TRANSFORMER WINDING OIL FLOW RATE & HOT SPOT TEMPERATURE: A STRAIGHTFORWARD RELATIONSHIP?

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ABSTRACT

A trustworthy prediction and measurement of the winding hot spot temperature is central in establishing the thermal design quality of a power transformer. In the past, hot spot factors have played an important role in predicting them, but a direct calculation of the hot spot temperature and location using thermal simulations is entirely feasible nowadays.

This paper highlights when and why deviations in predicted hotspot temperature and location can be expected between different calculation tools, focusing on the winding oil flow rate as an important design parameter to control the hot spot level. Advanced simulations based on Computational Fluid Dynamics (CFD) reveal a complex – and sometimes counter-intuitive - relationship between the winding oil flow rate and the hot spot temperature. In this paper it is shown that high oil flow rates with OD cooling do not necessary lead to lower temperatures and may even pose a thermal risk. With ON and OF cooling, the associated lower winding oil flow rates may lead to large temperature gradients in the oil ducts which need to be properly managed in order to avoid unexpected hotspot temperature and locations. Consequently, it is possible to arrive at thermally stable designs for all cooling modes.

The findings in this paper will help customers to discuss design quality and present a showcase of the value of CFD application in transformer design validation.

KEYWORDS: ***Thermal design, thermal modeling, thermal network, CFD, windings, hotspot, hotspot factor, Power Transformer***

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INTRODUCTION: EFFECTS OF LOCAL FEATURES ON HOT SPOT POSITION AND LEVEL

The winding hot spot temperature sets the critical ageing rate of the winding insulation material and thereby affects the resilience towards mechanical and dielectric stresses throughout the transformer's operation. Therefore, the accurate determination of winding hot spot temperatures is one of the most important goals in the design and heat run test verification of a power transformer. Although hot spots certainly play a role in other parts of a transformer, it is a fact that the main losses are produced in the windings, the cellulose insulation material temperature limits are lower than the oil temperature limits and – last but not least - the confined winding geometry allows the modeling of the oil flow and heat generation and transport in a detailed and potentially very accurate fashion. As a consequence the accurate prediction of winding hot spot temperatures has a long history, it is strongly governed by standards like IEC and IEEE for heat run temperature rise tests [1,2] and will likely remain a point of attention and standardization in the foreseeable future.

Despite a long history of winding hot spot prediction, a full understanding of hot spot generation is still lacking. In particular the contribution of both physics details and design details on setting the level and position of the hot spot temperature is not yet fully grasped. As a consequence, given a particular transformer design it is often not fully clear which requirements to thermal modeling have to be put regarding the representation of physical processes, which level of modeling detail is needed, which modeling concept is to be used and which design parameters should be changed. The main goal of this paper is to reveal the usefulness of new simulation tools as compared to more traditional methods like thermal networks in explaining the rather complex relationship between winding hot spot temperature and winding oil flow rate as a key design parameter. With the insights obtained through the underlying study, this paper also aims to provide the customer with essential and concrete knowledge and guidelines for discussion of the quality of the thermal design of the windings at a design review.

A key difference between the winding hot spot temperature (rise) and the other two main heat run test parameters (average winding rise, top oil rise) is its dependency on local details regarding design and – as will become particularly apparent in this paper – physics. These two aspects deserve a separate discussion.

Regarding the local design details, it is clear that a number of local winding design aspects may have a strong influence on the position and level of the hot spot. The effect of added local insulation will be to increase the thermal resistance from the copper to oil, but its effect is very local as well. The effect of the interplay between spacer distribution and oil guide positions is much more complex and has effects on various levels. In [3] for example it is shown that these details in combination with the detailed loss distribution provide necessary input to accurate hot spot prediction. A key part of a design review therefore must be the agreement of the proper inclusion of these design details in the thermal model that is used.

An interesting aspect of the presence of local design details is that these have a profound effect on the local physics through the distributions of the temperature and oil velocities. In [4] the effect of local temperature gradients in the form of hot streaks in oil ducts as well as the correct representation of internal buoyancy are shown to strongly influence the setting of the hotspot temperature. This implies that the requirements on the thermal models for representing these local but important features need to be based on the expected physics-related features. This in turn implies that all stakeholders need to have a thorough understanding of the physics of heat transfer in complex transformer windings.

LITERATURE REVIEW: STATE OF ART REGARDING THERMAL MODELS (THNM & CFD)

The importance of winding hotspot determination is reflected in published efforts to predict the hot spot temperature using simple models based on hot spot factors [5,6] and thermo-hydraulic networks (abbreviated in this paper as THNM, sometimes also simply named “thermal network model”) [7-10] corroborated with measurements on winding models with electrically heated parts to simulate the effect of winding cable losses [11,12]. Given the generally well-defined and confined nature of a winding, the use of a THNM is a logical and computationally efficient approach to model the combination of oil and heat transport and – as a consequence - the prediction of the position and level of the hot spot temperature.

In the last decade the role of advanced simulation tools have become apparent in the thermal modeling domain. A thorough overview of this domain in terms of the developments, state of the art as well as a proper literature overview has newly become available in [13]. In summary, the CFD simulation approach (Computational Fluid dynamics, an approach where the full heat and oil flow equations can be resolved numerically in great detail in complex geometries and therefore has the potential to provide for very accurate results) was first applied in [4] to show the importance of representing internal buoyancy in network models (i.e. mixed convection instead of forced convection), and to discuss the effect of thermal gradients in oils on the position and strength of the winding hot spot temperature. In [14-15] the effect of design parameters (flow rate, number of discs per pass, 2D vs. 3D modeling) was investigated, showing a good agreement between THNM and CFD models as long as the number of discs per pass was not very large.

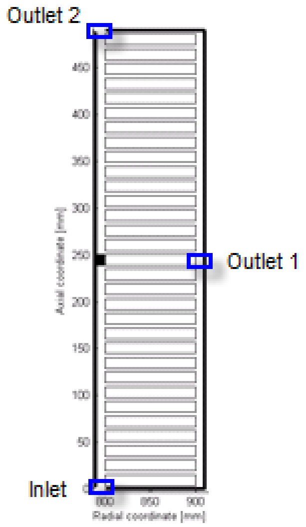
ANALYSIS: WINDING THERMAL BEHAVIOR AS A FUNCTION OF WINDING OIL FLOW RATES

Since the winding oil flow rate is an important design parameter, it is useful to discuss its effect on the winding thermal behavior first. Next, the risk associated with very high winding oil flow rates is covered. Finally, the effect of local thermal gradients in oil ducts on the overall thermal behavior is reviewed, since they are a common feature emerging in the vertical cooling duct of oil guided (zig-zag cooled) windings as “hot streaks” [4] with a potential to influence the overall winding thermal behavior.

If the aim is to obtain a numerically very accurate prediction of the winding hot spot temperature, it is generally required to apply a full-scale winding model; flow details that develop through the winding in a certain winding pass between oil guides eventually may have a large impact on the position and strength of the hot spot in the passes further downstream [4]. However, for a qualitative analysis it is useful and sufficient to apply models of reduced size. This allows the systematic analysis of the effect of certain parameter changes on the physical processes that establish the detailed temperature distribution in each pass or at the duct interface between two passes.

In this paper a two-pass, two-dimensional axisymmetrical CFD model is used which is able to describe all essential physical processes and boundary conditions in sufficient detail.

A schematic sketch of the geometrical model and the boundary conditions are shown in Figure 1.



Geometry parameters	[mm]
Inner Winding Radius	**800**
Inside Duct Width	**10**
Outside Duct Width	**10**
Disc Height	**11.66**
Horizontal Duct Height	**4.00**
Disc Width	**100**

Boundary Conditions	
Inlet Temperature	**70 [ºC]**
Disc Surface Loss	**701.2 [W/m^2]**

Figure 1: Geometry of the two-pass model that underlies all results in this paper.

The two-pass model consists of 31 discs with an oil guide(washer) located at the inside of disc number 16 creating one lower pass with 16 horizontal ducts and one upper pass of the same size. The inlet is located at the bottom of the inner vertical duct and is modelled with a velocity inlet boundary condition and the outlet is located at the top of the same duct and is modelled with a pressure outlet. At the interface between pass one and pass two, a monitor surface is created as “Outlet1”.

The modeling assumptions closely resemble those in [4] with the fluid flow solved by the Navier-Stokes equations for incompressible flow and the density represented by the Boussinesq approximation. In the discs, winding losses are applied and heat conduction occurs, and heat transport through the oil in the ducts happens mainly through mixed convection. The winding mass flow rate is a key input parameter (i.e. inlet velocity). At the model inlet, a uniform or parabolic velocity profile can be prescribed, as well as a uniform or linearly increasing or decreasing temperature distribution. Given these inlet condition options, the first pass is the most important one to reflect and systematically study what is happening in the downstream second pass (and subsequent passes of a full winding), and in the sequel the results will therefore focus mostly on the first pass.

The effect of oil flow rate on temperature distribution and hotspot generation

Focusing on the winding oil flow rate as the key parameter, five different inlet velocities presented in Table 1 have been used in order to demonstrate the typical flow behavior in a pass (representative of ON, OF and OD cooling mode conditions).

Boundary Conditions	U_1	U_2	U_3	U_4	U_5
Inlet Velocity [mm/s]	**0.8X**	**X**	**1.6X**	**5.0X**	**6.7X**

Table 1: The velocities applied at the inlet of the two-pass model.

In order to better visualize and compare the local oil distributions in a pass the radial velocities in each horizontal duct have been normalized by the average radial velocity of the ducts for each inlet velocity.

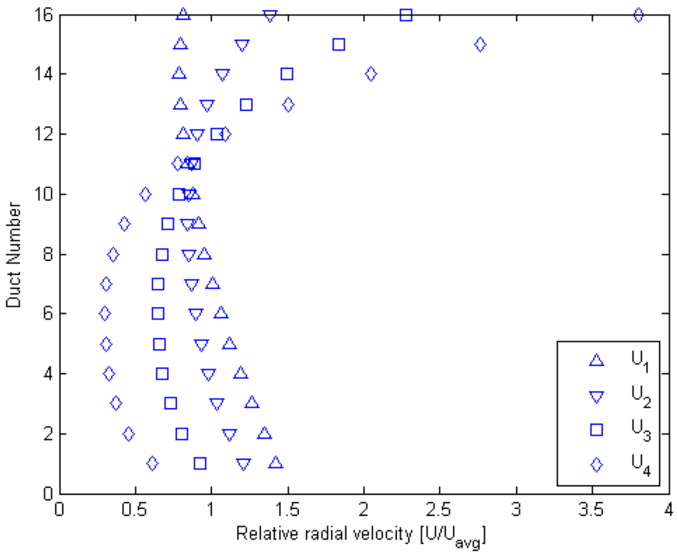


Figure 2: Oil distribution in the horizontal ducts of the first pass as a function of winding oil flow rate (i.e. inlet velocity).

Figure 2 reveals the typical change in oil flow distribution in the horizontal ducts as a function of the oil winding flow, in accordance with the observations in [4]. For low oil flow rates the maximum velocity occurs in the lower part of the pass, whilst for increasing winding flow rate the maximum velocity shifts to the upper region of the pass. For a given disc loss distribution, the temperature of the oil exiting the horizontal ducts is inversely proportional to the oil velocity. Due to the relatively low thermal diffusivity of oil (Prandtl Number $Pr > 50$), the separate thermal contributions of the oil volumes leaving the horizontal ducts remain visible in the temperature distribution along the cross-section of the main vertical duct at the outlet of pass 1, as depicted in Figure 3.

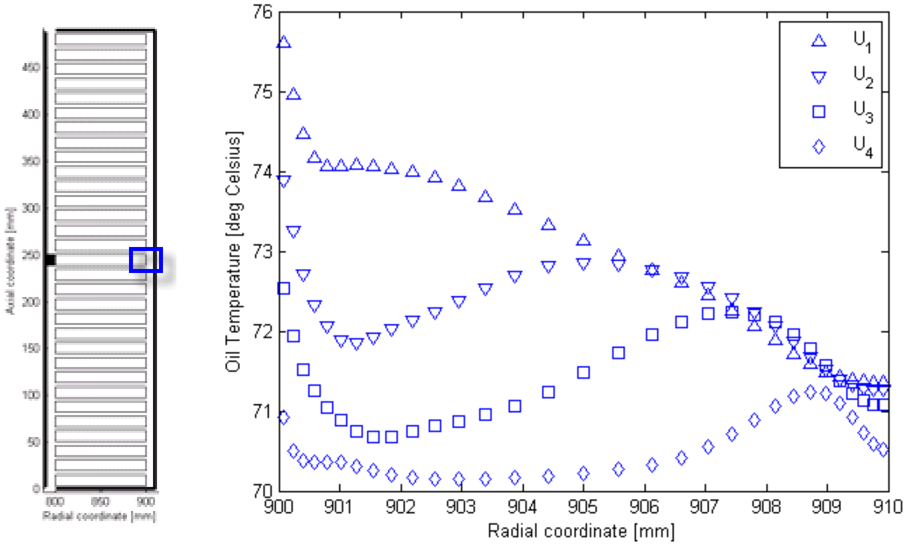


Figure 3: Oil temperature distribution across Outlet 1 of pass one for the different inlet velocities.

A comparison between CFD(with uniform inlet temperature) and an ABB in-house THNM in Figure 4 illustrates the ability of THNM to reproduce very good agreement for the velocity and maximum disc temperature distribution in the first pass. However for the second pass the velocity distribution is less accurate which indicates that the temperature profile in the vertical duct actually influences the velocity distribution.

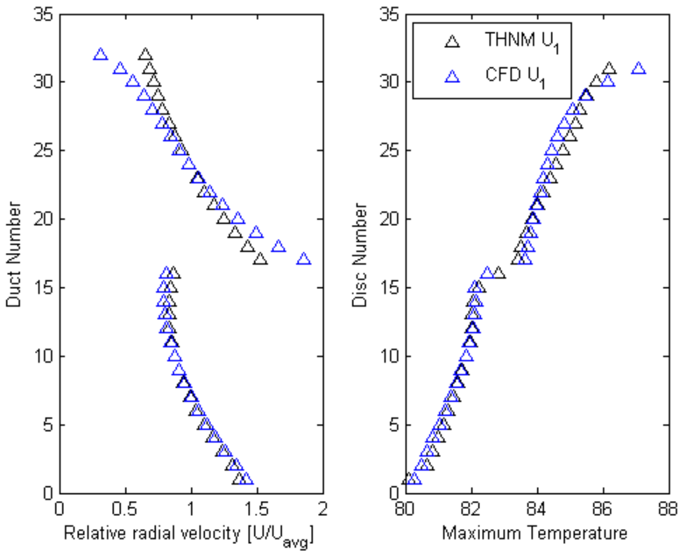


Figure 4: A comparison of relative velocity distribution and maximum disc temperature for THNM vs CFD model for a relatively low velocity U_1.

One of the goals of this study is to investigate the effect of the thermal distribution at the cross-section as shown in figure 3 on the oil and heat transport in the downstream passes. Although the distributions shown in Figure 3 are not exactly linear, a change in slope can be discerned as a function of winding oil flow rate. Consequently, to study the effects of the thermal gradients at the outlet of the first pass, the model is used in this study with either uniform or linear temperature gradients with both negative and positive slopes represented. This discussion follows after the investigation of the thermal behavior at high winding oil flow rates.

The limits of high winding oil flow rates

The OD cooling mode provides for a compact cooling solution by which the cooling oil is channeled directly through the major loss-generating components, as windings, in order to maximize the cooling efficiency. Consequently the winding oil flow rate and associated oil velocities in the winding ducts can be an order of magnitude larger than is the case with ON or OF cooling. The maximum winding oil flow rate is generally assumed to be limited by the risk of streaming electrification with a design limit on the maximum permissible oil velocity in the windings [19].

However, we have encountered a number of cases in which there was a marked difference between the CFD results and the corresponding results as generated by the THNM mentioned earlier. The THNM is capable of including all design details that are important for accurate hot spot prediction, like oil guide positions, variable spacer height distributions and local extra insulation.

The difference in CFD and THNM results is caused by a phenomenon that is characterized by the generation of local hot spot close to and downstream of oil guides. Also, the local hot spot may be captured by a CFD model but not fully by a THNM-based approach (something that is also remarked in very recent publications [13,16]). A distinct feature of the two-pass CFD model in this paper is that it is still able to demonstrate this behavior in a simplified geometry.

Figure 5 reveals that for relatively high and increasing inlet velocities the local hot spot becomes visible and intensified. Above a certain inlet velocity, the hotspot temperature starts to increase (it is positioned just downstream of an oil guide) whereas the winding oil temperature gradient continues to decrease.

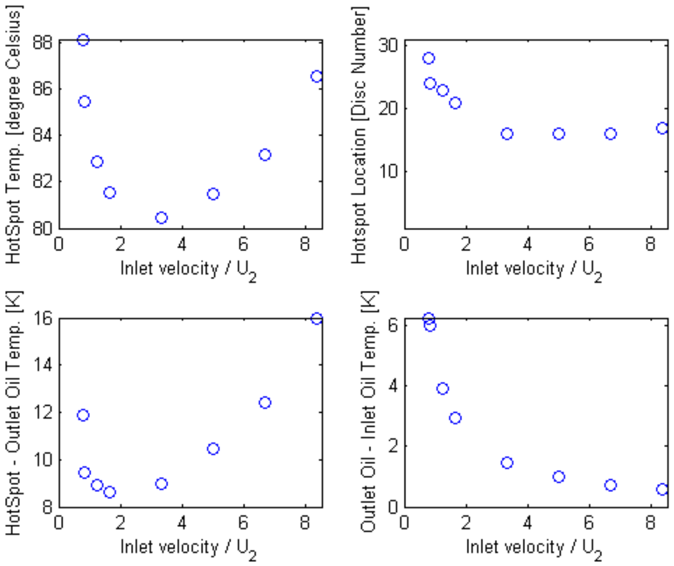


Figure 5: Disc maximum temperature and position as a function of flow rate, for a two-pass model showing that for increasing winding inlet oil velocity after a certain threshold value the hotspot temperature rises again, as opposed to the winding outlet to inlet temperature gradient.

Since the hot spot is characterized by a marked increase of temperature (of the order of 10K) a proper understanding of this phenomenon is necessary for its mitigation. Figure 6 shows a comparison of CFD and THNM-generated disc temperature results for an OD-based design for a high resp. lower winding oil flow rate. These pictures reveal two remarkable aspects: 1) one strong local hot spot in the disc just above the oil guide in the CFD results and 2) the absence of this high temperature region in the THNM results (apart from an otherwise good agreement between the distributions)

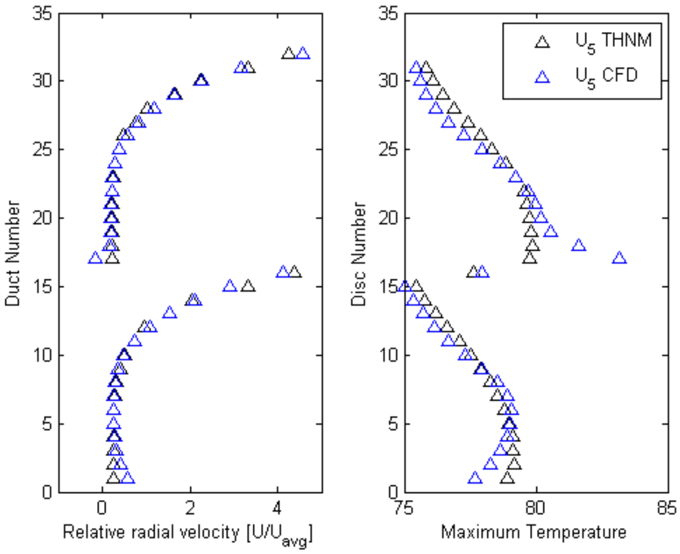


Figure 6: Comparison of CFD and THNM-generated results regarding the distribution of the maximum disc temperature from the bottom to the top of the two pass model. The left picture shows the velocity ratio with a negative ratio in duct 17 resulting in a several degree higher local temperature peak in disc 17 in the right picture.

Focusing on the high winding oil flow rate, a detailed view on the hot spot location as shown in Figure 8 reveals that the local return of hot oil through the duct just above the winding – and as a consequence the reduced cooling of the discs adjacent to this duct – is the main cause of the existence of such a hot spot.

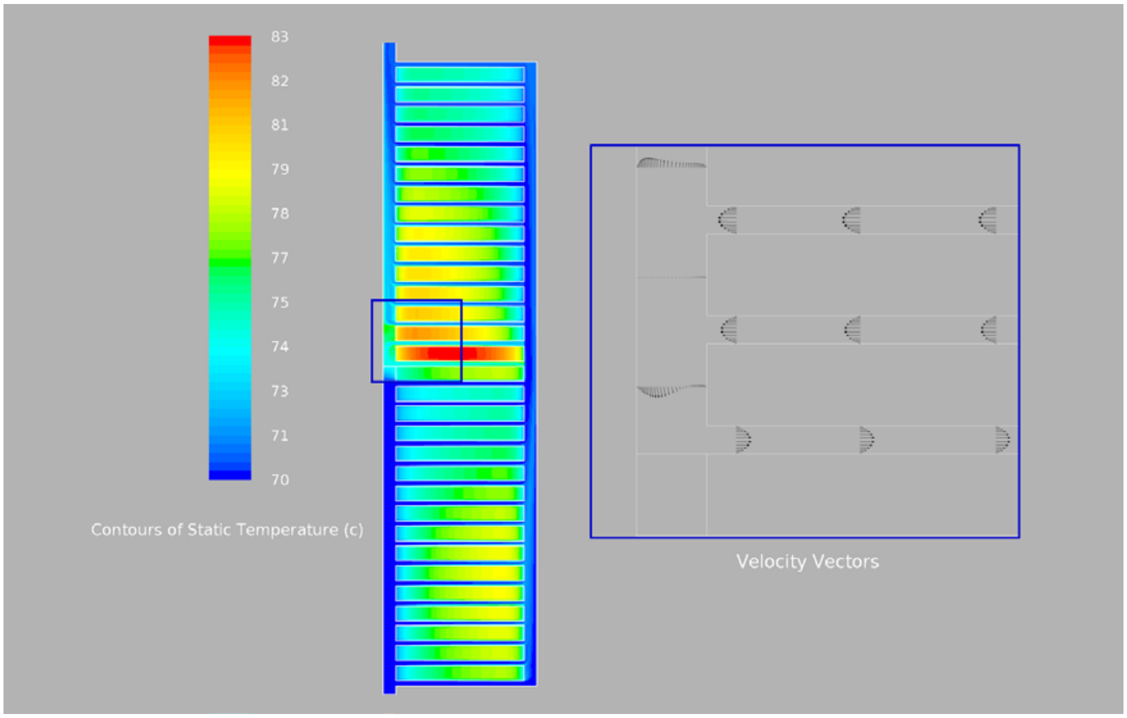


Figure 7: Contour of the local temperature and oil velocity distributions in the ducts in the vicinity and downstream area of a disc with an oil guide (U_5).

The parametric study shows that a reduction of the oil flow rate removes the local recirculation and thereby the local hotspot from the CFD results.

The mechanism for the generation of hot spots for high oil mass flow rates can be understood by purely hydrodynamic arguments. The high flow velocity oil in the horizontal ducts just below the flow guide acts as a jet into the vertical duct and causes a separation of flow where the oil predominantly flows near the insulation cylinder away from the winding discs. The velocity profile at a cross section opposite the oil guide is strictly non-parabolic due to the adverse pressure gradient that occurs in this region. By definition the THNM approach does not resolve the pressure distribution across the ducts and is therefore unable to capture the phenomenon. At lower oil mass flow rates the phenomenon is less apparent and THNM is suitable to describe the relevant physics.

An analysis by CFD is recommended in case of a design with high winding oil flow rates, since a THNM-based approach may not to catch the phenomenon described.

Oil temperature gradients in the main cooling ducts: their effect and requirements on models

The insulation fluids that are used in transformers are characterized by a relatively high viscosity and low thermal conductivity in comparison to many other fluids in industrial applications. As a consequence of these properties and the complex flow path in a winding, the oil in the main vertical cooling duct is generally thermally stratified, i.e. a local temperature difference along the oil duct cross-section exists, as was shown in Figure 3. Such a localized effect cannot be regarded by a THNM since this modeling approach assumes a single, duct-averaged quantity. Thus the question emerges under which conditions such a local thermal gradient has a significant effect on the oil velocity and temperature distribution, which physical process explains the effect, and under which circumstances a simulation method like CFD that can resolve these details is recommended to be applied to guarantee an accurate prediction.

To this end a setup of single pass model is applied with the following parameter combinations:

1. Inlet temperature gradient [K/mm]: 0 (uniform), 0.4 (positive), -0.4 (negative)
2. Winding oil flow velocity U_1 (low) , U_4 (high)

The inlet temperature gradient (item 1, in K/mm across the section) was estimated as follows: In Figure 3 it is shown how different inlet velocities affect the temperature gradient in the vertical duct at the outlet after the first pass. The gradient becomes larger for lower oil flow rates and it's therefore most relevant to investigate how such gradients would affect the results in the pass downstream. For the lowest velocity, U_1, the gradient is almost linear with an average slope of -0.45 K/mm. Based on this result it was concluded that 0.4K/mm is a realistic value and that a linear temperature profile could be used in order to evaluate the flow behavior in a pass.

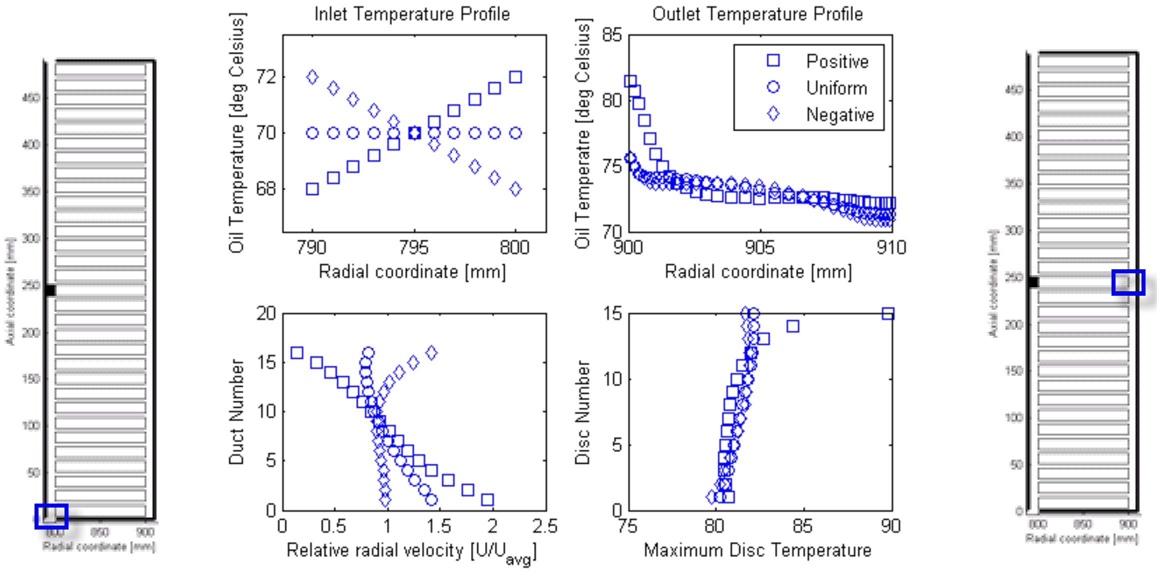


Figure 8: Distribution of the disc temperature and oil velocities between the discs in the first pass at moderate flow velocity U_1, for three different inlet temperature distributions in the inner vertical duct (Positive, Uniform, Negative). Inlet temperature profile is applied at the inlet marked in the left picture. Temperature profile is presented for Outlet 1 of pass one marked in the right picture.

The results in Figure 8 show that there is a strong effect of the initial thermal gradient on both the flow and temperature distribution in the pass. The initial temperature tends to either improve the flow distribution (negative initial temperature gradient, with a lower maximum temperature in the pass as a consequence) or make the flow imbalance worse (positive initial temperature gradient), leading in this particular case to a very strong local hotspot whose level exceeds the other cases by almost 10K.

The physics that links the initial temperature gradient with the resulting outlet temperature and flow distributions may be either buoyancy or the temperature dependency of the viscosity of the oil. To discriminate between these two, the simulations were performed again but now without any buoyancy effects by setting the gravitational acceleration coefficient *g* to zero. This assumption implies that only forced convection is taken into account, as opposed to mixed convection for the original set of results.

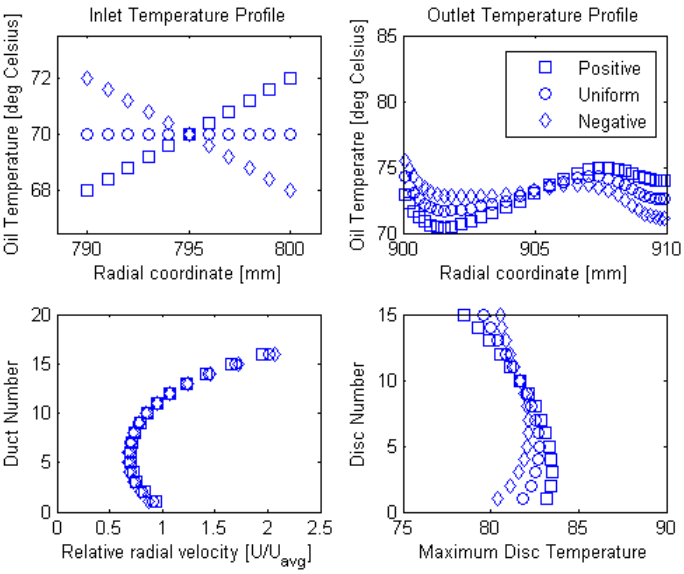


Figure 9: The effect of removing buoyancy (by setting the gravity acceleration to zero, leading to heat transfer by forced convection) as compared to the original simulation results representing mixed convection as presented in Figure 8. Inlet temperature profile is applied at the inlet and temperature profile is presented for Outlet 1.

In Figure 9 the velocity profiles looks very different from the ones in Figure 8 and they overlap each other almost perfectly. The large difference between the velocity profiles in Figure 8 and Figure 9 shows that buoyancy indeed is a dominant physical factor. Also, the small difference in velocity distribution results for the zero buoyancy case reveals that the effect of temperature-dependent viscosity is very limited, and the outlet temperature differences in the oil remains of the same order as their inlet counterparts. These results then imply that mixed-convection is an important heat transfer process in transformer windings and should be taken into account in any winding thermal model, confirming the conclusions in [4].

For larger winding flow rates (at velocities typically for OD-cooling the influence of the initial temperature gradients on the flow distribution in the pass is much more limited, indicating that the effect of the initial temperature gradient on the buoyancy is very limited. Figure 10 shows the resulting distributions of velocity and temperature for a relatively high inlet velocity U_4.

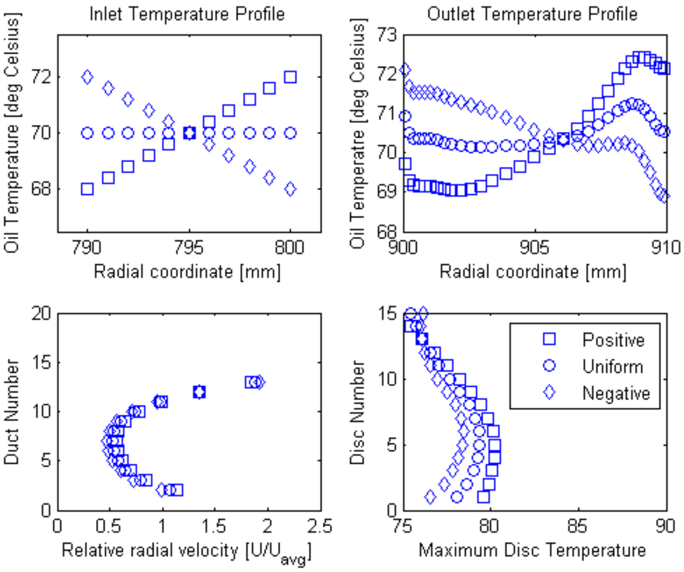


Figure 10: Distribution of the disc temperature and oil velocities between the discs in the first pass at a relatively high inlet velocity U_4, for three different inlet temperature distributions in the main duct (positive, uniform and negative)

The initial temperature gradient still has some influence but not nearly as large as with lower winding flow rates that are typical for ON/OF. This suggests that the transport of the hot streaks in the oil that are represented in our model by the initial thermal gradient will not amplify. Consequently, it appears useful to limit the oil temperature gradient in the main duct as this is then expected to be the main source of variability in the hot spot temperature.

DISCUSSION & SYNTHESIS: COMPETING THERMAL & HYDRODYNAMIC PROCESSES

The main observations in this paper can be summarized as follows:

> The relationship between winding oil flow rate and hot spot temperature position and strength is complex and sometimes counter-intuitive (“higher oil flow rate might give higher instead of lower hotspot temperature”)
>
> At the interface between two passes, two important physical phenomena occur in the vertical (main cooling) duct cross sections at the level of discs with oil guides. They play a role in influencing local winding temperature maxima and the winding hot spot temperature.
>
> The first phenomenon – with a thermal cause – is the presence of a thermal gradient across the main vertical duct which, if sufficiently strong, may significantly affect the oil flow distribution in the horizontal ducts between the discs of the pass downstream: The stratification leads to differences in inlet oil temperature to the horizontal ducts, resulting in larger buoyancy and thereby larger velocity in the horizontal ducts. Consequently the pressure balance in the downstream pass differs from the situation where no thermal gradient in the main cooling duct would be present, which is by definition the modeling assumption for a THNM. The examples in this study show that the phenomenon is particularly visible at low oil flow rates for which the buoyancy term plays a larger role than the viscous forces.
>
> The second – purely hydrodynamic – phenomenon is the combination of the hydrodynamic suction and non-parabolic duct profile at and just above the disc with an oil guide, gaining importance at higher winding flow rates. This phenomenon causes a potential risk of low or reversed oil flow in the first duct(s) above the disc with an oil guide, with a local hot spot as a consequence. For the second, hydrodynamic phenomenon, the resolution of the non-parabolic oil velocity profile is a key aspect of the CFD model contribution. Both phenomena can

only resolved by CFD, as revealed by the various example cases presented in this study, since they are associated with specific local physics details in the duct that cannot be resolved by a THNM approach.

CONCLUSIONS

The findings reported in this paper lead to the following conclusions:

This study shows that there does not appear to be a guaranteed monotonic correlation between winding oil flow rate and hot spot temperature, i.e. “More is not always better”

This and earlier studies shows that the hotspot magnitude and location can change for different oil flow rates.

For low oil flow rates (typically for the ON and OF cooling modes), a relatively small temperature gradient in the vertical cooling duct (at the outlet of a pass) can strongly influence the velocity distribution in the horizontal ducts and local hotspot temperature in the following pass between two oil guides. Uneven velocity distribution predicted by a THNM can in reality be even more skewed due to the thermal streaks and are therefore recommended to be verified by CFD. The thermal stratification in the vertical cooling duct can be mitigated by keeping the horizontal velocity distribution as even as possible. If done properly, the THNM can be expected to be reasonably accurate as a consequence.

For high oil flow rates this study visualize the fact that local oil flow distribution can become very uneven and might cause low flow region just above an oil guide where a local hotspot can occur. The magnitude of the local hotspot can become so big that it dominates the advantage of lower top oil temperature due to the larger oil flow rate. The results of this study strongly suggest to apply a CFD verification, in order to check that the hydrodynamic phenomenon does not create strong (local) hot spot which are missed by the THNM approach for high flow rate situations. If such hot spots emerge, the designed winding oil flow rate may need to be reduced as a consequence.

The CFD approach provides the potential to capture the sketched phenomena applying to certain flow ranges, in contrast to the THNM approach. Thus, CFD shows to be a potentially important verification approach for the thermal winding design, as well as a resource for gaining deeper understanding of the thermal behavior of transformer windings.

This study demonstrates the coupling between the upstream and the downstream passes and highlights the importance of modelling the full winding height in order to resolve the temperature gradients and velocity profiles in the vertical duct correctly.

The results that have been obtained by this study (and other studies) allow to define categories of designs for which CFD is indeed the recommended approach, whilst they also give pointers to refine the THNM-based approach for thermal design, by including certain parameters in the winding design regarding hot spot behavior.

RECOMMENDATIONS

The study presented here gives important information for the design review discussion between customer and transformer producer. For the customer the following guidelines can be presented, in order to enrich the design review process and increase the quality level of the thermal design regarding winding hot spot temperature estimation:

The thermal behavior of a transformer winding is complex and for it to be understood requires a high level of physical knowledge, proper simulation and design tools which are fed with sufficiently detailed design information. The design should be a final one, and its thermal design model should include at least the detailed spacer height distribution, extra insulation and the detailed loss distribution in the winding. This applies to all thermal models applied for the verification of the final design, irrespective of the model type (THNM or CFD).

In a design review, the models that are used to predict the thermal behavior need to be able to reflect the physical phenomena:

- For ON and OF modes, a discussion on the way to mitigate the first phenomenon (thermal stratification in the main cooling duct) must be held, which requires that the thermal model that is used by the manufacturer is able to adequately show that the oil flow distribution in all passes is reasonably uniform and the oil temperature increases are under control by a clear definition of the oil guide and spacer height distribution.
- For OD cooling, a CFD-based check for a too high winding oil flow rate is recommended.

A measurement of the hot spot temperature using optical fiber sensors can only be accurate if it is placed at the proper position. This position should be determined using an accurate thermal model calculation based on the knowledge that is presented in this document. For very high flow rates it is recommended to put fiber sensors not only at the predicted highest loss location but also at locations just above the oil guides.

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