

**ANALYSIS OF OIL FLOW DISTRIBUTION IN POWER TRANSFORMER WINDING COOLING
DUCTS USING TEMPERATURE MEASUREMENTS**

Laneryd T.^{1*}, Bel Fdhila R.¹, Rahmani M. A.¹, and Gustafsson A.²

*Author for correspondence

¹ABB Corporate Research, 721 78 Västerås, Sweden,

²ABB Power Products Division / Transformers, 771 80 Ludvika, Sweden

E-mail: tor.laneryd@se.abb.com

ABSTRACT

In this paper a method of temperature front measurement is proposed to quantify flow distribution within the cooling ducts of a power transformer winding. The winding will be prefilled with transformer oil at a certain temperature, and oil at another temperature pumped into the system. Velocities can then be estimated by keeping track of the oil temperature change in the oil ducts using temperature sensors. Due to the effect of buoyancy, the velocity field will not be constant during the temperature front measurement but with the help of transient CFD modeling the variation can be taken into account. The method has been successfully tested on a mock-up model of a transformer oil-guided disc winding section, and a comparison has been performed with steady state measurements using Laser Doppler Anemometry as well as both steady and unsteady CFD modeling results. Application of the temperature front method in real transformers will also be discussed.

INTRODUCTION

The technology of using large power transformers to raise voltages to high levels for more efficient transmission over long distances is over a hundred years old. The typical design of a power transformer, consisting of copper winding coil wound around a magnetized steel core, immersed in an oil tank, has not been altered significantly in this time. However, the increase in demand for electricity has led to an increase of the power transformer capacity resulting in more losses and more severe thermal requirements.

Power losses are induced in both the core and the winding leading to high local temperatures which adversely affect the lifetime of the transformer due to the rapid aging of insulating materials at high temperatures. The challenge in transformer thermal design is to manage these so-called hotspot temperatures so that the power transformer will last the expected lifetime.

Transformer oil serves a dual purpose of electrical insulation and cooling. Forced or naturally induced oil flows through cooling ducts of varying degree of geometrical

complexity are used to convect away heat while fulfilling requirements on insulation strength.

There are many possible transformer winding types but a very common configuration for high power loss densities is the oil-guided disc winding, where the oil flows through a labyrinth of parallel horizontal cooling ducts. To reduce hotspot temperatures the oil flow should be well distributed through these cooling ducts. An adverse pressure gradient would lead to stagnation or flow recirculation which would eliminate convective heat transfer and cause severe hotspot temperatures. Transformer manufacturers use thermal network models [1] and CFD modeling as a part of their regular design process to ensure a suitable oil flow distribution in the winding. The flow is characterized by mixed convection and it is therefore important to include the effect of buoyancy in the CFD model.[2] Typical Reynolds numbers for the oil ducts are small enough that flow is laminar and no turbulence modeling is required. To validate the numerical models, experimental measurements are necessary. For laboratory models, methods such as Laser Doppler Anemometry can be employed.[3] Experimental methods to investigate the oil flow inside transformer windings are less developed due to the limited space available for sensors and the inaccessibility for remote measurement devices due to the high voltage insulation.

In this paper a new method is proposed to measure oil flow distribution in a transformer disc winding. Temperature sensors are commonly inserted into the discs of the winding to evaluate hotspot temperatures.[4] If instead a series of temperature sensors are inserted into the cooling ducts, an oil flow with a sudden change of temperature could be tracked. This temperature front could be either hotter or colder than the initial oil temperature of the winding.

To evaluate the new method, a mock-up model of a transformer disc winding section was constructed and fitted with temperature sensors in the oil ducts. For comparison, steady state velocities were both measured using Laser-Doppler Anemometry and computed using a CFD model. Methods had to be developed to interpret the signals from the temperature front measurement. The behavior of the temperature front under

different temperature conditions was simulated using a CFD model. Finally, temperature sensors were also fitted inside a full size winding and measurements performed.

TRANSFORMER WINDING MOCK-UP MODEL

A mock-up model of one section of a transformer winding has been constructed. The frame has been made of aluminium with a Plexiglas cover for visual access. The model is created with 20 identical, removable discs that can be stacked on top of each other within the winding frame. The discs have spacer pegs extending from the bottom surface to fix the distance between them, and depressions on the top surface to fit the pegs of the disc above. The distance between the discs is 3 mm. The discs have two holes where temperature sensors can be fitted to make measurement at the centre of the horizontal ducts near the inlet and outlet, without the cables of the sensors disturbing the flow. On the disc sides are cavities with enough space to draw the cables to the back wall of the winding frame and then along this wall to the lid opening at the top, thereby minimizing the obstruction of flow in the vertical channels. The cavities containing the cables are filled with epoxy glue to make the sides of the discs smooth.

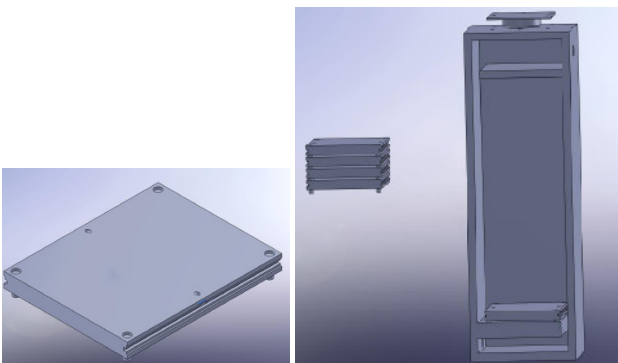


Figure 1 Right: Aluminium frame with stackable discs representing a transformer winding section. Left: one disc.

The aluminium frame includes collars at inlet and outlet. The bottom collar has increased thickness because it has to support the weight of all the discs. The top duct has extended height to make room for the cables from the temperature sensors going out through the top lid. The frame and some stacked discs are depicted in Figure 1.

The frame and the discs together compose the winding model which has a total height of 300 mm. In addition the experimental set-up includes an oil-flow circuit with a gear pump to generate the oil flow. A gear pump was selected among other types of pumps because it has a well-defined amount of flow which furthermore can be controlled by a frequency converter. Oil is taken from a container where it is heated up using hot water from a Haake Bath heating system. The oil-flow circuit is sketched in Figure 2.

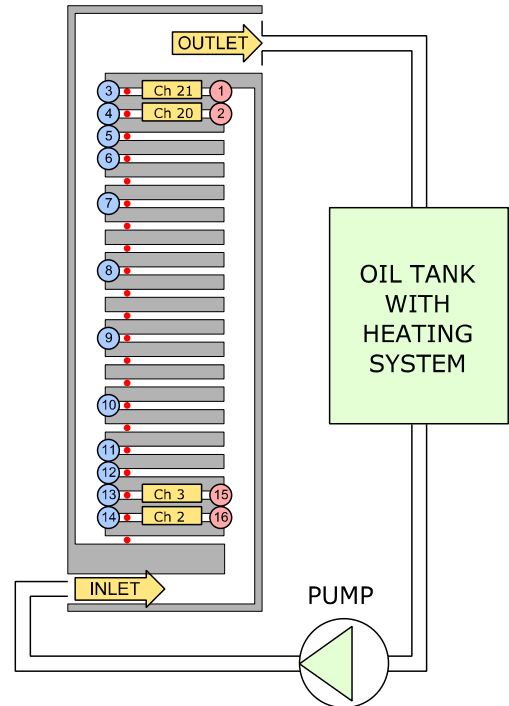


Figure 2 Schematic picture of the oil flow circuit including measurement locations for the aluminium mock-up model. Numbered circles indicate temperature sensors and red dots indicate locations where LDA is performed.

STEADY STATE FLOW FIELD

To be able to verify the temperature front method in the mock-up model, it is necessary to obtain the steady state flow field by other means. Two different methods have been used: experimentally through Laser Doppler Anemometry (LDA) and numerically through Computational Fluid Dynamics (CFD).

Velocity measurement with LDA is based on frequency measurement emitted by particles that are naturally present or artificially added to the fluid media. The Laser Doppler Anemometry system in use is produced by Dantec. It includes a 10 W Argon Ion Laser, and has the capability to simultaneously measure two velocity components. Further information on the theory behind LDA can be found in [5]. In this application it was not necessary to introduce additional seeding particles because the transformer oil contains air micro bubbles due to the exposure to air in the oil tank. The laser optics are mounted on a traverse in front of the winding model Plexiglas window. The traverse it used to accurately position the measurement location. The measurement volume is 0.12 mm in the direction normal to the duct walls. A parabolic profile is fitted to four measurement points inside each cooling duct to obtain the average duct velocity which is then normalized to obtain the correct total flow rate as set by the pump. The winding model has been painted black to avoid laser reflexes. A photograph of the LDA measurement being performed is shown in Figure 3.

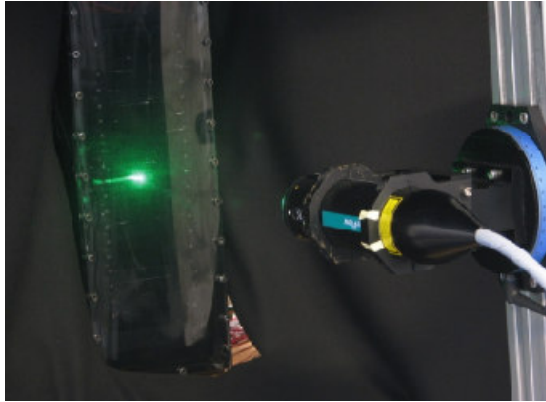


Figure 3 Close up of laser-beam measuring flow velocity in horizontal duct.

The LDA measurements are performed under isothermal conditions at room temperature with the pump running at constant speed. The measurement locations are shown in Figure 2. They are chosen near the outlet of the horizontal ducts to ensure a fully developed profile.

The CFD analysis is performed using a two-dimensional model solving the incompressible Navier-Stokes equations. The effect of buoyancy is taken into account through the Boussinesq approximation. All material properties are considered constant except oil viscosity which varies with temperature. The steady-state CFD computation is performed under isothermal conditions at room temperature of 295 K so that buoyancy and temperature-dependence of viscosity does not affect the solution. Typical viscosity is 8 mm²/s. The Reynolds number is around 500 in the vertical ducts, less in the horizontal ducts, so the flow is laminar.

The steady-state flow velocities in all channels are plotted in Figure 4. The comparison between LDA measurement and CFD analysis show a good agreement between the experimental and the numerical results and by that confirm the quality of the local measurements. This flow is used as a reference case in this paper.

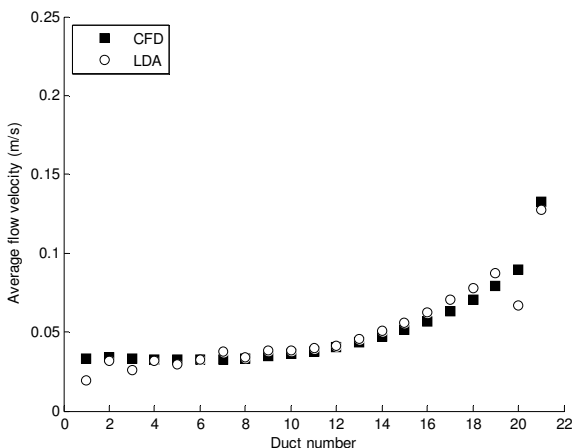


Figure 4 Comparison between computed flow velocities using a CFD model and measured flow velocities using LDA.

TEMPERATURE FRONT VELOCITY MEASUREMENT

The idea is to initially keep the oil in the winding section at a known constant temperature, pump in fresh oil at a different temperature, and measure the time response of temperature sensors located within the oil ducts. Assuming the heat is predominantly convected it is possible to obtain flow velocities by knowing the distance between sensors. The advantage of this method is that it can be used in a real transformer winding where access for flow measurements is severely restricted.

In the temperature front measurements, oil is heated to above room temperature in a separate container while the oil inside the winding model is kept at room temperature.

Before initiating the measurement, the pump is started but the flow redirected to a different circuit creating a closed loop. To start the measurement, the hot oil is directed towards the winding model by switching the valve position. Changes in the signals from temperature sensors located within the horizontal ducts between discs are captured by a data acquisition system and stored on a computer to be analysed afterwards.

The number of temperature sensors that can be used simultaneously is limited by the number of channels on the data acquisition card. A special high-speed 16 channel card is used to be able to perform 10 measurements per second at each sensor position. The number of sensors is also limited by the amount of wiring that can be contained within the aluminium frame. The sensor locations of the 16 measurement points are given in Figure 2. The locations are chosen predominantly near the top and bottom of the winding section because typically extreme velocities occur in these channels. In the channels with sensors located at both inlet and outlet the oil velocity is obtained by measuring the temperature front time shift between the sensor positions. The other channel velocities are obtained by calculating the passage time of the temperature front at each channel inlet using a continuity approach.

Two types of temperature sensors are considered and compared; thermocouples and thermistors. Their technical and theoretical information is available in a lot of dedicated references, e.g. [6]. Due to their better signal quality, stability, low noise and especially their fast time response, the thermistors are chosen to perform measurements in our experimental facility. In four horizontal ducts (two at the top and two close to the bottom) thermistors were located at both ends, 10 mm from the inlet and outlet to avoid edge effects. Temperature measurements of the heated front passing through these ducts can be directly converted to a flow velocity through the duct. The oil inside the model is initially at room temperature of 295 K and the heated front is at a temperature of 333 K. Oil is pumped at 0.4 litres/second.

Channel 3 (near the bottom of the winding model) and channel 20 (near the top) are representative of the temperature front flow behaviour. Measurement results for the thermistors installed in these ducts are plotted in Figure 5. Time $t=0$ represents the time of the switching of the valve. It takes some time before the oil enters the winding model. The plot therefore starts at $t=10$ s.

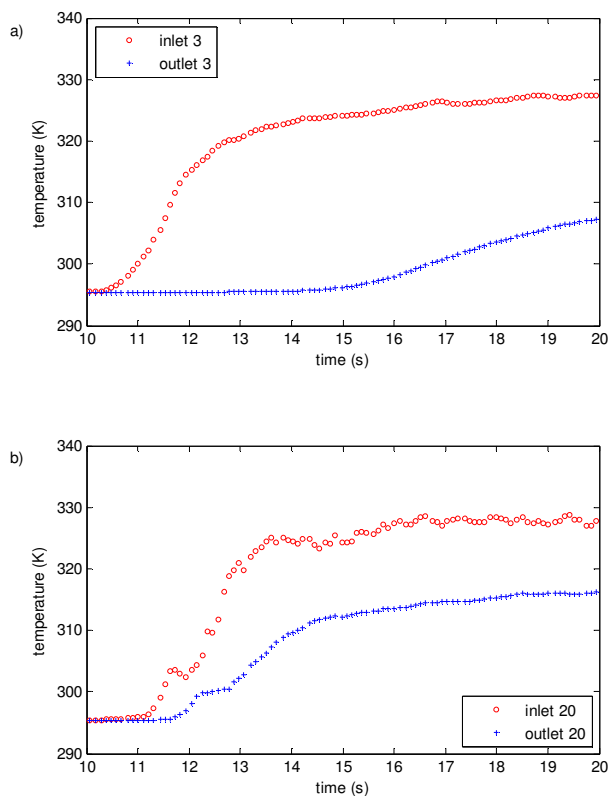


Figure 5 Thermistor measurements in ducts at the top and bottom of the winding section. Each subfigure represents one duct with the dots representing a point measurement in the duct 10 mm away from the inlet (upper curve) and outlet (lower curve).

In Figure 5-a is shown that the hot liquid quickly reaches the sensor positioned at the inlet of channel 3. The major temperature change occurs approximately within the time interval 10.5-13 seconds. The temperature continues to increase smoothly to reach around 325 K at 20 s process time. At the same time the outlet of channel 3 remains at initial temperature for the first 15 seconds due to the slow velocity in the channel and starts then to increase slowly. Figure 5-b represents the temperature plots at inlet and outlet of channel 20 which is situated at the upper part of the winding. The hot temperature front reaches the inlet of the upper channel with around 1 s time lag compared to the lower channel. Around 0.5 seconds later the front reaches the outlet of the upper channel. There is an obvious disturbance in the measurement data when the temperature stops increasing for a few tenths of a second. This is due to the edge effects at the top of the vertical duct and can also be seen in the CFD analysis to be discussed in a later section.

ANALYSIS OF MEASUREMENT DATA

To identify the time when the hot temperature front reaches the sensor, the time derivative of the measured temperature is computed. Noise in the signal is eliminated by specifying a threshold value that the time derivative has to exceed according to equation:

$$\frac{dT}{dt} > \kappa$$

Parameter κ has to be chosen with some care. It should be large enough to avoid influence of signal noise but small enough that it triggers when the temperature front arrives even if it is smeared out.

Once the times when the temperature front passes the sensors at two successive locations are known, the flow velocity in the cooling duct can be obtained. In the experimental setup there are several cooling ducts with temperature sensors located only at the outlet. Information about the flow velocity in these ducts can be obtained by considering continuity. Since the mass flow in the upper ducts are known, it is possible to calculate the time when the hot temperature front passed through the vertical channel next to the inlet of the duct below. In the ducts towards the middle of the winding section the oil flow distribution is expected to be smoother so if there is no thermistor the flow velocity can be interpolated from adjacent channels. The calculation procedure is illustrated in Figure 6. The reasoning is valid as long as the time dependent fluctuations of the flow field are small. In reality the flow field will be unsteady due to the effect of buoyancy, but the error can be reduced depending on the temperature difference of the incoming oil.

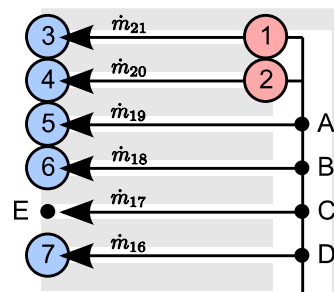


Figure 6 Method for velocity calculation in ducts without temperature sensors at inlet and/or outlet. Numbers 1-7 represent sensor locations and letters A-D represent points where the time can be calculated by a continuity argument. At letter E the velocity has to be interpolated from adjacent ducts.

A comparison between the temperature front measurements obtained by the method described above, the steady state solutions obtained from CFD simulations and the LDA measurements are shown in Figure 7. An overall agreement between the three temperature profiles is observed. The 2D CFD simulations provide us with a smooth behaviour from low flow velocities at bottom channels to high flow velocities at top channels. The measurements show some profile discrepancies

at these extreme locations which is likely due to 3D effects. The hot temperature front method overestimates the flow velocities near the top of the winding and underestimates them at the bottom. This is due to the effect of buoyancy.

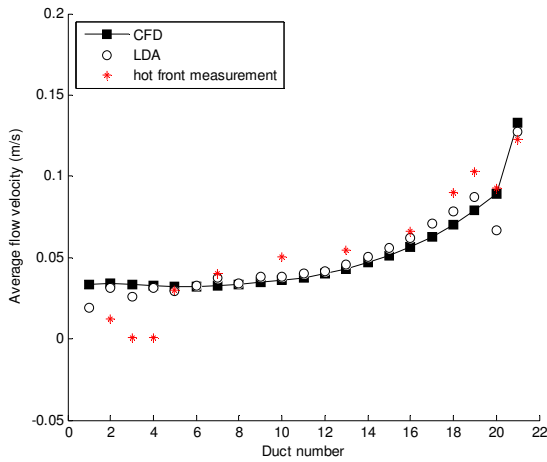


Figure 7 Calculated flow velocities based on hot temperature front measurement data compared to the steady state solutions computed by CFD and measured by LDA.

TEMPERATURE FRONT CFD CALCULATION

Transient CFD simulations are set up for a number of cases as described in Table 1. Case I corresponds to the same parameter settings as the measurements described in the previous section. Case II is a hot temperature front with a reduced temperature difference and Case III is a cold temperature front. The cases are run on the same mesh and with the same physical parameter settings as the steady state CFD analysis. The initial value of all velocity components are set to zero and the initial temperature is set according to Table 1. Computational data is stored every 0.1 seconds of physical time to achieve the same temporal resolution as the measurement data. In Figure 8 is shown a CFD simulation in progress corresponding to the parameter setting in Case I.

Table 1: Temperature front CFD cases.

Case number	Initial temperature in winding (K)	Temperature from inlet (K)
I	295	333
II	295	313
III	313	295

In Figures 9 to 11 the temperature is plotted versus time at inlet and outlet of the cooling ducts 3 and 20, i.e. at the proximity of the top and the bottom of the winding section. A comparison of the results in Figure 5 and Figure 9 (experiment and simulation with the same flow parameters) indicates that the CFD result displays a much sharper temperature derivative than what the measurements show. This can be explained by three-dimensional effects as well as heat conduction through the aluminium frame being neglected in the CFD analysis.

Otherwise, the correspondence between CFD and measurement is quite good. In the upper reported channels there is a sudden decrease of temperature following the abrupt increase during the arrival of the heated front. This decrease appears in both the CFD and measurement results, and is due to mixing with cold oil at the top of the first vertical duct occurring after an initial hot streak has entered the upper channels. In the lower reported channel, the temperature sensor at the outlet indicates a very slow temperature increase. The CFD simulations show that even though hot oil quickly enters the lower channels, after about two seconds (the situation shown in Figure 8), a column of hot oil has filled the vertical channel closest to the inlet and the resulting buoyancy force reduces the pressure so that oil flow in the lower ducts slows down and even reverses. Because of the slow oil velocity the temperature front is smeared out by the influence of the surrounding aluminium walls before it reaches the end of the duct. Similarly the CFD simulation indicates a decreasing temperature at the duct inlet but this is not confirmed by the experiment. The oil temperature quickly converges to a stable level mainly imposed by the oil being pumped into the winding. However, in the measurements there is even after 10 seconds still a substantial difference between inlet and outlet temperature levels due the losses e.g. by conduction in the winding frame.

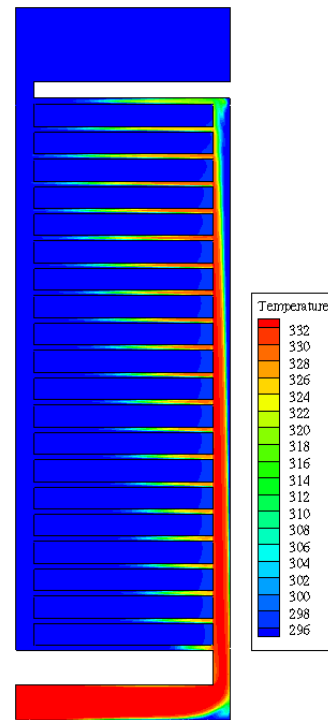


Figure 8 Hot temperature front CFD analysis.

For a hot temperature front with lower temperature difference, such as the one shown in Figure 10, the effect of buoyancy can be reduced and a measurable velocity can be obtained also in the lower ducts. For a cold temperature front, as is shown in Figure 11, the buoyancy force acts in opposite direction which ensures a good flow distribution in both the upper and the lower ducts.

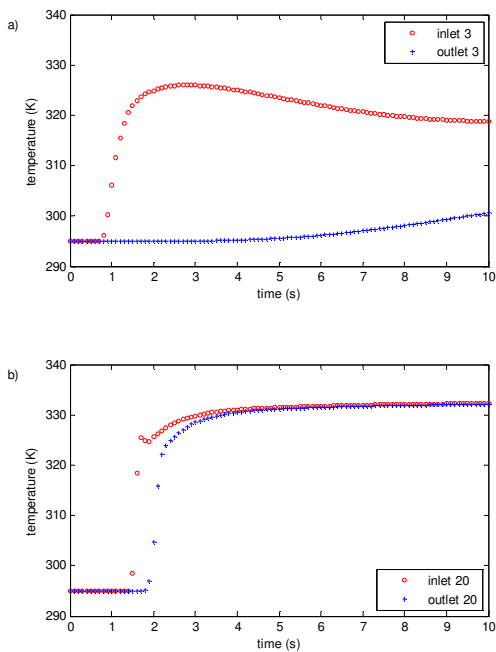


Figure 9 CFD results for Case I, i.e. hot temperature front with $\Delta T = 38$ K.

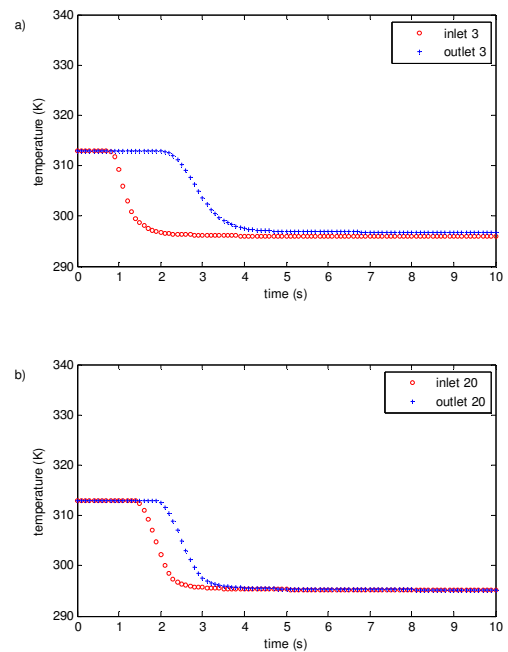


Figure 11 CFD results for Case III, i.e. cold temperature front with $\Delta T = -18$ K.

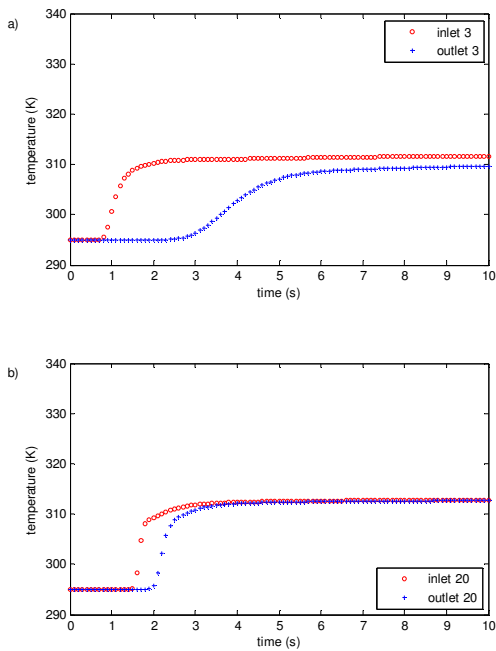


Figure 10 CFD results for Case II, i.e. hot temperature front with $\Delta T = 18$ K.

To further clarify the influence of the buoyancy on the oil flow, Figure 12 shows the velocity at each channel for the steady case and also for the transient cases at 10 seconds. The hot temperature front results show a clear deviation from the steady state profile with reduced oil velocities in the lower ducts and increased flow velocities in the upper ducts due to the buoyancy force. The cold temperature front deviates less from the steady state profile due to viscosity effects and because the original oil can more easily escape in this case.

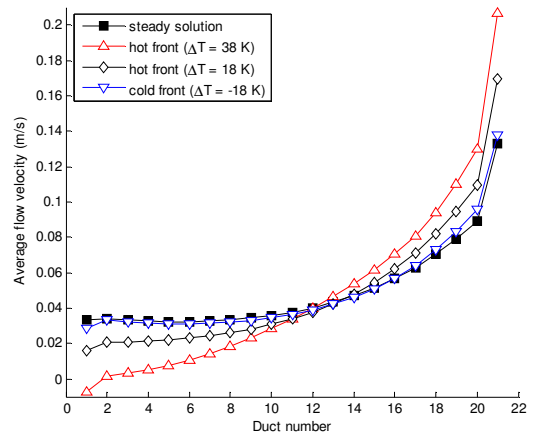


Figure 12 Duct flow velocities according to CFD solution after 10 seconds for the different temperature front settings.

In Figure 13 are plotted the results when the temperature front analysis method is applied to the CFD data, i.e. the flow velocities are calculated by the time difference when the temperature front reaches the sensor locations using 10 samplings per second. The sampling rate is not high enough to clearly resolve the higher flow velocities. However, the lower flow velocities are more important because they indicate potential hotspot locations and here the resolution is sufficient. The effect of the buoyancy for the different cases is also clearly seen in the figure.

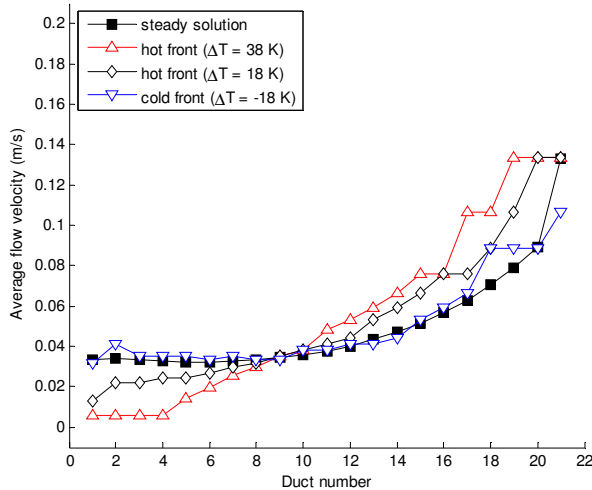


Figure 13 Duct oil flow velocities calculated using the temperature front arrival time based on CFD data.

MEASUREMENTS IN REAL WINDING

Measurements have been performed at the ABB transformer factory in Ludvika on a full size transformer mock-up. The tank enclosure in Figure 14 contains one full scale transformer winding mounted with thermistors positioned in a similar way as in the laboratory model.

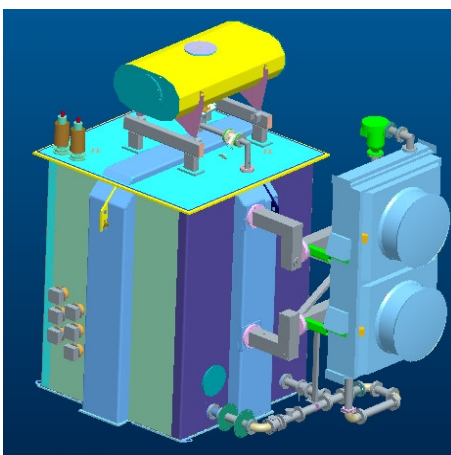


Figure 14 Full size transformer mock-up including external cooling equipment.

To create a temperature front through a real winding, the pump to the cooling equipment is shut off temporarily so that the stagnant oil in the cooler is cooled down to a slightly different temperature than the oil in the winding. When the pump is started up again, a large amount of cold oil in the cooling equipment is pushed into the model. Thermistors placed in the winding are shown in Figure 15. The results are coherent with the laboratory measurements and CFD simulations.



Figure 15 Thermistors mounted at the oil outlet of a full size winding.

In real transformer windings, the thermal sensors must be non-magnetic and withstand harsh conditions during long time. Thermistors are therefore not always feasible, especially not in highly stressed areas. A good alternative is fiber optic sensors which are developed for and widely used in transformer technology. The accuracy of fiber optic sensors is nowadays similar to thermistors and their time response is fast which makes them suitable for these kinds of measurements.

CONCLUSION

Electrical losses in transformer windings generate enough heat to deteriorate the insulation material, thereby reducing the lifetime of the transformer. The transformer oil, used for its electrically insulating properties, flows through cooling ducts to transport the heat by convection away from the locations where losses are induced. A continuous and sufficient oil flow through the winding channels is a prerequisite for successful cooling. A stagnation or even a slowdown of the flow can generate excessive hotspots with undesired consequences.

To measure the oil velocities in narrow ducts and inaccessible areas where velocity probes and complex technologies are not suitable, the temperature front tracking method has been developed. It is based solely on temperature sensors (in this case thermistors) that are located in chosen channel positions.

The method consists of tracking the temperature gradient separating hot and cold oil layers while pumping oil at a temperature different than the oil initially in the transformer.

The temperature front method results tested in a laboratory winding mock-up model have been compared with Laser Doppler Anemometry measurements as well as Computational Fluid Dynamic simulations. Good agreement between the three techniques has been observed and this proves the success and usefulness of the simplified front tracking technique.

Based on the results of the overall investigation, experimental and numerical, it was found that the buoyancy

force has a considerable effect on the flow field. For a hot temperature front it will accelerate the oil velocity in the upper winding channels and decelerate it at the lower channels. For a cold temperature front, the force acts in the opposite direction. To reduce the effect of buoyancy the temperature difference should be made as small as possible. Further experiments should be performed to verify the behaviour of the cold temperature front.

REFERENCES

- [1] Imre, L., Szabo, I., and Bitai, A. Determination of the steady state temperature field in naturally oil-cooled disc-type transformers, *Proc. 6th Int. Heat Transfer Conf.*, Toronto, ON., Canada, Vol.II, pp. 123-128
- [2] Kranenborg, E. J., Olsson C.O., Samuelsson B. R., Lundin L-Å, Missing R. M., Numerical Study on Mixed Convection and Thermal Streaking in Power Transformer Windings, *Proceedings 5th European Thermal-Sciences Conference*, Editors: G.G.M. Stoffels, T.H. van der Meer and A.A. van Steenhoven, ISBN 978-90-386-1274-4, Eindhoven, 2008
- [3] H.Nordman, O.Takala, Transformer Loadability Based on Directly Measured Hot-Spot Temperature and Loss and Load Current Correction Exponents, CIGRE Biannual meeting 2010, Paris, France, 2010
- [4] Yamaguchi, M., Kumasaka, T., Inui, Y., Ono, S. The Flow Rate in a Self-Cooled Transformer, *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-100, No. 3, March 1981.
- [5] Albrecht, H.-E., Damaschke, N., Borys, M., Tropea, C., *Laser Doppler and Phase Doppler Measurement Techniques*, Springer, 2003
- [6] Ernst R. G. Eckert and Richard J. Goldstein, *Measurements in Heat Transfer*, 2nd Edition, McGraw-Hill, 1976