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STUDY ON IMPROVEMENT OF PASSIVE COOLING IN DISTRIBUTION TRANSFORMERS

KRZYSZTOF KASZA*, LUKASZ T. MATYSIAK*

* ABB Corporate Research Center
ul. Starowislna 13[a], 31-038 Krakow, Poland
e-mail: krzysztof.kasza@pl.abb.com
e-mail: lukasz.matysiak@pl.abb.com

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Abstract. In this paper the method for improvement of the heat transfer in the heat sinks having a form of vertical palate with fins is presented. In the first part theoretical background related to natural convection and radiation is discussed with focus on the optimum fin spacing and limitations in the heat radiation. Later the working principle of the proposed method, which is based on the application of additional panels that improve radiation from the surface of the fins, is explained. Finally, the example results from concept validation are shown and the potential application in cooling of distribution transformer is evaluated.

1 INTRODUCTION

Thermal management is important aspect in design of electrical apparatus like transformers, which are responsible for power distribution. Operational temperature has direct influence on the reliability and lifetime of those devices and, thus, keeping temperature limits and preventing from overheating is vital. Transformers and other power distribution equipment are expected to have long operational time, even up to 30 years, with minimized service and for that reason the passive cooling methods, e.g. natural convection of air, are dominating in their thermal management.

The heat transfer coefficient for natural convection of air is relatively low. The required cooling rate is obtained by increasing of the heat transfer surface using ribs or fins. The geometry of the fins and in particular the distance (air gap) between surfaces of the adjacent fins, has direct influence on the heat dissipation efficiency. The optimum spacing between fins may be found using various analytical formulas [1][2] or by computer simulations. However, in practice the fin-to-fin distance may be larger than optimum one because of technical or manufacturing limitations. That is common situation in distribution transformers with so called corrugated fin tanks, which example is shown in **Figure 1**. The fins are shaped by bending and welding of thin steel sheet and the fin-to-fin distance is determined by dimensions of the applied tools.

In this paper the method for improvement of heat transfer in passive cooling systems is presented. The considered cooling setup is based on the heat sink in a form of vertical plate with fins, as shown in **Figure 2**. First, the heat transfer phenomena in such system are discussed including the evaluation of the optimum fin spacing. Later the method for improvement of the heat transfer by radiation from the fin surface is presented. At the end the method is experimentally validated and theoretical calculations are made for possible application in distribution transformer.

Figure 1: Example of medium distribution transformer with corrugated fin tank.

2 HEAT TRANSFER IN VERTICAL PLATE WITH FINS

The heat is a form of energy transfer and it is driven by temperature difference. The flow direction is from regions of high temperature to the ones of low temperature. Three main heat transfer mechanism are distinguished in thermodynamics theory, namely conduction, radiation and convection [3]. In the passive cooling systems, which are based on the heat sinks in a form of vertical plate with fins (as shown in **Figure 2**), natural convection is the heat transfer mechanism that usually determines the overall cooling efficiency. The conduction is not a limitation, since the heat sink is usually made of metals like aluminum or steel, characterized by high thermal conductivity. The importance of the radiation is decreasing with increase of the fins width (W) and height (H), which is often done in order to enlarge the heat transfer area for convection.

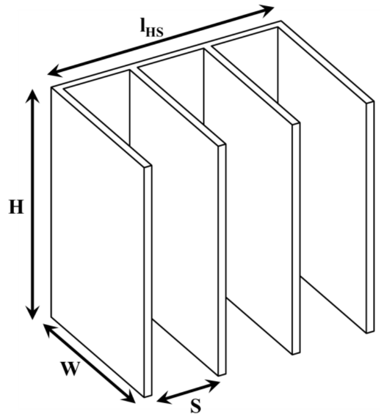

Figure 2: Basic configuration and parameters of the heat sink in a form of vertical plate with fins.

In the convection the total heat transfer rate q through the heat sink with fins depends on the heat transfer coefficient h, temperature difference between heat sink wall T_w and ambient air T_{amb} and the area of the heat transfer A:

$$q = Ah(T_w - T_{amb}) \tag{1}$$

The total area of the heat sink shown in **Figure 2** may be increased by using higher or wider fins or their larger number. In case of space limitations the last option is the only one and then fin spacing S must be decreased, if additional fins are applied.

The fin spacing and fin-to-fin distance (i.e. distance between surfaces of the adjacent fins, which is equal to fin spacing minus fin thickness) has direct influence on the convective heat transfer coefficient. It is easy to imagine that fins, which are placed too close to each other, block the air flow, limit its velocity and, thus, decrease the heat transfer coefficient. The dependence between the heat transfer coefficient and fin spacing is shown in general manner in **Figure 3**, with solid line. It is worth noticing that if fin-to-fin distance is large enough, it has no influence on the heat transfer coefficient and its value remains constant.

On one hand, adding new fins by reduction of their spacing increases the area of heat transfer, but, on the other side, at some point causes reduction of the heat transfer coefficient. It means that the efficiency of the heat sink may be optimized and the optimal fin-to-fin distance, that is providing the highest heat transfer rate, may be found as shown in **Figure 3** with dashed line. One may notice that the optimum spacing of the fins is achieved for slightly reduced value of the heat transfer coefficient. It means that the additional heat transfer area, which is gained by decreasing of S, is partially able to compensate the loss in the value of the heat transfer coefficient.

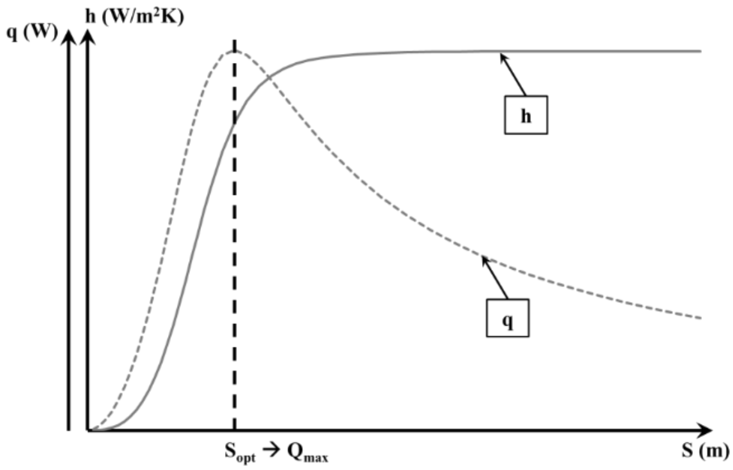

Figure 3: The dependence of the convective heat transfer coefficient and total heat transfer rate on fin spacing.

The optimum performance of the heat sink is a combination of its geometrical parameters and temperature configuration. It is stated, in one of the earliest works related to that subject (by Elenbaas [1], from 1942), that the optimum designs are characterized by similar value of the Rayleigh number. The first approximation of that value, given by Elenbaas, is ~50. In the later works the value ~60 is proposed [3] and basing on that simplification the equation for the optimum fin spacing may be provided:

$$S = (60\mu\alpha H/(\rho g\beta\Delta T))^{0.25} \tag{1}$$

where μ is dynamic viscosity, α is thermal diffusivity, ρ is density, g is gravitational acceleration, β is coefficient of thermal expansion and ΔT is temperature difference between fin wall and ambient air.

In the heat sink shown in **Figure 2** the heat transfer rate by radiation is much smaller than the one by convection. That disproportion is getting bigger with the increase of the dimensions of the fins, i.e. their height and width. The limitations in the radiation are related to the heat sink geometry as it is depicted in **Figure 4a**. Although, the fins increase the potential surface for heat emission, the view angle to ambient environment, which may absorb energy, is relatively narrow (dotted arrows). In most of the possible directions for heat emission the fin surface "sees" the surface of adjacent fin, which has similar temperature, and the lack of temperature difference prevents radiation – as it is depicted by solid arrows in **Figure 4a**.

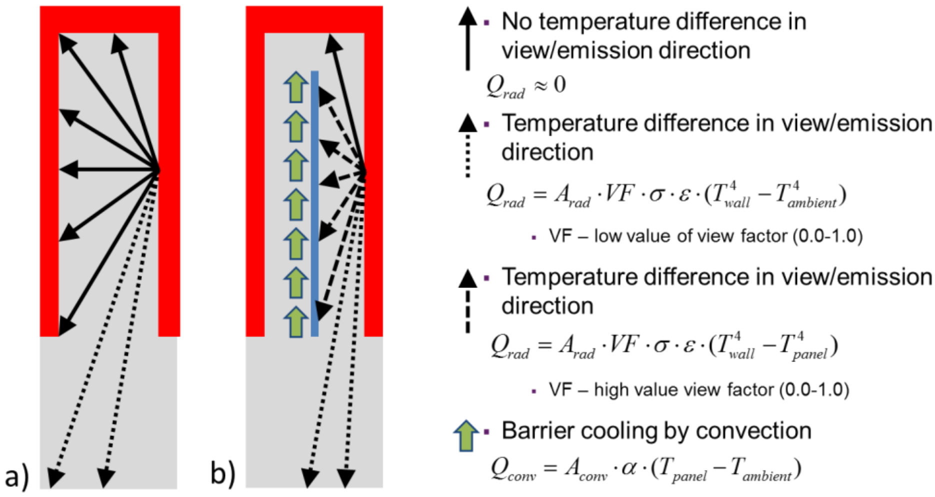

Figure 4: Heat transfer by radiation in heat sinks with fins.

In **Figure 5** the heat transfer coefficient value is presented as a function of fin-to-fin distance. The presented results were computed for fins having infinite width and two heights: 400 and 800 mm. Uniform temperature distribution equal to 100 °C was assumed at fin surface for the purpose of calculations and the ambient conditions were set to 40 °C. The solid lines were obtained basing on analytical formulas and the value of the heat transfer coefficient represents only the effect of natural convection. On the other hand, the dashed lines came from computer simulations and include effects of both natural convection and radiation. The constant increase of the heat transfer coefficient with the increase of the fin spacing is caused by radiation. The view angle to the absorbing environment increases as distance between the fins enlarges. Nevertheless, the results from **Figure 5** confirm that in the typical heat sink the heat transfer rate by radiation is relatively small.

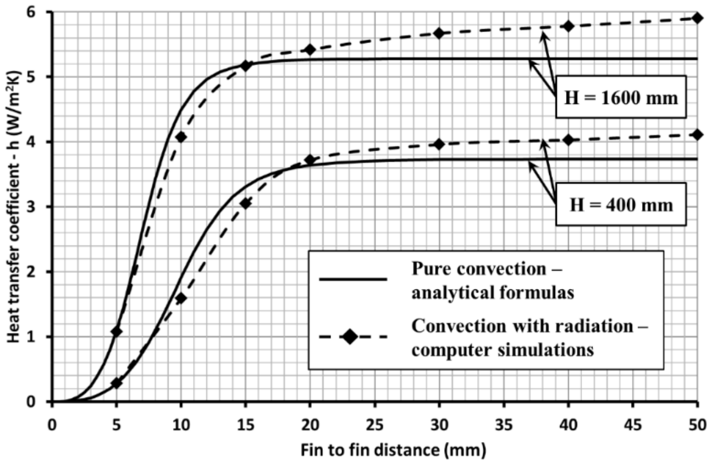

Figure 5: The influence of radiation on overall heat transfer coefficient.

3 THE RADIATION PANEL CONCEPT

The concept for improvement of the radiation from vertical fins is presented in general form in **Figure 6** and its working principle will be explained later using the **Figure 4b**. It is based on using additional panels, which should be placed between the fins and parallel to them. In that idea it is assumed that fin-to-fin distance is bigger than optimal, e.g. due to technology limitations and such panels have only limited influence on the natural convection air flow between the fins and the convective heat transfer coefficient.

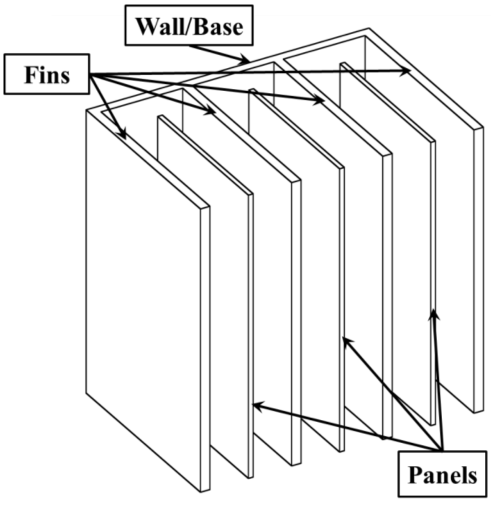

Figure 6: The schematic view of the concept of panels for increasing radiative heat transfer from fins.

The potential application of the proposed solution in cooling of distribution transformer is presented later in this article. The another utilization of this method in panel radiators for house heating is discussed in [4]. The results presented by authors confirm the importance of the radiation in passive heating. They also indicate that in some configurations the method increases the heat output by 60%. Although, the performance of the solution with panels is worse in comparison to traditional radiator with large number of small ribs, some advantages like smaller manufacturing cost or lower susceptibility to dust and easier cleaning are pointed out.

The working principle of the proposed method is illustrated in **Figure 4b**. The panel is placed between fins and it is not thermally connected (by means of conduction) with fin surface. During the operation the panel has lower temperature than fin surface and that is why radiation from the fins is possible. It is depicted with dashed arrows. The efficiency of that system depends on temperature of the panel, which results from the heat balance between the panel heating by radiation and the panel cooling by convection.

The application of the prosed solution is limited by the fin-to-fin distance. In case of very small gap between the panel and the fin surface the air flow is blocked, causing decrease of the convective heat transfer. It is shown in chart in **Figure 7**, in which the cooling efficiency of the heat sink with fins only is compared to the cooling efficiency of the heat sink with fins and panels. These results came from computer simulations in which fins had infinite width, four different heights, uniform temperature distribution at their surface equal to 100 °C and temperature of ambient air at the level of 40 °C. The value of the heat transfer coefficient in **Figure 7** includes both convection and radiation effects. The observed improvement is even over 50 % and in some part depends on the fin height, but in major is determined by the fin-to-fin distance. The critical fin-to-fin distance, for which the heat sink without and with panels has the same heat transfer coefficient, may be defined for each fin height. The general rule is that its value increases with increase of the fin height.

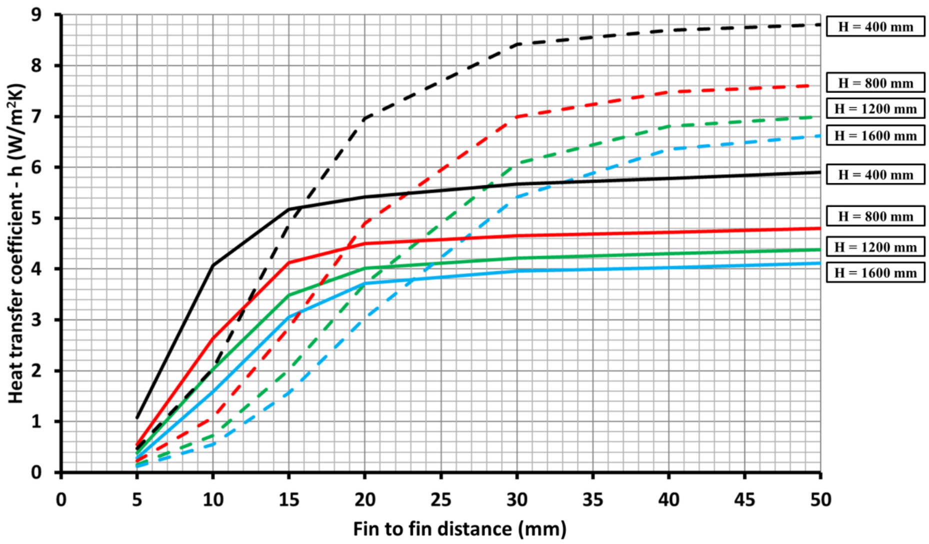

Figure 7: The comparison of the cooling efficiency of the heat sink without and with panels.

4 CONCEPT VALIDATION AND DEMONSTRATION

The experimental stand shown in **Figure 8** was used for validation of the cooling concept with radiation panels placed between vertical fins of the heat sink. It consisted of two vertical heated aluminum plates, which were either well-polished or covered with black chalk. The mirror like plates were used for analysis of the heat transfer which is mainly based on natural convection, while in case of the black ones the radiation effects were added. The insulation material (wood and polymer foam) was placed on one side of each aluminum plates in order to direct the heat flow. Nevertheless, some heat amount was transferred through the insulation and its quantity was estimated basing on measurements from thermocouples, which were placed inside the insulation. In each experiment the heaters were supplied with three different power levels, so the final results were in the form of a chart showing temperature-power relation.

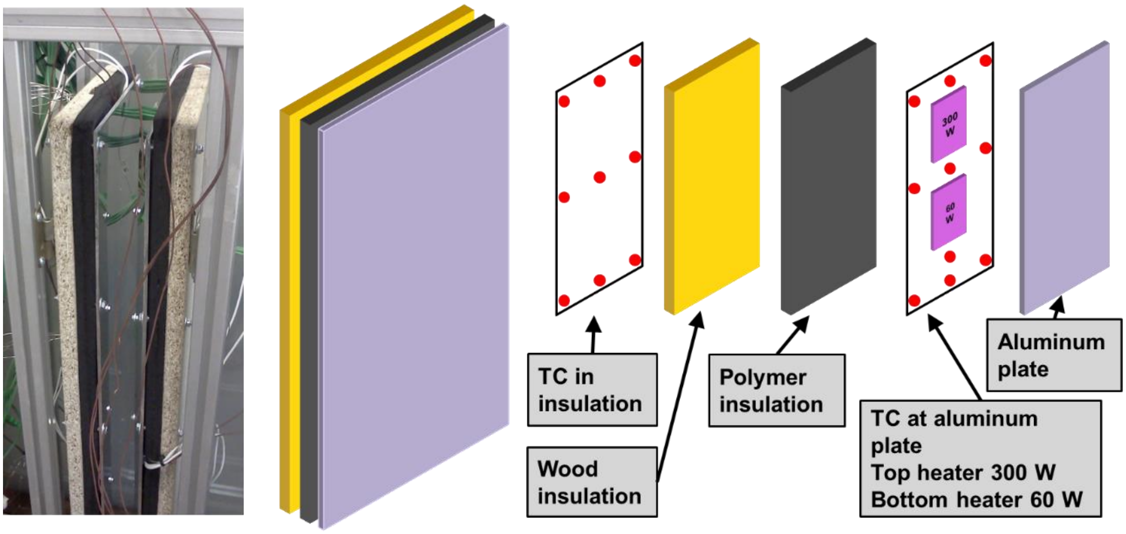

Figure 8: Experimental stand used for validation of the proposed cooling concept.

The performed tests included the following configurations:

A. Heat transfer through single polished plate.
B. Heat transfer through two polished plates, spaced about 80 mm from each other.
C. Heat transfer through single black painted plate.
D. Heat transfer through two black painted plates, spaced about 80 mm from each other.
E. Heat transfer through two black painted plates, spaced about 80 mm from each other and with black polycarbonate plate positioned between them.

The experimental results showing estimated total heat transfer rate through the single aluminum plate are shown in **Table 1**. The presented values were achieved for the same average plate temperature and very similar temperature distribution, with deviations smaller than 5 K. The obtained results confirm that, in case of pure convection, the adjacent fins have only minor influence on each other if the distance between the fins is large enough. Slightly better performance of the configuration B over A is either related to measurement accuracy or caused by so-called "chimney effect". The results from configuration C confirm the importance of the radiation in passive cooling. This heat transfer mechanism is equally important as the total heat transfer rate is doubled in comparison to pure convection. The configuration D indicates that radiation from the surface of fins is in major part blocked, while setup E confirms that it may be much improved by placing additional panel between the fins and parallel to them.

Table 1: The outcome of experiments performed with different configurations.

Configuration	A	B	C	D	E
Total heat transfer rate (W)	33.2	36.1	72.0	47.5	58.3
Average temperature in reference to ambient (K)	27.0	27.0	27.0	27.1	27.0
Maximum temperature in reference to ambient (K)	41.6	42.6	46.4	44.0	45.8
Minimum temperature in reference to ambient (K)	17.5	16.9	14.9	15.9	14.8

The concept demonstration presented below is based on the 160 kVA distribution transformer with tank having corrugated fins. In the considered example fins have height 500 mm and width 250 mm. The spacing between fins is 45 mm, but the actual distance between the surfaces of adjacent fins is only 37 mm. However, it is still much above the optimum and thus, as it is shown later, the panels are able to increase the cooling efficiency of the whole system.

The potential improvement in heat transfer is estimated basing on computer simulations, performed using ANSYS Fluent CFD software [5]. This software was also utilized in other calculations mentioned earlier in this paper. The geometry of numerical model was limited to single fin in order to minimize the computational time. It is presented in **Figure 9**, where also boundary conditions are marked. In this example the heating condition was modeled as temperature profile along the height of the tank with fin and the computed total heat transfer rate for single fin was the main result. It was later used for estimation of the improvement in total heat transfer rate through the whole tank. The numerical model included all mathematical and material formulations, which were required for accurate calculations, e.g. turbulent flow [6], discrete ordinates radiation model [7], temperature dependence of air properties [8].

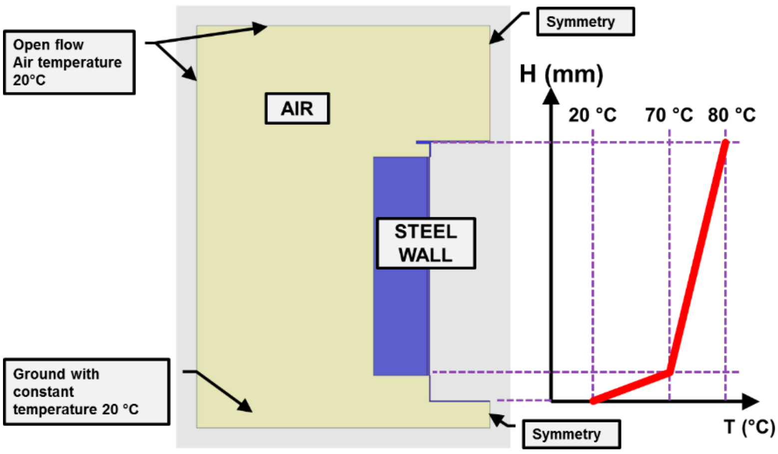

Figure 9: The model geometry and boundary conditions.

The computed heat transfer rate through single fin of 160 kVA transformer was almost 47 W. In the second simulation, with the plate of high surface emissivity placed between the fins, 63 W were required to keep the same temperature profile on the fin surface. It manse that the cooling efficiency was improved by about 34%, in terms of the heat transfer rate. In the considered transformer the surface of fins is about 76% of the whole tank surface. Thus, the improvement for the whole device would be smaller, but still its value would be meaningful.

5 CONCLUSIONS

The radiation may be equally important and efficient heat transfer mechanism as natural convection of air in the passive cooling. The method for improvement of the cooling efficiency of the heat sink in a form of vertical plate with fins was presented in this paper. This method may be applied for the heat sinks, which due to manufacturing or technology limitations do not have optimized fin spacing. In such case, it possible to increase total heat transfer rate from the fin surface, by placing additional panels between the fins and parallel to them. The obtained improvement is due to higher radiation.

The proposed concept was validated in the laboratory and the measured increase in total heat transfer rate was about 23%. In addition, its possible application for cooling of distribution transformer with corrugated fin tank was discussed. In this case the estimated improvement, in terms of the heat transfer rate was about 26%.

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