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# An experimental study of natural convection in a distribution transformer slice model

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ABSTRACT

The aim of this work is to obtain experimental information on the thermal and fluid dynamics of a distribution transformer. The transformer of interest is of the oil natural – air natural type and our interest is centered in the natural circulation that is produced in the oil volume. An experimental device was built to simulate a representative slice of the transformer and a purpose built PIV setup was used to obtain the flow velocity field. The device overall dimensions and the refrigerating oil are the same as those of commercial transformers of 1000 KVA (Tubos Trans Electric S.A. 1000 KVA Standard Distribution Transformer) Natural circulation is produced by a heating element simulating the heat produced by copper losses in the transformer. A double glass window allows visual access for flow visualization and PIV capture. The slice comprises two fins and the air side is bounded by two isolating boards, forming three air channels. Two reference powers were tested for the experiment: The power corresponding to design operating conditions and a lower power to observe the sensibility to power variations. The result reported in this work shows features of the flow pattern that give important information on the sort of turbulent mixing to be expected. The transient evolution was measured and the thermal characteristic time of the system was estimated. It was found that the convection during the start-up transient is significantly stronger than during steady state operation.

## 1. Introduction

The main motivation of this work is to measure experimentally the oil flow pattern and the heat transfer in an ONAN (Oil Natural Air Natural) type power transformer. This type of transformers are oil filled. This oil acts both as electrical insulator and as coolant fluid, maintaining the temperature of electrical components within acceptable limits. Transformers produce heat in the ferromagnetic core and in the coils due to unavoidable power losses. The oil is heated by the core and the coils and circulates to the hollow fins, where it is cooled down. The fins provide an exchange surface with the air and heat is transferred, again by natural convection to the atmosphere, therefore the ONAN denomination. In the design of interest, fins are integral part of the walls being manufactured by folding a metal sheet. The resulting flexibility of the walls allows to compensate the volume changes of the oil without an expansion tank.

There are both, country specific regulations (In Argentina we have the [1]) and international standards [2,3] that define the allowable operation conditions for these devices. These regulations give mathematical models for the calculation of operating temperatures in the transformer, in particular the temperature of the hottest spot of the winding. The [2] also suggest a series of working temperature boundaries to avoid premature degradation of the oil or the transformer materials. In spite of these regulations it is still up to the manufacturer to achieve a design that satisfies these limits while minimizing the size and cost of the transformer. This is a rather challenging task that normally involves trial and error and ends up with varying degrees of over dimensioning.

These thermohydraulic devices have been widely studied in order to improve their efficiency and lifespan. One of the aspects of greatest interest is the point of maximum temperature or the hottest-spot winding temperature, due to the fact that it is the principal factor in determining the life time due to loading. Researchers use different methods to determine the hot spot temperature [4]: proposed a numerical method to obtain the temperature distribution in the power transformer windings in a transformer with non-directed oil forced (NDOF) and directed oil forced cooling. They took into account the winding structure in contrast to the calculation procedure given in the

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international Standards ([2]) which contains simplified calculation methods [5]. presented a thermal modeling based on the thermal-electrical analogy and heat transfer theory to predict the top-oil and hot-spot temperature in ONAN cooled transformers. In posterior works [6,7], took into account the oil viscosity changes and power loss variation with temperature in their improved thermal modeling. The life span of the transformer is also strongly influenced by the condition of the solid insulation (paper and pressboard). At higher temperatures, the solid insulation can suffer deterioration reducing its life span [2]. A discussion of this topic can be found in the work of [8]. The authors also suggest a method for life cycle prediction based on measurements of insulating resistance at several temperatures. It is also known that the dielectric oil, can degrade over time to the point that the device can not withstand severe events such as overvoltage or short circuit [9]. Hajidavalloo et al. in Ref. [10] added an experimental component analyzing the temperature rise in a ONAN type transformer by effects of radiation. Their model predicts the temperature values measured in their experimental study. They also evaluated the use of a protective awning to extend the life time of the device.

The ONAN heat transfer scheme has proven reliable and cost effective. Yet the assessment of these schemes require to tackle the combination of two natural convection systems, and a complex geometry involving different length scales, and the variable properties of the fluids involved. These characteristics make both, experimental and numerical assessments, rather challenging. Also, this heat transfer scheme involves different phenomena that have been studied separately due to their engineering interest. The natural convection problem has been widely studied for its engineering applications in solar collectors [11] and research reactors [12], among others. For these studies the geometries are typically simplified cubic or prismatic cavities with fixed boundary conditions. We can mention the studies by Refs. [13–15] on the natural convection flow in a wide range of Rayleigh numbers, or the works of [16–19] on the influence of the temperature dependence of the fluid properties on the flow patterns. The transition to turbulence is a topic that has been studied for natural convection problems with constant properties of the fluid [20,21], being an unexplored topic for the case of variable properties. When determining the flow field and the temperatures in an ONAN transformer, these phenomena have to be accounted for to produce a realistic result, making both experimental and numerical assessment quite challenging. The experimental studies regarding these devices are limited. Most of the works available in the literature, only involve temperature measurements in transformer prototypes equipped with temperature sensors at some points of interest within the device [5,10,22–25]. Typically, such thermo probes are thermocouples or optical fiber based temperature sensors [25]. All experimental works mentioned above have been used to verify thermal models. Therefore, the experimental measurement of the flow field in these devices is still a rather unexplored area.

Natural convection in oil cooled transformers has been widely studied from the computational point of view. The CFD approach allows not only to predict the hot spot temperature but also the temperature distribution and the flow pattern. The knowledge of the fluid field inside transformer can then be used to optimize its cooling. [26–28], among others, studied the thermal distribution and flow pattern in a disc-type power transformer by CFD modeling of the cooling channels in the winding. Regarding ONAN type transformers, and due to the complexity of the problem, modeling all the details of the transformer structure is still computationally expensive. Thus, depending on the researcher, several geometric simplifications are used, [24,29–31]. [30], built two separated models, one for the solid active parts of the transformer, i.e. winding and core, and one for the oil tank. Then they coupled the results of the thermal solver with the CFD solver in an iterative process obtaining the temperature distribution. They point out that an experimental validation of their oil local velocity results is quite difficult. [24], and [31] presented a simplified mathematical model of the oil flow and heat transfer inside an ONAN transformer. In both models, the oil flow domain is reduced to a slice of the complete transformer, with some differences in the solution method and in the simplifications considered. The models predict a stratified temperature distribution and a notable rising oil plume generated at the outlet of the winding channels [24]. used a turbulent model, justified by their high Rayleigh number estimations, however the thermal models used to predict the hot-spot temperature of [6] assume laminar flow inside the transformer. The nature of the flow inside these devices is not clear yet due to the lack of experimental studies regarding the flow pattern. This flow could as well be laminar, fluctuating or turbulent.

In this work we perform measurements on an experimental device that simulates a representative slice of an ONAN distribution transformer. There have been several considerations to make this slice a good representation of the real transformer. The device uses a commercial transformer oil and the overall dimensions are the same as those of a commercial transformer of 1000 KVA (Tubos Trans Electric S.A. 1000 KVA Standard Distribution Transformer). The experimental device is composed of a heating element simulating the heating by copper losses in the transformer. A double glass window allows visual access for flow visualization and PIV capture. The slice comprises two fins and the air side is bounded by two isolating boards, forming three air channels. The power supply per unit depth was set to two different values, 2600 W/m and 3862 W/m. The second power corresponds to design operating conditions while the first (lower) power was chosen to observe the sensibility to power variations.

We present firstly a series of tests aimed to verify the satisfactory behavior of the experimental device. Then we present measurements of the heating transient and finally the steady state operation of the device. The experimental results are in good agreement with the steady state numerical solutions of [24] and [31], showing a stratified temperature distribution and a similar flow pattern in the studied region. We also performed preliminary numerical simulations using a 3D model of the slice used in the experiment. Based on the experimental results we decided not to introduce a turbulence model. The results of the numerical simulation are compared with the experimental measurements.

## 2. Experimental setup and measurement method

The Experimental Device (ED) was build in order to simulate a representative section of an ONAN (Oil Natural - Air Natural) 1000 KVA distribution transformer encompassing two fins. In the ED the heating by cooper losses in the transformer winding are simulated by an electrical heating element. A double glass window allows visual access for flow visualization and PIV capture. To achieve thermal similarity on the air natural convection side, the two fins were shielded with polystyrene foam boards, forming three air channels as sketched in Fig. 1 (Top view). This figure also shows the device dimensions and the reference coordinate system. The heating element consists of an aluminum structure as detailed in Fig. 1 (b). This structure was built with seven aluminum vertical plates 0.365 m high. These plates were connected through 12 lateral spacers and 6 central spacers that help uniformizing the temperature while keeping a rigid structure. The separation between the plates is about 8 mm and the free flow area is about 23 $cm^2$. Three Watlow FIREROD cartridge electrical heaters, with a diameter of 6.5 mm and a heating length of 50 mm each, were inserted perpendicular to these walls. These heaters were uniformly distributed along the vertical and in a good thermal contact with the aluminum plates. The seven aluminum plates and the spacers that conform the heating element achieve a satisfactory temperature uniformity given the high conductivity of aluminum as compared to the working fluid (coolant oil). The power was supplied to the heaters by means of a variable auto transformer.

According to data provided by Tubos Trans Electric S.A. from dissipation measurements of a transformer in no-load operation, power loss in the core accounts for 1740 W while the copper losses at full-load