oil, Gas-To-Liquid Oil, Synthetic Ester

I. INTRODUCTION

Transformer life expectancy is affected by the ageing of paper insulation within the winding, which is determined by its experienced temperature. The hot spot temperature (HST) can be defined as the hottest temperature in the transformer winding structure which causes the severest paper ageing. In disc type power transformers, liquid is circulated through cooling ducts within the transformer winding to transport heat from within the winding to the external cooling medium. The thermal and physical properties of the liquid, such as density (σ), kinematic viscosity (ν), thermal conductivity (k_c), and specific heat (C_p), influence its cooling performance [1, 2]. Cooling performance is characterized by first the heat transfer coefficient, which is a local cooling factor, and second by liquid flow distribution within the winding, which is a global cooling factor [3].

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Muhammad Daghrhah, Zhongdong Wang and Qiang Liu are with the School of Electrical and Electronic Engineering at The University of Manchester, Manchester, M13 9PL, UK (e-mail: zhongdong.wang@manchester.ac.uk).

Andree Hilker is with Shell Global Solutions (Deutschland) – GmbH

Attila Gyore is with M&I Materials, Manchester, M32 0ZD, UK

NOMENCLATURE

σ	Density (kg/m^3)
ν	Kinematic viscosity (mm^2/s)
C_p	Specific heat ($J/kg.K$)
Re	Pass inlet Reynold number $Re = D_h \times V_{in}/\nu$
H_d	Winding model radial cooling duct height (m)
W_d	Winding model axial cooling duct width (m)
k_c	Thermal conductivity of liquid ($W/m.K$)
β_{Th}	Volumetric thermal expansion coefficient of liquid ($1/K$)
V_{in}	Winding model inlet velocity (m/s)
P_L	Pressure loss over winding model (Pa)
T_B	Winding model bottom liquid temperature ($^{\circ}C$)
P_{loss}	Power loss injection in each plate (W)
V_{max}	Maximum velocity in radial cooling duct (m/s)
V_{av}	Average velocity in radial cooling duct (m/s)
D_h	Hydraulic diameter of axial duct (m)
A_c	Inlet cross sectional area of axial cooling duct (m^2)
W_p	Wet perimeter of axial cooling duct (m)
HST_{rise}	Hot spot temperature rise over T_B (K)
T_{top}	Winding model top liquid temperature ($^{\circ}C$)
p_{Th}	Thermosyphon driving force (Pa)
g	Acceleration of gravity (m/s^2)
ΔH	Height difference between centres of radiator and winding (m)
ΔT	Liquid temperature increase from T_B to T_{top} (K)
$P_{loss,total}$	Total losses in the winding model (W)
$\dot{m}$	Winding model inlet mass flow rate (kg/s)
f_i	Friction coefficient of component i in the hydraulic loop
L_i	Equivalent pipe hydraulic length of component i (m)
C	Constant
R_i	Richardson number ($R_i = Gr/Re^2$)
Gr	Grashof number
T_{mw}	Mean winding temperature ($^{\circ}C$)
T_{mo}	Mean liquid temperature ($^{\circ}C$)

Under Liquid Directed (OD or KD) cooling modes, the flow distribution is affected by pass inlet Reynold number (Re), and by the winding geometries such as the radial cooling duct height (H_d), the axial cooling duct width (W_d), and the number of discs per pass [4, 5]. Under Liquid Natural (ON or KN) cooling modes, the developed liquid flow rate is affected by the thermosyphon pressure induced forces within the winding structure and the total pressure loss within the transformer hydraulic loop [6-8].

Mineral oils are traditionally used as the insulating and cooling media in power transformers. Recently alternative transformer liquids, such as ester based liquids and gas-to-liquid based oils, emerged as alternatives in power transformers compared to mineral oils. Ester based liquids are biodegradable and have high flash and fire points. A comparison was made for the thermal performance of a 50

1 MVA, 141 kV/13 kV transformer that was filled in with 57 desired. The pressure loss over the winding model (P_L) is 2 mineral oil and natural ester [9]. It was reported that under 58 measured under directed cooling mode using differential 3 KNAN cooling mode an increase in the HST by 12 °C was 59 pressure sensors with ± 10 Pa accuracy. The liquid is heated 4 observed in the low voltage winding when filled with natural 60 within the winding model and circulated through the radiator 5 ester compared to when filled with mineral oil. Hence, it was 61 to be cooled down. To control the winding bottom liquid 6 concluded that retrofilling transformers designed for mineral 62 temperature (T_B), an external controlled heater was connected 7 oil with natural ester requires careful considerations. The 63 in series with the winding model. The winding model consists 8 impact of mineral oils and ester based liquids on transformer 64 of 3 passes, where each pass consists of 10 aluminium plates 9 winding temperatures was investigated [10]. It was observed 65 modelling disc segments [5, 15-17]. Each plate was made with 10 that when using ester liquid the flow velocities within radial 66 dimensions 100 mm $\times$ 104 mm $\times$ 10 mm, and can be heated 11 cooling ducts were lower, compared to when using mineral 67 using two resistive cylindrical heaters embedded within the 12 oil, which was the reported reason for the increase in the 68 plate. Power losses (P_{loss}) in plates are controlled. 13 winding temperatures. A 15 MVA, single phase, 154 kV/22.9 69 Thermocouples were used to record average plate 14 kV transformer was filled with mineral oil and then with 70 temperatures within the winding model with accuracy ± 1 °C. 15 natural ester [11]. Temperature rise tests were conducted and 71 Each plate was embedded with two thermocouples and their 16 an increase of near 16 °C in recorded HST was observed in the 72 average is used as a representative average plate temperature. 17 low voltage winding after retrofilling using natural ester. 73 The winding model was constructed from polycarbonate 18 Though it was indicated that ester filled transformer would 74 sheets and the sheets were milled to create $H_d = 4$ mm and W_d 19 have the same expected life despite it operates at higher HST 75 = 10 mm. Particle Image Velocimetry (PIV) system was used 20 compared to the expected life when the transformer is filled 76 to measure liquid flow rates within radial cooling ducts of the 21 with mineral oil. A model for a 66 MVA, 225/26.4 kV 77 third pass in the winding model. The PIV system consists of 22 transformer was studied both experimentally and numerically 78 dual head laser source, laser optics, a camera, a synchronizer, 23 with 3D CFD simulations under ON cooling regime [12]. 79 and a software to process captured images [18]. The PIV 24 Better prediction accuracy was achieved when simulating a 80 system records velocities by tracking the movement of seeding 25 3D domain exclusive only to the winding structure and setting 81 particles within the flow. The seeding particles used in this 26 up the boundary conditions from experimental measurements 82 study were silver coated hollow gas spheres with diameter 27 of winding inlet oil flow and inlet temperature. In [13], oil 83 range from 10 to 14 microns. The laser source fires two 28 flow measurements were conducted using optical methods 84 consecutive pulses with known time difference and the camera 29 under OD cooling modes with tests conducted under pass inlet 85 captures correspondingly two raw images. Using the time 30 Reynold numbers from 667 to 4000. The winding geometries 86 difference between the two laser pulses and the seeding 31 were 6 plates/pass and both radial and vertical cooling ducts 87 particles displacement in the captured pair of images, liquid 32 were 6 mm each. It was indicated that 2D CFD predictions 88 velocities within cooling ducts are calculated using the 33 over-estimated plate temperatures whereas 3D CFD 89 software.

34 predictions matched well with temperature measurements. In 35 another study, it was found that higher inlet flow rate and 36 higher inlet oil temperature caused higher deviations from 37 experimental measurements [14].

38 In this paper, an experimental study is carried out to

39 compare the thermal performance between different

40 transformer liquids in terms of liquid flow and temperature

41 distributions in a zig-zag disc type winding model under

42 imitated directed and natural cooling modes. Used

43 experimental setup is introduced in section II. Comparisons of

44 the thermal performances of tested liquids under OD/KD

45 cooling modes are presented in section III. Comparisons of the

46 thermal performances of tested liquids under ON/KN cooling

47 modes are presented in section IV. Discussion and conclusions

48 are given in sections V and VI, respectively.

49 II. EXPERIMENTAL DESCRIPTION

50 A. Experimental setup

51 Used experimental setup, as shown in Fig. 1, consists of a 52 disc type winding model, a radiator, a pump and a flow meter. 53 The pump is used to force the liquid to circulate through the 54 system. The winding inlet velocity (V_{in}) is measured using a 55 positive displacement flow meter with 0.5% accuracy of 56 reading. A throttling valve is used to set and control V_{in} as

51 Fig. 1. Sketch of experimental setup, the laser sheet was 15 mm in the z- 52 direction away from the wall near the camera

As indicated on Fig. 1, PIV measurements are conducted near the end of a radial cooling duct in the direction of flow and the laser sheet was positioned 15 mm in the z-direction farther from the winding model wall near the camera. The camera field of view is 2 cm. More detailed descriptions of the PIV system and oil flow measurement in radial cooling duct are presented in [18].

Liquid flow profile within a radial cooling duct is a laminar profile in typical transformer operating conditions. Using the PIV system, the maximum velocity (V_{max}) of its quasi-parabolic shape is extracted from the PIV image. The average duct velocity (V_{av}) is approximately related to V_{max} using $V_{av} = V_{max} / 1.5$. It was checked that this approximation is acceptable within 10% comparison accuracy both experimentally, by comparing summations of volumetric flow rates in the third pass radial cooling ducts to that measured by a flow meter at the inlet of the winding model, and by comparing to CFD simulations in our previous publication [19]. The experimental setup and the PIV system were presented in more detail in [18, 19].

B. Liquids under investigations

Three different liquids were used. Firstly, a mineral hydrocarbon based transformer oil (MO) [20]. Secondly, a gas to liquid hydrocarbon based transformer oil (GTL) [21]. The third liquid was a synthetic ester based transformer liquid (SE) [22]. Table I summarizes the values of key thermal parameters of the liquids at three different operating temperatures. The system is filled with liquid using a liquid tank connected to the experimental setup. Air can leave the experimental setup through both bleeds above the winding model and the radiator. Before using different liquid, a strict procedure was used to drain the old liquid from the system before testing the next liquid. Drainage of the old liquid was conducted by dismantling and cleaning the winding model and the pipe work and by flushing the radiator with the new liquid.

TABLE I
THERMAL PROPERTIES OF USED LIQUIDS

Liquid properties at operating temperatures (°C)		σ $\frac{kg}{m^3}$	ν $\frac{mm^2}{s}$	k_c $\frac{W}{m.K}$	C_p $\frac{J}{kg.K}$	β_{Th} $\frac{1}{K}$
Mineral oil (MO)	40	858	9.2	0.132	1794	N/A
	60	845	5.2	0.130	1877	0.00078
	80	832	3.4	0.128	1956	N/A
Gas-to-liquid (GTL)	40	793	9.6	0.142	2271	0.00081
	60	780	5.6	0.140	2365	0.00081
	80	767	3.7	0.138	2458	0.00084
Synthetic ester (SE)	40	956	28	0.143	1933	0.00077
	60	941	14	0.141	1994	0.00078
	80	926	8	0.139	2023	0.00079

III. COMPARISON UNDER DIRECTED COOLING MODES

Under OD/KD cooling modes, liquid is forced to circulate within the winding using a pump. Washers within the winding structure force the liquid to flow in a zig-zag fashion. According to [4, 19], liquid flow distribution is influenced by dimensionless numbers such as the Re number and geometrical based dimensionless numbers α , β , and γ [4]. Since the Re is defined as $Re = (D_h \times V_{in}) / \nu$, only ν and V_{in}

affect the Re for fixed winding geometry. Higher ν causes lower Re resulting in more uniform liquid flow distribution within the winding radial cooling ducts [4, 19]. The uniformity of liquid flow distribution is indicative to the fair share of flow rates amongst the pass radial cooling ducts. ν is a temperature dependent parameter, which is also related to liquid type.

A. Liquid flow and temperature distributions under different V_{in}

To investigate the influence of different liquids on liquid flow and temperature distributions, experiments were conducted under four different V_{in} of 0.1 m/s, 0.2 m/s, 0.27 m/s, and 0.3 m/s. Uniform loss distribution in each plate with $P_{loss} = 50$ W/plate, which is equivalent to 2010 W/m², was applied. T_B was fixed to 70 °C.

Fig. 2 shows liquid flow and temperature distributions in the third pass within the winding model at V_{in} of 0.1 m/s. Liquid flow distributions of MO and GTL are almost identical whereas SE caused slightly more uniform flow distribution which means that there is a more fairer share of oil velocities amongst pass radial cooling ducts compared to MO or GTL. A fully uniform flow distribution would indicate that each cooling duct would have the same flow rate.

The calculated Re of SE is almost half that of the other oils as shown in Table II. Liquid flow distributions for tested liquids are relatively uniform which lead to uniform temperature distributions. Temperature profiles of tested liquids are almost comparable.

Fig. 3 represents liquid flow and temperature distributions at V_{in} of 0.27 m/s. At this relatively high inlet liquid velocity, liquid reverse flow starts to occur in duct 1 for both MO and GTL. The flow distribution using GTL is almost the same compared to MO as they have close inlet pass Reynold numbers. Due to its higher ν , SE causes more uniform flow distribution and so offers more resistance to liquid reverse flow phenomenon. Compared to the previous test under V_{in} of 0.1 m/s, liquid flow distributions are less uniform which directly cause less uniform temperature profiles. The occurrence of liquid reverse flow causes higher HST_{rise} for both MO and GTL compared to SE.

TABLE II
TESTS SUMMARY UNDER DIRECTED COOLING MODE WITH $T_B = 70$ °C

V_{in} [m/s]	Liquid Type	T_{top} [K]	Re^*	HST_{rise} [K]	HST location	Reverse flow
0.1	MO	78.6	443	17.5	Plate 4	No
	GTL	78.1	387	17.9	Plate 4	No
	SE	76.7	173	18.6	Plate 3	No
0.2	MO	74.7	887	14.3	Plate 1	No
	GTL	74.6	774	15.3	Plate 1	No
	SE	71.8	346	13.4	Plate 1	No
0.27	MO	73.7	1183	17.6	Plate 1	Yes
	GTL	73.8	1032	17.2	Plate 1	Yes
	SE	74.1	461	12.4	Plate 1	No
0.3	MO	73.8	1330	15.9	Plate 1	Yes
	GTL	73.5	1161	16.6	Plate 1	Yes
	SE	73.4	520	12.3	Plate 1	No

* Re was calculated using ν at $T_B = 70$ °C and $D_h = 0.018$ m

Fig. 2 Liquid flow and temperature distributions under directed cooling modes with $V_{in} = 0.1$ m/s, $P_{loss} = 2010$ W/m², and $T_B = 70$ °C.

Fig. 3. Liquid flow and temperature distributions under directed cooling modes with $V_{in} = 0.27$ m/s, $P_{loss} = 2010$ W/m², and $T_B = 70$ °C.

B. Pressure loss under isothermal conditions with uniform liquid temperature = 70 °C

At a fixed winding geometry and V_{in} , higher viscosity liquid would lead to higher pressure losses in the winding. Under isothermal testing conditions with uniform liquid temperature of 70 °C, P_L was measured under a range of V_{in} from 0.05 m/s to 0.35 m/s for the three different liquids as shown in Fig. 4. Pressure measurement ports were fixed on the centre line of the first pass inlet washer and the centre line of the third pass outlet washer.

MO and GTL cause comparable pressure loss over the winding model. SE causes higher pressure loss over the winding model compared to the other two liquids.

To summarize, three main observations are being made. First, with higher V_{in} , liquid flow distribution in the third pass radial cooling ducts is less uniform for all liquids and this directly results in less uniform temperature profiles. Less uniform reflects that more liquid flows in top radial cooling ducts compared to bottom cooling ducts which cause higher temperatures in bottom plates. Second, MO and GTL showed similar liquid flow and temperature distributions whereas SE caused more uniform liquid flow and temperature

distributions. Hence, SE offered higher resistance to the occurrence of liquid reverse flow. Third, assuming a retrofilling scenario with the same pump and so fixed pressure loss over the winding of 300 Pa as shown in Fig. 4, SE would cause lower V_{in} close to 0.22 m/s compared to the two other liquids which would cause V_{in} close to 0.27 m/s. Lower V_{in} , and higher ν , indicate lower Re . Lower Re leads to more uniform flow distributions within the winding passes [4, 19]. With lower Re , liquid reverse flow is less likely to occur under SE. Under $V_{in} = 0.27$ m/s, liquid reverse flow occurred under MO and GTL and it did not occur under SE and so the HST was lower when using SE.

Fig. 4. Measured P_L over the winding model under isothermal conditions with uniform liquid temperature = 70 °C.

IV. COMPARISON UNDER NATURAL COOLING MODES

Under ON/KN cooling modes, the flow is driven by the developed thermosyphon force (p_{Th}) within the transformer hydraulic cooling loop. At steady state, V_{in} is reached when p_{Th} is equal to the total pressure loss in the hydraulic loop [6]. According to [6], p_{Th} can be calculated using (1). ΔT can be related to the total electric losses in the winding ($P_{loss,total}$) and to the inlet mass flow rate ($\dot{m}$) as presented in (2). $\dot{m}$ is related to V_{in} using σ and A_c as shown in (3). P_L can be calculated by adding all pressure drops around the hydraulic loop. Darcy – Weisback equation shown in (4) can be used for evaluation of pressure drops within individual sections of the winding model and transformer loop [6, 23, 24].

$$p_{Th} = g \sigma_o \beta_{Th} \Delta T \Delta H \quad (1)$$

where σ_o is the liquid density at a reference temperature, β_{Th} is the liquid thermal expansion coefficient, g is the acceleration of gravity, ΔH is the height difference between radiator and winding centres, and ΔT is the increase in liquid temperature across the winding as defined in (2).

$$\Delta T = \frac{P_{loss,total}}{\dot{m} \times C_p} \quad (2)$$

$$\dot{m} = \sigma \times A_c \times V_{in} \quad (3)$$

$$P_{L,i} = f_i \times \frac{L_i}{D_{h,i}} \times \sigma \times \frac{V_{in,i}^2}{2} \quad (4)$$

where f_i is the friction coefficient, L_i is the equivalent duct length, and the i subscript refers to the i component in the

1 hydraulic loop

2 In the following analysis, a global view of the hydraulic
3 loop of the experimental setup is considered in which the
4 entire hydraulic loop is lumped and modelled with an
5 equivalent pipe in order to relate liquid only parameters, such
6 as viscosity, density, and thermal expansion coefficient, to the
7 inlet velocity developed naturally by the systems'
8 thermosyphon induced pressure. This approach does not look
9 into detailed modelling of pressure losses internal to the
10 winding model ducts and joints. For this detailed modelling of
11 pressure losses, readers can refer to published work related to
12 network modelling [24-29]. Network models are less accurate
13 but they demand less computational resources compared to
14 CFD simulations. As such, they are used by designers in early
15 stages during the transformer design iteration process.

16 Assuming that at a specific steady state operating point, the
17 experimental setup hydraulic loop can be modelled as an
18 equivalent pipe with an equivalent length L_{eq} and an
19 equivalent hydraulic diameter $D_{h,eq}$ such that the flow is
20 laminar. Laminar flow is a reasonable assumption for ON/KN
21 cooling modes. Also, assume that average inlet liquid flow
22 velocity equals to V_{in} and pressure drop over the pipe equals
23 to P_L .

24 In this case, the equivalent friction coefficient f_{eq} can be
25 presented by (5). To relate V_{in} to liquid only dependent
26 properties, first, (3) is substituted in (2) and the resulting (2) is
27 substituted in (1). Then, (5) is substituted in (4). By equating
28 resulting (1) and (4), i.e. $p_{Th} = P_L$, (6) is produced. The first
29 term in (6) is related to the winding model geometries and to
30 the total power losses whereas the second term is related to
31 only liquid properties. In the current experimental setup, (6)
32 can be used approximately to answer the question as what
33 would be the new V_{in} if using a new liquid in the winding
34 model under the same winding model power losses and
35 geometrical conditions compared to the old liquid case to
36 reflect a retrofilling scenario.

$$f_{eq} = \frac{C}{Re} = \frac{C \times v}{D_{h,eq} \times V_{in}} \quad (5)$$

37 where C is a constant which depends on the flow regime
38 and the pipe shape

$$V_{in}^2 = \left\{ \frac{2g \times D_{h,eq}^2 \times \Delta H \times P_{loss,total}}{C \times A_c \times L_{eq}} \right\} \times \left\{ \frac{\beta_{Th}}{v \times C_p \times \sigma} \right\} \quad (6)$$

39 In tests conducted henceforth, P_{loss} is fixed to 30 W/plate
40 which is equivalent to 1200 W/m². T_B is maintained at 60 °C.
41 V_{in} is still controlled by external pump and valve. To check
42 whether the testing conditions can represent natural cooling
43 regime within the winding model, Richardson number (R_i) is
44 calculated for all conducted tests. R_i is presented in (8) and
45 defined as the ratio of Grashof number (G_r), shown in (7), to
46 the Re number square. According to [30], if $R_i \ll 1$, then the
47 cooling regime is considered OD/KD dominated regime. If
48 $R_i \gg 1$, then the cooling regime is considered ON/KN
49 dominated regime.

$$G_r = \frac{g \beta_{Th} D_h^3}{\nu^2} \times (T_{mw} - T_{mo}) \quad (7)$$

$$R_i = G_r / Re^2 \quad (8)$$

50 where T_{mw} is the mean winding temperature and T_{mo} is the
51 mean liquid temperature.

52 In the following, performances of different liquids are
53 compared under two different approaches. The first approach,
54 section A, is designed to run experiments under fixed V_{in} . The
55 second approach is to compare MO and SE under a more
56 realistic scenario in which the system determines V_{in} based on
57 equation 6

58 A. Flow and temperature distributions under different V_{in}

59 Tests were conducted with three different V_{in} of 0.026 m/s,
60 0.021 m/s, and 0.017 m/s which are within the expected range
61 of ON/KN transformers [7]. Table III represents key test
62 results with the calculated R_i number for each test. It is
63 observed that lower V_{in} causes less uniform liquid flow and
64 temperature distributions, i.e. more dominated natural cooling
65 regimes, which are reflected in higher R_i numbers. In general
66 under ON/KN cooling modes, more liquid flows into pass
67 bottom cooling ducts and less liquid flows into pass top
68 cooling ducts [8]. Individual tests are discussed as follows.

69 Fig. 5 shows recorded liquid flow and temperature
70 distributions at steady state for tests under V_{in} of 0.026 m/s.
71 Liquid flow and temperature distributions follow almost an
72 opposite trend to that under OD/KD cooling modes. MO and
73 GTL have almost the same liquid flow distributions whereas
74 SE has relatively more uniform flow distribution contributing
75 to higher flow rates into pass top cooling ducts. For both MO
76 and GTL, oil stagnation was observed in duct 11 but it did not
77 occur for SE. Occurrence of oil stagnation under natural
78 cooling was also reported using CFD simulations in [31, 32].
79 Therefore, SE has lower HST_{rise} compared to the other
80 liquids. Using SE, it can be observed that the Re number is
81 almost half of the other liquids and the R_i number is slightly
82 lower.

83 Results under V_{in} of 0.021 m/s are shown in Fig. 6. Liquid
84 stagnation occurs in duct 10 under both MO and GTL whereas
85 it did not occur when testing under SE. Liquid stagnation
86 causes a large increase in temperature of nearby plate; in this
87 case it is plate 9. Liquid flow distribution was almost identical
88 when testing using MO and GTL and it was more uniform
89 when testing with SE. As a result of liquid stagnation not
90 occurring under SE, HST_{rise} was lower compared to the other
91 liquids. In comparison to tests under V_{in} of 0.026 m/s, higher
92 R_i numbers are observed which indicate more dominating
93 ON/KN regimes.

94 TABLE III

95 SUMMARY OF TEST RESULTS UNDER ON/KN COOLING MODE WITH
96 CALCULATED DIMENSIONLESS PARAMETERS. TESTS WERE CONDUCTED UNDER
97 $T_B = 60$ °C

Liquid Type*	T_{top} [°C]	T_{mw} [°C]	HST_{rise} [K]	Re^*	G_r^*	R_i
Tests conducted under $V_{in} = 0.026$ m/s						
MO	80.4	80.3	36.5	117	28436	2.1
GTL	76.6	77.5	33.6	102	20435	2
SE	77.3	78.3	25.8	46	3939	1.9
Tests conducted under $V_{in} = 0.021$ m/s						
MO	83.7	85	49.2	97.7	36968	3.9
GTL	80.6	82.9	47.5	85	26645	3.7

SE	81.2	80.4	36.5	38.2	3919	2.7
Tests conducted under $V_{in} = 0.017$ m/s						
MO	87.7	89.8	54	78.2	44584	7.3
GTL	82.6	86.1	54	68.2	32396	7
SE	83.5	85.2	52	30.5	5450	5.8

1 * Re and G_r were calculated using v at $T_B = 70$ °C and $D_h = 0.018$ m

2 Results under V_{in} of 0.017 m/s are shown in Fig 7. With
3 lower V_{in} , more dominating natural cooling regime is
4 produced with higher R_i numbers. Similar to previous tests,
5 MO and GTL gave almost identical flow distributions. Liquid
6 reverse flow occurred under both MO and GTL, in duct 8 and
7 duct 9, whereas liquid stagnation occurred under SE in duct
8 10. It was observed that higher viscosity liquids delay the
9 occurrence of oil stagnation top of the pass under natural
10 cooling modes. Because of the occurrence of liquid reverse
11 flow and liquid stagnation, the differences in the HST_{rise}
12 between the liquids were minimum amongst the conducted
13 tests in this section.

14 Fig. 5. Liquid flow and temperature distributions under ON/KN cooling mode
15 with $V_{in} = 0.026$ m/s and $T_B = 60$ °C.

18 Fig. 6. Liquid flow and temperature distributions under ON/KN cooling
19 modes with $V_{in} = 0.021$ m/s and $T_B = 60$ °C.

21

22 B. Comparison of MO and SE under a specific retrofilling
23 scenario

24 In the previous section, the performances of different
25 liquids were compared under fixed V_{in} which is not reflective
26 to actual transformer retrofilling condition. However, as
27 demonstrated in (6) the liquid properties influence the
28 developed V_{in} under ON/KN cooling modes.

29 Fig. 7. Liquid flow and temperature distributions under ON/KN cooling
30 modes with $V_{in} = 0.017$ m/s and $T_B = 60$ °C.

32 It was reported in literature that when retrofilling a power
33 transformer with a new liquid, in point of view of thermal
34 aspects, careful considerations need to be made since the HST
35 may be increased [9-11]. The main reason for the increase in
36 the HST is the reduction of the developed V_{in} when using a
37 different liquid which has higher viscosity. Under the present
38 experimental setup, V_{in} is controlled instead of allowing the
39 system to determine its value similar to what was conducted in
40 [17]. For this reason, (6) can be used, though requires further
41 verifications, to approximately answer the question as of what
42 would be the naturally developed V_{in} when using a new liquid
43 under the same winding model geometries and operating
44 conditions, presented in the first term in (6), so that different
45 liquids performances are judged fairly. As an example, a
46 specific case study is discussed in which SE is compared to
47 MO in a hypothetical retrofilling scenario. According to (6)
48 and the liquids information shown in Table I at temperature 70
49 °C, MO would have an inlet velocity ($V_{in,MO}$) of 1.69 times
50 higher than that of SE ($V_{in,SE}$), i.e. $V_{in,MO} = 1.69 \times V_{in,SE}$. It is
51 very important to emphasize here that this relationship is only
52 valid for the related testing conditions and the studied winding
53 arrangements. Further experimental validations are required to
54 justify the validity of (6) in a broader context.

55 Tests were conducted under uniform losses of $P_{loss} = 30$
56 W/plate or equivalently 1200 W/m². T_B was maintained at 60
57 °C. The winding model geometries are relatively close to the
58 specified low voltage winding of a 22 kV, 250 MVA
59 transformers mentioned in [25]. Table IV provides a summary
60 of key test results in which $V_{in,MO} = 0.028$ m/s and $V_{in,SE} =$
61 0.017 m/s. Test results are presented in Fig. 8. A difference in
62 the HST_{rise} between MO and SE of 26 °C was recorded while
63 only 6 °C difference in T_{top} was recorded between the two
64 liquids. Though this case may be the worst case possible of a
65 bad retrofilling choice for ON/KN transformer, it is intended

1 to raise the awareness that appropriate consideration and
2 selection of good transformer candidates is important to fully
3 benefit from the advantages provided by alternative liquids.
4 The increase in the HST under SE, in this studied case, is
5 because liquid stagnation occurs in duct 10 and that liquid
6 flow distribution under MO is much more uniform compared
7 to SE. This can show that the proper selection of the candidate
8 for retrofilling of any transformers is really important. It is
9 expected, based on the previous tests, that GTL would perform
10 similar to MO under the current experimental setup
11 geometries and testing conditions.

TABLE IV
TEST UNDER RETROFILLING SCENARIO WITH T_B FIXED AT 60 °C

Liquid Type*	V_{in} [m/s]	T_{top} [°C]	T_{mw} [°C]	HST_{rise} [K]	Re^*	G_r^*	R_i
MO	0.028	77	78	26	125	25544	1.6
SE	0.017	83.5	85.2	52	30.5	5450	5.8

* Re and G_r were calculated using v at $T_B = 70$ °C and $D_h = 0.018$ m

Fig. 8. A comparison between the thermal performance of MO and SE under a specific retrofilling scenario in which according to (6), which required experimental validations, MO develops 1.69 higher flow rate compared to SE.

V. DISCUSSIONS

Under directed cooling modes, it was predicted that dimensionless numbers, such as the Re number and the ratio between the radial to the axial cooling ducts (α), influence liquid flow distribution in a pass [4]. The Re number is a function of V_{in} and v . Higher v , or lower V_{in} , leads to a lower Re and hence a more uniform flow distribution. Ester based liquids have higher viscosities compared to mineral and gas-to-liquid oils and so they develop a more uniform flow distribution within the winding passes. Higher viscous liquids provide more resistance to the occurrence of liquid reverse flow in pass bottom cooling ducts. Nonetheless, the ester liquid causes higher pressure loss within the winding and so for the same pump, lower V_{in} develops and so even more uniform liquid flow distribution is produced.

Under natural cooling modes and for the zig-zag disc type winding model, results showed that the difference in the HST between different liquids is relatively small when liquid reverse flow, or liquid stagnation, occurs under all liquids in

38 pass top cooling ducts. To compare the liquids' thermal performances fairly, (6) was used to roughly estimate as of what would be the new V_{in} when using a new liquid compared to the old one. The reported data of measured inlet and outlet liquid temperatures under similar transformer loading levels indicate that mineral oils have a near 1.6 higher $\dot{m}$ compared to natural ester [9, 11] which supports the estimated relationship between $V_{in,MO}$ and $V_{in,SE}$ using (6), though experimental validation of (6) is still required before further expansion of conclusions. Ester based liquid was compared to mineral oil, using (6), in a retrofilling scenario and it was observed that the differences in the HST_{rise} and in T_{top} between the two oils are consistent with reported measurements in the literature under actual retrofilling tests [11] for zig-zag disc type power transformers. Results facilitate that the difference in T_{top} may not be a good indicator of the difference in the HST_{rise} . Ester based liquid may increase the HST due to its higher viscosity which causes lower V_{in} to develop. Still, in the industry the measurement of top liquid temperature could be carried out easier.

VI. CONCLUSION

Experimental investigation and comparison of the thermal performance of different transformer liquids were conducted under both OD/KD and ON/KN cooling modes. A disc type zig-zag winding model was used and inlet liquid velocity was controlled and set to desired values. Three liquids were compared which are a mineral hydrocarbon based transformer oil (MO), a gas to liquid hydrocarbon based transformer oil (GTL), and a synthetic ester based transformer liquid (SE). Under both OD/KD and ON/KN cooling modes, MO and GTL gave similar liquid flow distributions within the winding model and very close temperature profiles. Under OD/KD cooling modes, SE showed more resistance to the liquid reverse flow phenomenon and gave more uniform liquid flow distribution. Nonetheless, SE caused higher pressure losses within the winding model. Under ON/KN cooling modes and in a retrofilling perspective, SE increased the HST compared to MO under the conducted testing conditions and winding model geometries.

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