International Conference on Renewable Energies and Power Quality (ICREPQ'18)
Salamanca (Spain), 21th to 23th March, 2018
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.16 April 2018

Hydraulic assessment of nanofluids based on mineral oil and natural ester in windings of power transformers

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Abstract. It is common for electric power transformers to be cooled by mineral oil. However, this type of oil has begun to be replaced by oils of natural origin (esters), due to environmental and fire safety reasons. The latter are biodegradable and have an ignition point much higher than that of mineral oils. On the other hand, different authors have found that the dielectric and refrigerant properties of the oils used in transformers can be improved when some types of nanoparticles are added. In order to assess this improvement, this work presents the results obtained by a research in which different nanofluids, produced through commercial dielectric oils (mineral and natural), nanoparticles of titanium (IV) oxide and magnetite, were thermally characterized. The results of this characterization have been used to perform simulations based on computational fluid dynamics. This comparison has allowed to observe the pressure drops and the mass flows in the internal channels of the windings of a real power transformer.

Key words

Transformer, nanofluids, biodegradable oils, pressure drop, mass flow.

1. Introduction

Power companies have been using power transformers since the development of transmission and distribution networks. These electric machines are extremely robust and normally exceed 40 years of life. Most of them use mineral oil (a petroleum product) as dielectric and cooling fluid. The voltage levels of electric power transmission systems are increasingly high. This growth must be complemented by insulation systems with better dielectric capacities, with respect to conventional equipment [1]. In this way, a lot of research can be found in improving the dielectric properties of insulation, mainly paper and oil [2].

The fluids used in electric power transformers perform two main functions: to serve as electrical insulation between the different active parts of the machine, and to favor the evacuation of the heat generated. Typically highly refined oils are used, but they have a low thermal conductivity and therefore low cooling efficiency [3].

The advantages derived of nanoparticle addiction in the dielectric oil used by power transformers, have recently begun to be explored. In this line, the two most outstanding characteristics of these mixtures are: the improvement of the dielectric strength of the fluid and the increase in the cooling capacity of the electric machine, caused by the increase in thermal conductivity [4]. It has been shown that heat transfer in electromagnetic devices can be substantially improved by the use of magnetic fluids.

The addition of Fe_3O_4 nanoparticles to mineral oils can reduce the value of "hot spots" in transformer windings. The temperature of these points can be shortened up to 5ºC [5]. In addition, the increase in cooling capacity may be associated with the decrease in the amount of oil needed [6]. Recent studies have shown that by adding TiO_2 or Fe_3O_4 nanoparticles in transformer oil, it acquires better electrical insulation properties and greater resistance to the thermal aging caused by moisture [7, 8].

With respect to the previous scientific works that have studied the refrigeration of transformers with nanofluids, recent works are mentioned below.

In 2003, Snyder et al. carried out a first numerical simulation in which they studied the magnetoconvection of a ferrofluid inside a cube, in the presence of a magnetic field gradient and a temperature gradient [9]. Six years later, in 2009, Lee and Kim studied the effect produced by an alternating magnetic field on the cooling capacity of a magnetofluid [10].

A more complex numerical study [11] appeared 10 years after the publication of the first study, May 2013. The authors proposed a thermo-fluid-magnetic model in order to compare the cooling efficiency in a winding with a nanofluid, a transformer oil and air. The validation of the numerical results of this last study was carried out through a real platform that replicated experimentally the numerical study.

In June 2013, Pislaru-Danescu et al. carried out a much more comprehensive theoretical-practical study, in which they compare the temperature measurements in a ferrofluid -consisting of a colloidal dispersion of magnetite particles in a mineral oil- with those measured in mineral oil. For this comparison the authors proposed two approaches: first, by means of a numerical thermo-fluid-magnetic analysis of several 2D and 3D models of a small single-phase transformer (36kV, 40kVA); and second, by calculating the temperatures from the heating test performed on single-phase transformer mentioned [12]. A study derived from this last article is the one published by the same authors in November of 2013 [13]. Finally, February 2014, Weimin Guan et al [14] published an article analyzing the influence of the local density of nanoparticles and electrophoresis on the distribution of temperatures and refrigerant speeds. To do this, they simulated a 2D model of a single-phase, low-power transformer using a thermo-fluid-electric numerical model. This research will seek to expand current knowledge about the application of dielectric nanofluids to power transformers. This paper includes activities related to the production-characterization of these fluids and their performance in the cooling ducts of windings. Thus, the study will assess the suitability of using nanoparticles in transformer dielectric oil, using these results to quantify the influence of the nanofluids in the geometrical design of the transformers.

2. Experimental setup

The base liquids used to produce the studied nanofluids were two commercial dielectric oils, a mineral oil and a natural ester, Table I. The used nanoparticles were also commercially available. The TiO_2 was characterized by Transmission Electron Microscopy, using a JEOL JEM 2100 equipment operating at 120 kV. Fig. 1 shows the morphological characterization of TiO_2 nanoparticles, and Table II lists the properties of this type of nanoparticles. The other nanoparticle used was magnetite (Fe_3O_4), which has been supplied in the form of a colloidal dispersion (ferrofluid). Its most representative properties are shown in Table III.

Table I. – Specifications of oils used for the nanofluids

Property	Mineral oil	Natural ester
Breakdown Voltage (kV)	30	> 75
Kinematic Viscosity at 40ºC (mm^2/s)	10.3	39.2
Density at 20ºC (g/cm^3)	0.84	0.91
Pour point (ºC)	-48	-25

Table II. – Specifications of TiO_2 nanoparticles

Property	Specification
Density (g/cm3)	3.89
Morphology	spherical
Specific surface area (m^2/g)	> 120
Purity (%)	99.5
Average diameter (nm)	80

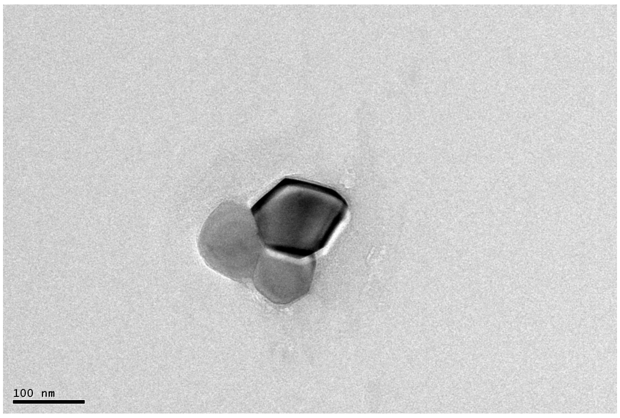

Fig. 1. Morphological characterization of TiO_2 nanoparticles.

Table III. – Specifications of ferrofluid (Fe_3O_4)

Property	Specification
Density (g/cm^3)	0.92 - 1.47
Content of magnetite nanoparticles (% v)	3 - 15
Boiling Point (°C)	205-255
Solubility in Water	Negligible
Oil soluble dispersant content (% v)	6 - 30
Content of carrier fluid (% v)	55 - 91

Table IV. – Studied nanofluids

Code	Oil	Nanoparticle	Concentration
A	Mineral	TiO_2	0.072%v
C	Mineral	TiO_2	0.036%v
E	Mineral	Fe_3O_4	0.072%v
G	Mineral	Fe_3O_4	0.036%v
B	Ester	TiO_2	0.072%v
D	Ester	TiO_2	0.036%v
F	Ester	Fe_3O_4	0.072%v
H	Ester	Fe_3O_4	0.036%v

Oil-based nanofluids were prepared by dispersing nanoparticles on base oil. The dispersion was carried out uniform through an ultrasonic bath (Elmasonic P300H) at 37 kHz and for 12 hours. For each fluid, two different concentrations of nanoparticles have been used, 0.036%v and 0.072%v. The nanoparticle concentration and the nanoparticles used to obtain the studied nanofluids are gathered in Table IV.

3. Computational fluid dynamics analysis

Nanoparticle addition to dielectric liquids has some benefits, such as a raise on the breakdown voltage. However, it has not been tested the impact on the cooling properties of these fluids. In order to assess the impact of adding nanoparticles to dielectric liquids over the cooling capacity of these, a study is performed to determine the deviation on the pressure drop. The pressure drop is an important parameter that determines the pumping cost of the dielectric fluid. In case of ON transformer, is related with the mass flow through the windings, affecting the cooling of these. A natural ester and a mineral oil are compared with four different nanofluids (four based on mineral oil and four based on natural ester) with different nanoparticles and concentrations.

For the present study, an isothermal 3D model of a part of a low voltage winding is considered. This model has been developed using the software ANSYS ™.

The numerical model is based on the Fluid Dynamics physics, the main governing equations are the Navier–Stokes equations for incompressible fluids in stationary regime (see Eqs. (1) and (2), where the symbols ρ, u, p, I and μ are density, velocity vector, pressure, identity matrix and dynamic viscosity, respectively). In Eq. (2), F represents the buoyancy forces, while the other right-hand term represents the pressure and viscous forces, respectively.

$$\rho(u\cdot\nabla)u=\nabla\cdot(-pI+\mu(\nabla u+(\nabla u)^T)-\frac{2}{3}\mu(\nabla\cdot u)I)+F \tag{1}$$

$$\nabla\cdot(\rho u)=0 \tag{2}$$

The geometry represents one pass of a power transformer low voltage winding that consists of 19 conductor discs in a radial and axial cooling configuration. The geometry is based on a transmission transformer 66 MVA e 225/26.4kV ONAN/ONAF [15] that is currently in service in the Hydro-Québec grid, Fig.2. The model consists in an inlet and an outlet section. A 3D CAD model of a 10º portion of the winding will be considered. In order to compare different liquids with different viscosities and densities, a Reynolds number is used as the inlet condition.

$$\mathrm{Re} = \frac{\rho u D}{\mu} \tag{3}$$

D: diameter of the pipe through which circulates the fluid.
u: liquid velocity.
ρ: liquid density
μ: dynamic viscosity

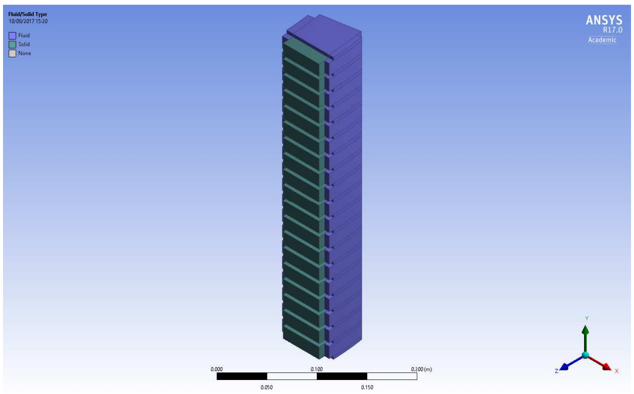

Fig.2. 3D CAD model of a low voltage winding (66 MVA).

The dimensions of the ducts in the considered winding can be seen in Fig. 3. A set of 10 different Reynolds numbers in a range between 1 and 600 are taken for each fluid considered in this study. Reynolds numbers considered are 1, 5, 10, 20, 40, 80, 100, 200, 400 and 600. Pressure drop and mass flow fraction through radial channels are observed for each case.

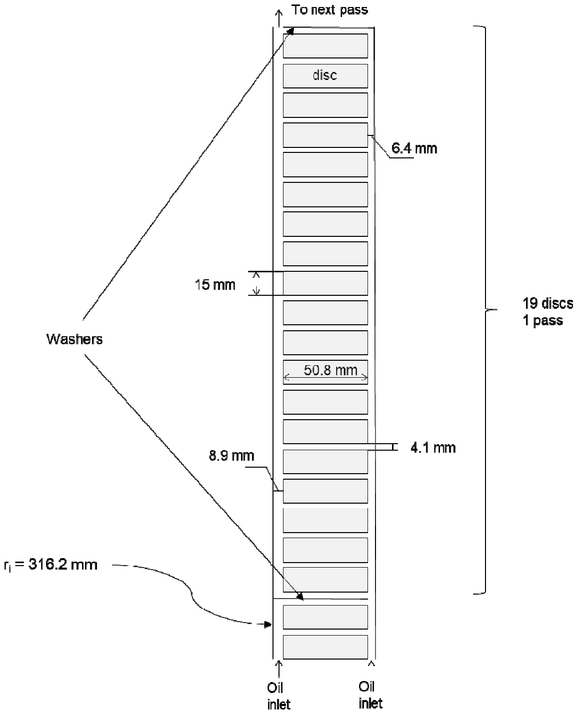

Fig.3. 19 discs-pass in the low voltage transformer winding.

4. Results

For each analysis, pressure drop and mass flow distribution is observed for a constant Reynolds number at the inlet. Regarding the mass flow distribution, it only depends on the Reynolds number at the inlet, so pressure drop only depends on the fluid properties. However, different Reynolds number leads to a different mass flow distribution, Fig.4.

Taking into account the pressure drop, Fig.5 and Fig.6, there is a difference between the nanofluids based on natural ester and those based on mineral oil, being the pressure drop over ten times higher in the natural ester based nanofluids.

From a technical point of view, fixing the volumetric flow or the mass flow at the inlet seems more interesting that fixing the Reynolds number. With these two variables fixed, different Reynolds numbers will appear at the inlet of the pass.

Considering the data obtained from previous simulations, a correlation between pressure drop and Reynolds number at the inlet has been developed. A curve fitting with a second-degree polynomial without independent term is chosen for each case. Three different mass flow rates have been selected; 0.78, 3 and 5kg/s, representing typical flows of cooling systems, ON and OD. The comparison between cases is presented in Tables V and VI.

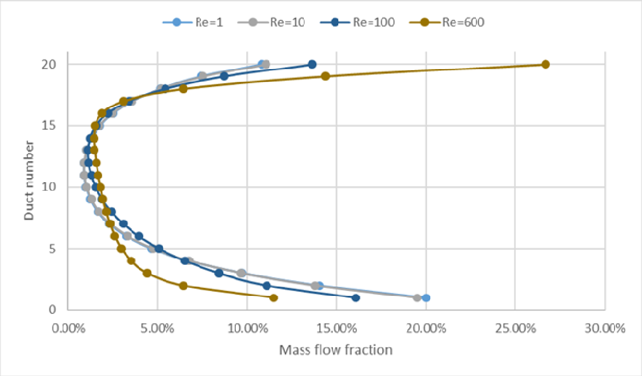

Fig.4. Mass flow distribution along the 19 conducting discs.

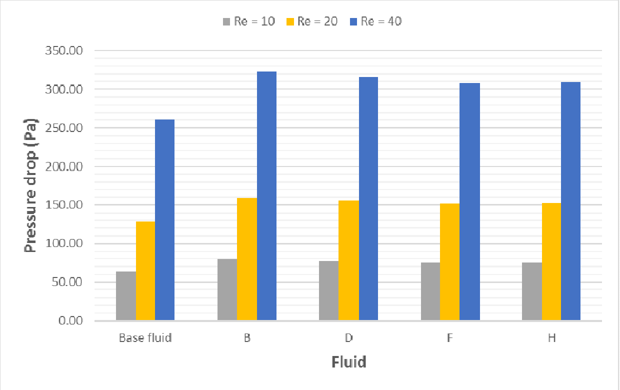

Fig.5. Pressure drop (Pa) for the nanofluids based on natural ester.

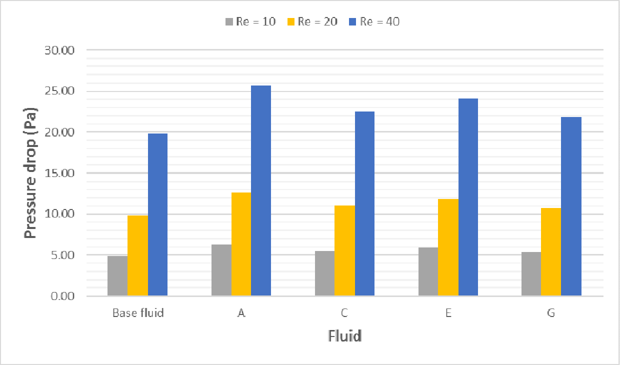

Fig.6. Pressure drop (Pa) for the nanofluids based on mineral oil.

Table V. – Nanofluids based on mineral oil

	0.78 kg/s		3 kg/s		5 kg/s	
	Re	ΔP	Re	ΔP	Re	ΔP
Base	90.74	45.78	348.99	229.06	581.65	461.30
A	79.82	51.98	306.98	252.10	511.64	498.54
C	84.51	48.07	325.04	237.05	541.73	473.43
E	82.10	49.86	315.75	244.50	526.25	486.66
G	86.20	47.65	331.54	235.94	552.57	472.29

Table VI. – Nanofluids based on natural ester

	0.78 kg/s		3 kg/s		5 kg/s	
	Re	ΔP	Re	ΔP	Re	ΔP
Base	24.08	147.43	92.61	616.12	154.35	1100.54
B	21.71	164.15	83.51	680.77	139.19	1208.81
D	21.88	162.11	84.15	672.66	140.25	1194.92
F	22.22	160.03	85.45	664.76	142.41	1181.91
H	22.10	160.50	85.01	666.45	141.68	1184.55

5. Conclusion

The addition of nanoparticles to a dielectric fluid increases its fluid resistance, leading to a higher pressure drop with respect to its base fluid. The main reason is an increase of the fluid viscosity caused by nanoparticle addition. In this case, an increase on the pressure drop of 8-13% has been observed for a reference case.

When comparing mineral oil based and natural ester based nanofluids, lower Reynolds numbers and higher pressure drops have been observed for natural ester based fluids. In this case the pressure drop for the same mass flow at the inlet is about three times higher.

Acknowledgement

The authors of this research wish to thank the Ministry of Economy for financial support to the National Research Project: Improvement of Insulation Systems of Transformers through Dielectric Nanofluids (DPI2015-71219-C2 1-R).

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