# NUMERICAL STUDY ON MIXED CONVECTION AND THERMAL STREAKING IN POWER TRANSFORMER WINDINGS

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## Abstract

The flow and temperature distribution in oil-guided disc windings of power transformers is characterized by mixed convection. In this investigation a two-dimensional CFD model has been used in order to study the flow distribution between parallel cooling ducts, and the results are compared with results obtained for forced convection, i.e. when buoyancy is neglected. The buoyancy term in the model has a significant influence on the flow distribution, and for some cases also the magnitude of the hot spot temperature of the winding is influenced. When the coolant is a high Prandtl number fluid, hot streaks from the outlets of horizontal ducts can impact the temperature distribution in the discs further downstream; however a fine discretization is needed to capture this effect.

## 1 Introduction and background

While power transformers have been around for more than a hundred years preserving their fundamental principles of operation, they have evolved into very complex technological products. They consist of an oil-filled tank with a core, windings and supporting apparatus where the oil acts both as an electrical insulator as well as a medium for the transport of heat generated in the core and windings towards externally mounted cooling equipment.

The thermal management of a transformer is very important in controlling the amount of ageing due to high temperatures which cause the oil-impregnated paper insulation in the windings to degrade and may cause electrical failure. Recommendations for the thermal design of power transformers are found in loading guides, e.g. IEEE (1999) and IEC (2005). These documents include models for calculation of average winding temperatures and hotspot temperatures during steady state operation as well as for transient operations; however these models do not address the local distribution of temperature and coolant flow inside the windings. It is thus up to each transformer manufacturer to make use of appropriate tools such as network models and CFD (Computational Fluid Dynamics) in the design process.

Numerical modeling of the temperature and flow distribution in power transformers has been addressed since more than 40 years; see e.g. Allen and Allan (1963) and Allen and Finn (1969). Today transformer manufacturers are using numerical models in the daily design work in order to assure control of the expected temperature distribution including e.g. the hotspot temperatures in the different windings as well as the average winding temperatures and top, bottom, and average oil temperatures. These models are network models that incorporate formulas for pressure drop and heat transfer in the different parts of the transformer, e.g. layer windings, disc windings, disc-layer windings, core, tank, and cooling equipment. Detailed studies can be made with regular CFD programs; however CFD is not yet feasible for the daily design work due to the required computer time. One complication for CFD models of transformer cooling is that the flow in the tank is three dimensional and unsteady. However in the ducts of the active part and in the cooling equipment the flow is often laminar and steady.

In this paper the focus will be on oil cooled disc windings in which the oil flows in parallel horizontal ducts separating the discs in which heat is generated. In Imre et al. (1978) the steady state temperature distribution in naturally oil cooled (ON) disc type transformers was modeled using a mass flow network and a thermal network. In a subsequent paper, Imre et al. (1981), a network model that can be applied for transient situations was presented. In Oliver (1980) and Oliver (1981) a network model for disc windings is described for steady state conditions with known total oil flow. Joint numerical and experimental investigations of the flow and temperature distribution in disc windings were presented in Szpiro et al. (1982) and in Allen and Childs (1986), and an extended numerical investigation on the influence of the number of parallel ducts on the flow distribution within one section of parallel ducts was presented in Childs (1987). Yamazaki and Sakamoto (1992) investigated the flow distribution as function of the height of the horizontal ducts and the width of the vertical ducts. The coolant was a perfluorocarbon liquid, and network model results together with experimental results were reported. Network models for transformer cooling applications are also described in Declercq and van der Veken (1999), Del Vecchio and Feghali (1999), and Zhang and Li, (2002, 2006a, and 2006b).

Common characteristics of the reported network models are that the heat conduction in the disks is considered two-dimensional, i.e. in the radial and axial directions, whereas the convection is considered one-dimensional. In the coolant, conduction is neglected, which is physically sound for actual designs but could be causing numerical problems if the velocity in a duct becomes zero. The design task that is particular for disk windings is to assure sufficient oil flow in all the parallel ducts while keeping the pressure drop as small as possible. The flow distribution within a section of parallel ducts depends on the Reynolds number, the Rayleigh number, and the geometric proportions, i.e. number of parallel horizontal ducts, heights of the horizontal ducts, and widths of the vertical ducts. The cylindrical shape of windings also plays a role since the cross section area of the vertical ducts and the local cross section area of the horizontal ducts depend on the radial position. In practice, the minimum velocity might be at the bottom of a section (typical for forced flow) or at the top of a section (typical for buoyancy dominated flow). Depending of the proportions of pressure drop between vertical ducts, horizontal ducts and inlet/outlet losses the minimum velocity can be at the middle of a section, see e.g. Szpiro et al. (1982) and Zhang and Li (2006b). When the horizontal ducts within one section have different heights, it is important to check so that some large ducts do not create starvation of flow from other smaller ducts.

The comparisons between network models and experiments have all been related to forced convection, i.e. pumps have been used to control the total flow rate in the systems (known as Directed Oil (OD) cooling). In many transformer applications there is no pump that drives the flow but only the buoyancy of the coolant in the system, i.e. the thermosyphon principle (Natural Oil cooling (ON), or Forced Oil (OF) cooling if a pump between the coolers and the inlet of the transformer tank is added). In a network model for the flow distribution in disc windings, the pumping effect of the thermosyphon can be accounted for through pressure boundary conditions at the inlet and outlet, and the flow distribution is solved for as if the flow is forced. This approach seems to have been applied in all reports cited above except for Imre et al. (1978) and Imre et al. (1981). The influence of buoyancy on the flow distribution within one section might thus have been neglected, which is not motivated in many transformer applications. Flow visualization experiments, see e.g. Szpiro et al. (1982), have been carried out at isothermal conditions when there are no buoyancy effects influencing the flow distribution. However, as will be demonstrated in this paper the buoyancy effects in disc windings can be important for the flow distribution, and these effects should thus be included in network models for power transformers.

There are other flow effects that are conveniently investigated with CFD but which are difficult to include in a network model. One such effect is the hot streaks in vertical ducts. In the case of oil as coolant, the Prandtl number is large, typically from 40 to 400 depending on temperature range and oil type, and the flow is laminar. Thus the oil will not always be well mixed in the ducts. A hot streak of oil leaving a heated horizontal surface can survive into a subsequent section and can when entering a particular horizontal duct have a significant influence on the heat transfer in that duct. Also the buoyancy head generated after this duct will depend on the history along the hot streak that entered the duct. In a network model, the coolant is assumed to be well mixed in each node in the coolant network so that the temperature can be represented by the average temperature. It is thus not possible to account for the influence of hot streaks. However, using a CFD model with sufficient mesh resolution, the hot streaks can be resolved and their effect on flow distribution can be studied.

## 2 Model and numerical implementation

In this study a disc winding with six sections is modeled. The Fluent CFD package has been used for computing steady-state solutions of the Navier-Stokes equations and the thermal energy conservation equation. The disc winding is modeled using a two-dimensional axi-symmetric set-up (as sketched in Figure 1a). The model takes into account the oil ducts, the conductor material (copper) as well as the insulation material (Figure 1b).

The material properties of the transformer oil used are well defined; a temperature-dependent formulation is used for the viscosity, which causes the Prandtl number to vary as well (but always exceeding 50). The effect of internal buoyancy in the oil ducts of the winding is modeled using the Boussinesq-approximation with a fixed oil temperature at the winding inlet as reference. The effect of the cooling modes (ON, OF, OD) on the flow and temperature distributions is accounted for by specifying appropriate values for the oil velocity through the inlet of the winding.

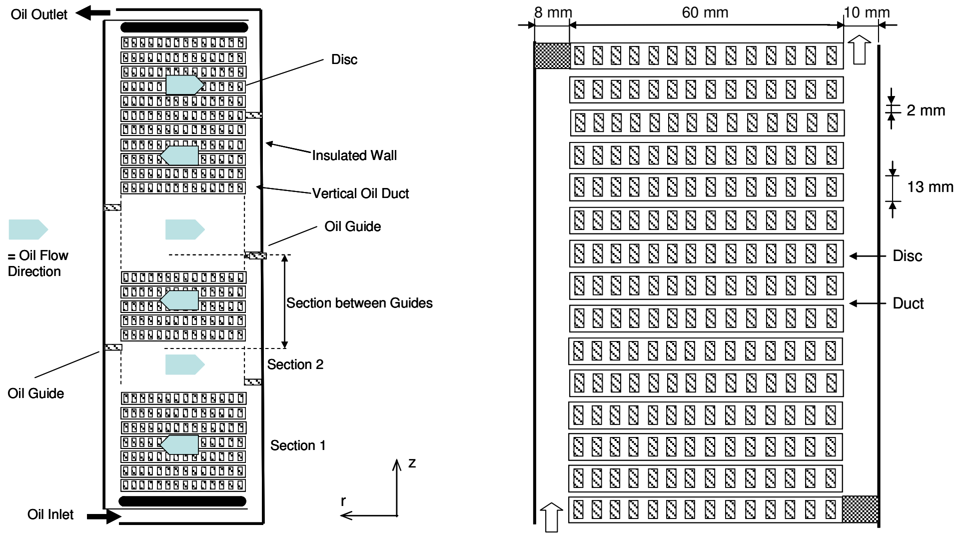

Figure 1: *Schematic of transformer disc winding geometry: a) cross-section of winding, b) detail of the winding showing a section between two oil guides.*

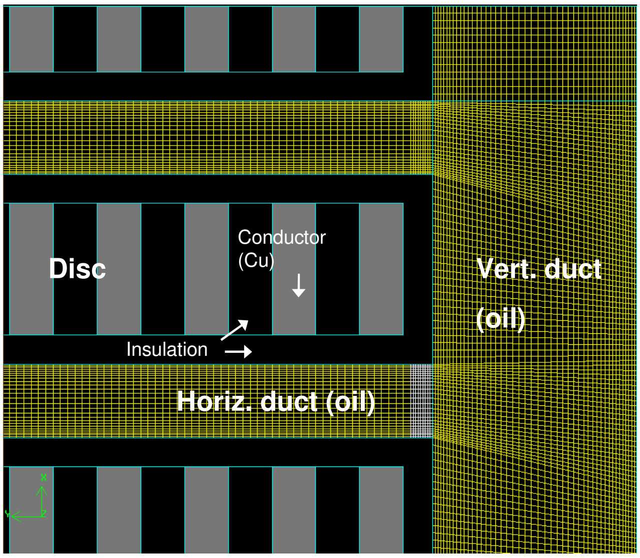

Figure 2: *Detail of the domain at the vertical oil duct. The grey blocks represent the copper conductors, the black domains surrounding them represent the oil-impregnated paper insulation, in the oil ducts the numerical grid is depicted (the domains of the conductors and insulation material are discretized in detail as well).*

The model equations are discretized using a finite volume method on a grid as depicted in Figure 2. In this figure it is also shown how the conductors are covered with oil-impregnated paper insulation material.

# 3 Results

In this section the results are presented for transformer winding simulations of three cases representing the three different cooling modes (ON, OF and OD). The model settings that discriminate these cases are given in Table 1.

For each of the cases in Table 1 two simulations were performed; one without internal buoyancy (i.e. by setting $g = 0$ in the model) and one with buoyancy ($g = 9.81$).

Case I is considered first, representing an OF cooling mode. In Figure 3 the average velocity in each horizontal duct and the maximum temperature in each disc are presented with and without internal buoyancy applied.

| *Case* | *Cooling Mode* | *Heat source ($W/m^3$)* | *Inlet velocity (m/s)* |
|---:|---:|---:|---:|
| I | OF | 472190 | 0.069 |
| II | ON | 472190 | 0.045 |
| III | OD | 1375324 | 0.200 |

Table 1: *Parameter values for conductor heat sources and oil inflow velocities (at the bottom of the winding) for the simulated cooling modes (OF, ON & OD).*

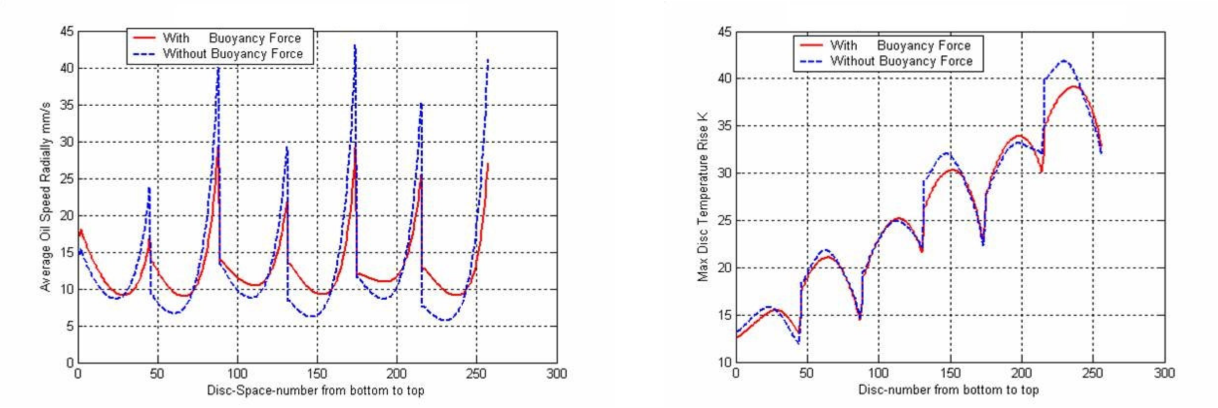

Figure 3: *Results for Case I (OF): vertical distribution of a) averaged velocities in horizontal ducts, b) maximum disc temperature rises with respect to winding inlet temperature. Red solid curves indicate that internal buoyancy is included; blue dashed curves indicate the absence of internal buoyancy.*

The results for Case I reveal a flow pattern in each section that is typical for flow dominated by forced convection (Figure 3a); due to the rapid deceleration of the oil flow in the vertical channels caused by the blocking oil guides, a large horizontal pressure difference builds up in the top of each sections giving rise to a local flow maximum in the uppermost horizontal duct. The local minimum velocity (which relates with the local hot-spot temperature, Figure 3b) occurs somewhere at the middle part of a section, the actual position being determined by the local pressure drops and inlet-outlet losses. If internal buoyancy is taken into account the increased buoyancy in the outflow vertical duct leads to a decrease in pressure at the bottom of the section, resulting in an increased horizontal pressure drop as well as rebalancing of the pressure drops in the other parts of the section, causing a slightly more even velocity distribution which in turn causes the minimum velocity to increase and the local hot-spot temperature to decrease. In Figure 3b it is shown for this practically relevant case that the calculated hot-spot temperature decreases with almost three degrees.

For Case II representing the ON cooling mode (modeled through a lower oil inlet velocity) it is shown in Figure 4a that internal buoyancy becomes dominant in determining the velocity distribution in horizontal ducts; the minimum velocity as well as the local hot-spot (Figure 4b) are now at the top of the section, whereas the results without internal buoyancy modelling agree qualitatively with Case I. Although the two velocity distributions shown in Figure 4a are completely different, the differences between the maximum and minimum temperatures are approximately equal and the calculated hot-spot temperatures differ with less than one degree.

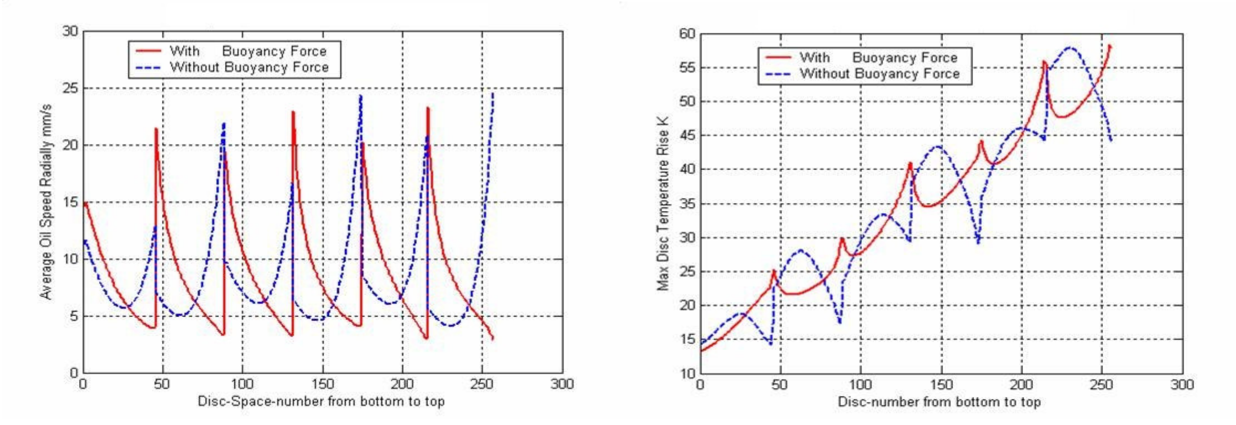

Figure 4: *Results for Case II (ON): a) horizontal duct velocities, b) maximum disc temperatures.*

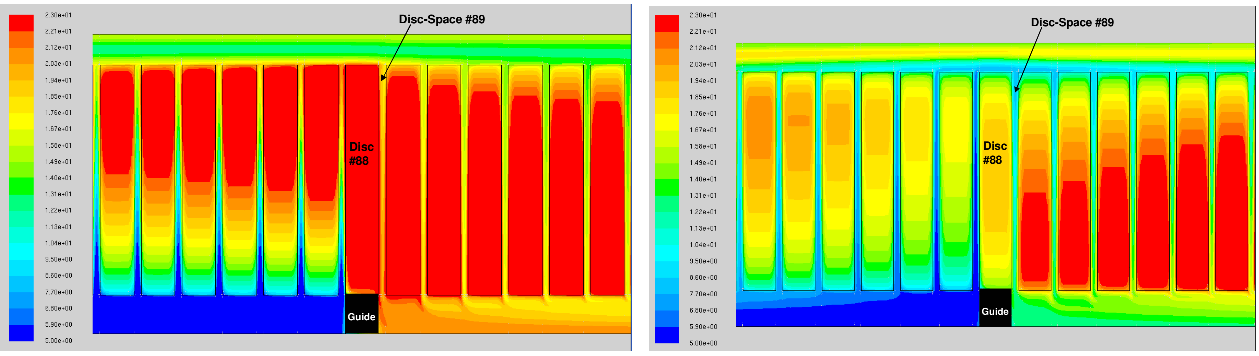

Figure 5: *Temperature distributions at the boundary of section 2 and 3 (Disc number 88): a) with internal buoyancy, b) without internal buoyancy. Note that the pictures are rotated clockwise: the winding upward direction is to the right.*

For this particular case a comparison between the velocity and temperature distributions in Figure 4 for the simulation with internal buoyancy reveals that the maximum velocity occurring at the first horizontal duct of a section does not correspond with the expected minimum section temperature in the adjacent discs; a local temperature maximum is actually created in the disc between two sections. It can be shown that it is the combination of the horizontal velocity distribution in the ”upstream” section and temperature stratification due to large Prandtl number that causes this temperature distribution.

In Figure 5 the temperature distribution between sections 2 (left side of disc number 88) and 3 (right side) for Case II simulations is shown for the simulations with and without internal buoyancy. When internal buoyancy is taken into account (Figure 5a), the relatively low horizontal velocities between discs at the top of section 2 (characteristic of internal buoyancy induced flows) causes the oil in these ducts to heat up quickly, which in turn generates a streak of warm oil at the edges of the discs. Due to the large Prandtl number this warm streak persists in the vertical duct that crosses the section boundary and subsequently enters the first horizontal ducts of the next section. This in turn causes the adjacent discs (in particular the disc between the sections) to get less efficiently cooled. As a result a local hotspot is created. In case internal buoyancy is neglected the upper ducts are well cooled due to the high horizontal duct velocities which are characteristic of forced convection. Now a cold streak is formed that subsequently cools down the first discs of the next section. As a result a local minimum temperature is reached.

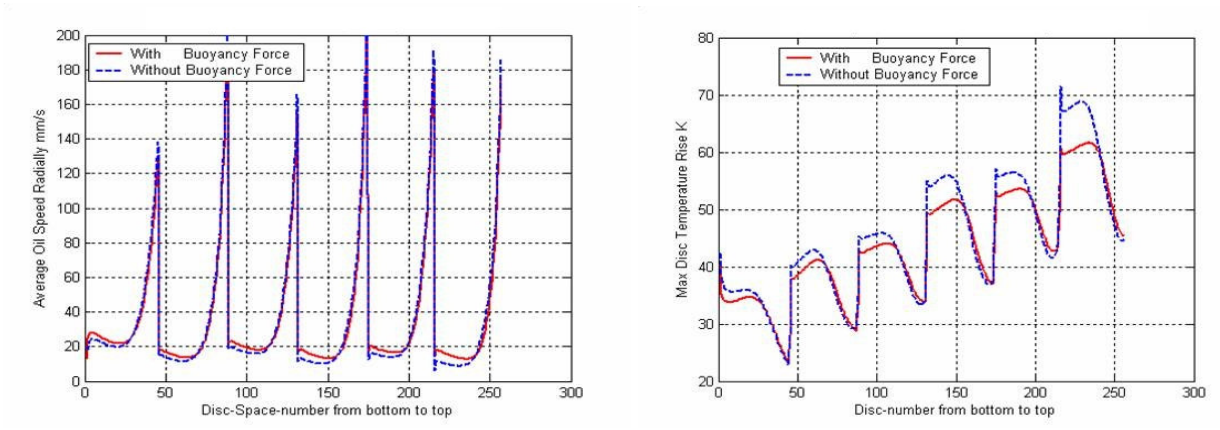

Figure 6: *Results for Case III (OD, high winding loss): a) horizontal duct velocities, b) maximum disc temperatures.*

Case III (OD, shown in Figure 6) represents a situation with higher thermal losses and higher flow rate. The heat source strength has been chosen such that the oil temperature rise in the winding is the same as in Case I.

Here the effect of internal buoyancy is significant: the simulation result without internal buoyancy shows a lower velocity and a higher hot-spot temperature distribution as compared to the result where internal buoyancy is included.

# 4 Conclusions

Internal buoyancy and hot streak formation are shown to play an important role in defining the oil flow and temperature distributions in a transformer disc winding. In the OF and OD cases of this study the velocity and temperature distributions are qualitatively similar for the pure forced convection and mixed convection assumptions. However, the local minimum velocities and maximum temperatures show a difference, with higher minimum velocities and lower maximum temperatures for the results with mixed convection. For the ON case, the velocity and temperature distributions become completely different depending on whether forced or mixed convection is assumed.

Detailed modeling of the flow and temperature distributions using CFD reveals the formation of hot streaks persistent in the vertical duct flow due to the large Prandtl number of the transformer oil. These hot streaks are subsequently drawn into the horizontal ducts between the first discs of the downstream section, leading to altered inlet temperatures in these ducts. Therefore the existence of these streaks can impact the flow and temperature distributions in a disc winding. A fine discretization is required to capture these thermal effects in a numerical model.

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