CFD ANALYSIS AND CLASSICAL APPROACH TO CALCULATE THE EFFICIENCY OF A RADIATOR IN POWER TRANSFORMER

S. M. Cho[1*], C. S. Kim[1] and J. K. Kim[1]
[1] Hyosung Corporation, South Korea.
*Email: topmoon@hyosung.com

Abstract: Thermal problems in power transformer recently have been issued due to their lifetime and reliability. With a tendency to minimize the product, accurate prediction about efficiency of the radiator becomes more important. In this background, this paper presents the method of calculation to estimate the efficiency of the radiator used in power transformer cooling system. Two classical models were adopted to solve heat transfer induced by natural convection between radiator and air boundary. Temperature distribution and heat transfer coefficient were analytically investigated. To compare the result with those real cases, CFD analysis and experimental investigation were companied. The overall efficiencies in each case of radiators were lower than we expected because of surrounding conditions which are different to real cases. This result can help to understand heat transfer phenomena in radiator and to utilize to design optimum cooling system of power transformer.

Nomenclature

ρ	Density
C_P	Heat capacity
$\dot{V}$	Volume flow rate
T_{air}	Ambient temperature
$\bar{h}$	Averaged heat transfer coefficient
$\overline{Nu}$	Nusselt number
Ra	Rayleigh number
Pr	Prandtl number
g	Gravity acceleration
β	Volume expansion coefficient [K^{-1}]
k	Thermal Conductivity

1 INTRODUCTION

With the development of technology, energy consumption has recently increased rapidly. A surge in demands on electrical power has overloaded power transformers and it has affected both lifetime and reliability which depend on thermal problems. In the case of the large power transformer, insulation oil is used to release the heat, which is transferred from the winding and the core to the radiators. This oil can be circulated throughout a tank and radiator by means of natural convection without additional device such as a pump. So, most customers prefer these types of the radiator cooled by natural convection because of the low noise and low power losses.

Since the temperature rise in a tank shortens a lifetime of Insulator, it consequently affects the reliability of the transformer. In addition, as it exceeds allowable point, the explosion can be caused by pressure rise due to the vaporization of oil. So the technique for design to keep the oil below allowable temperature is crucial. In the past, manufacturer didn't need to worry about the radiator efficiency because they used enough quantity for cooling. However, accurate prediction about efficiency of the radiator highly required with a tendency to minimize the power transformer.

With the recent development of computer based numerical analyses, it became possible to solve a complex thermal-fluid phenomenon by commercial tools. But some part of analysis for natural convection is still a problem on convergence, calculation time and accuracy. This study, to get over the problem mentioned above, estimated the efficiency of radiator by classical approach and implemented CFD analysis in order to raise the accuracy of the result.

2 CLASSICAL METHOD

2.1 Calculation model

The classical method to calculate the efficiency of radiator can easy to approach the difficult natural convection problems that are hard to converge. A sketch of one fin of the flat radiator, which is simplified for calculation, is shown in Fig.1. By dividing the fin of radiator into small element longitudinally, when oil flowing in radiator is cooled by air near the outer surface of the radiator, it is possible to assume that the loss rate of oil is equal to the heat transfer rate of the convected air on the element surface. Differential equation for this energy balance can be expressed as the following.

$$\rho_o C_{Po} \dot{V}\, dT = \bar{h}_{r-a} O_p \left(T(x) - T_{air}\right) dx \qquad (1)$$

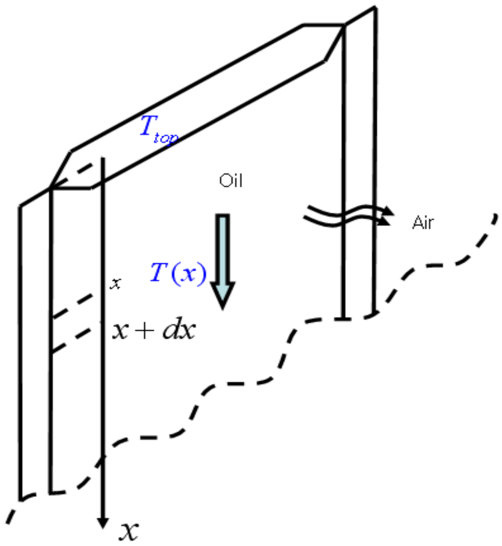


Figure 1: Sketch of a fin

Here, O_p is perimeter of radiator which is perpendicular to x direction. When x is zero, $T(x)$ is equal to T_{top} . So the solution of above equation can be represented as follows.[1] et al.

$$T(x)=T_{air}+\left(T_{top}-T_{air}\right)e^{-\frac{hO_p}{\rho c_p \dot{V}}x} \tag{2}$$

In order to calculate the temperature at (2) equation, convective heat transfer coefficient $\bar{h}_{r-a}$ must be obtained preferentially. Since this value varies with a shape of radiator and circumstance around it, radiator model should be divided in accordance with fin arrangement.

Fig.2 shows two convection-mechanism around a radiator. Firstly, the end fin of radiator can be assumed as vertical-flat plate and, in this case, Churchill and Chu [2]'s empirical equation has been well known for being used to obtain convective heat transfer coefficient, as follows.

$$\overline{Nu}_L=\frac{\bar{h}\cdot L}{k}=\left\{0.825+\frac{0.387\cdot \mathrm{Ra}_L{}^{1/6}}{\left[1+\left(0.492/\mathrm{Pr}\right)^{9/16}\right]^{8/27}}\right\}^2$$

When $Ra_L>10^9$ (3)

$$Ra_L=\frac{g\cdot\beta\cdot\left(T_S-T_{air}\right)\cdot L^3}{\nu}\mathrm{Pr} \tag{4}$$

The characteristic length (L) is height of a fin and ,in case of radiator for transformer, this value is big enough. So it is generally reasonable to regard Rayleigh number as 10^9 and over.

In case of inside fin, as shown at right-side of Fig.2, the flow becomes fully developed being merged each boundary layer due to their long channel distance versus those width. Elenbaas at al.[3-4] presented useful equation for flat plates ,which are parallel and symmetric to each other, as follows.

$$\overline{Nu}_s=\frac{1}{24}Ra_s\left(\frac{s}{L}\right)\left[1-\exp\left\{-\frac{35}{Ra_s(s/L)}\right\}\right]^{3/4} \tag{5}$$

In this case, for reason that a gap between fins gets to be characteristic length, Rayleigh number decrease sharply and Nusselt number also becomes small due to the relatively long height of a radiator. Averaged convective heat transfer coefficient between fins can be obtained from the following equation.

$$\bar{h}_2=\overline{Nu}_s\cdot k/s \tag{6}$$

This value is slightly small compared to the heat transfer coefficient on outer fins.

Generally, 80~90% of transformer losses are cooled through radiators and the rest are emitted through the tank by convection and radiation. Though the radiation losses also exist in radiator, the rates of those are very small due to the symmetrical shapes for each other. So in this study, radiation effect was not considered.

2.2 Calculation condition

The flow rate of oil, being circulated by density difference, varies depending on a structure of inside of a tank and a position of the heat source. In general, oil into a usual size header of a radiator (3~4 inch header) has flow range of 10~100 LPM when it is cooled naturally without pump.

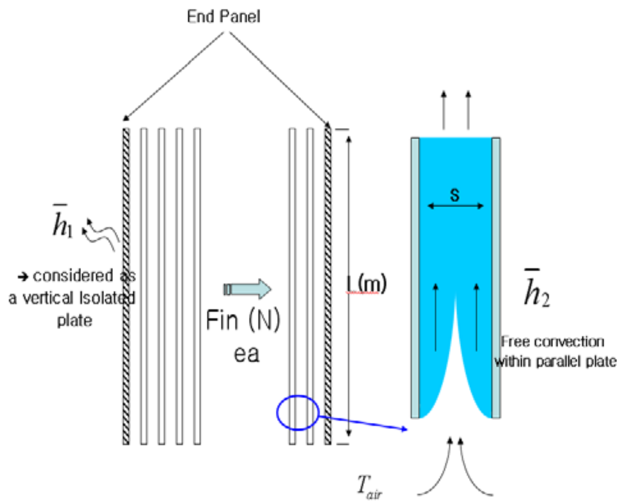


Figure 2: Schematic model of a radiator

Here, one notable thing is that the oil flow into each fin is not equally distributed. Equation (7), which is obtained and generalized in condition of 30,50,70 LPM by using commercial tools 'Fluent', shows the flow distribution with the fin order(N). The lower number 'N' means a thing close to the tank.

$$\dot{V}_{fin}(N) = (1.4092 - 0.0312N + 0.000416N^2)\left(\frac{\dot{V}_{total}}{N_{total}}\right) \quad (7)$$

The properties of oil used in this study vary depending on the temperature. These can be represented as follows .

$$k = 0.15217 - 7.16E-5T \qquad [W/mK]$$
$$\rho = 1067.75 - 0.6376T \qquad [kg/m^3]$$
$$\mu = 0.00213 + 38657 \times \exp(-T/19.96) \qquad [kg/m \cdot s]$$
$$c_p = 821.19 + 3.563T \qquad [J/kg \cdot K]$$

Since the equation (1)-(6) are functions of temperature and flow rate, an iterative calculation is necessary to get an accurate solution. Programming language 'Matlab' was used for calculation and specific details of the radiators are given in Table.1.

Table 1: condition for calculation

$\bar{h}$ (assumed initially)	5 (W/m^2K)
Total fin number	40 fin
Height of radiator(L)	2200~3500 (mm)
Ambient temperature	20 ℃
Temperature rise limit	55 ℃ (Inlet temperature :75℃)
Flow range	10~100 LPM
Gap (between fins)	45 (mm)

3 RESULTS AND DISCUSSIONS

3.1 Heat transfer coefficient (HTC)

Fig.3 (a) shows the value of averaged convective heat transfer coefficient (HTC) changing along the flow rate of oil that is entering the header at 3000 height of radiator. On the whole, HTC increases with the increase of flow rate, but only a little increment is shown over 20LPM. At the first and last fins, HTC showed the value of about 4.5 W/m^2K , which is a little bit smaller than initially assumed HTC. In case of the inside fins, HTC were within 2.6~3.0. These are very small values among the well-known HTC of natural convection. The reason of low HTC can be explained by shape of radiator witch has relativley long height compared to channel gap. Thus, cooling effect

(a)

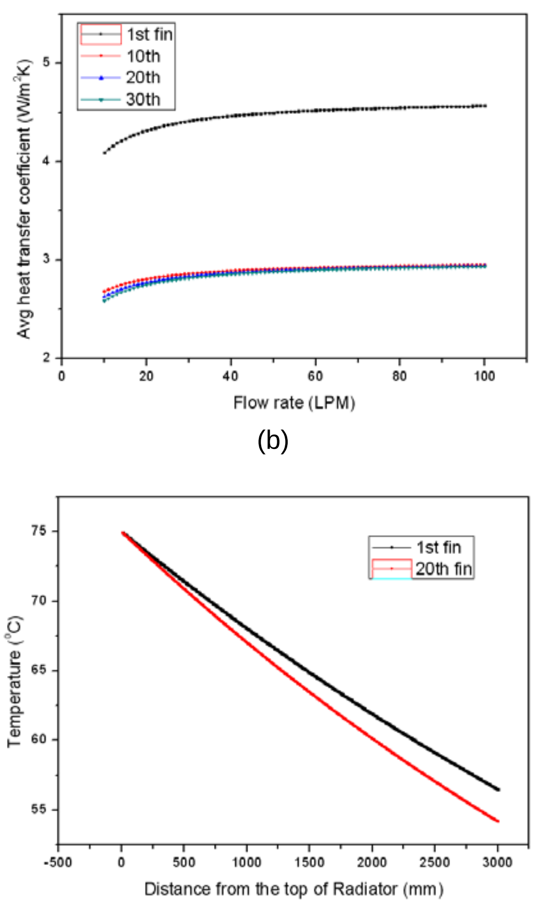


Figure 3: (a) Avg HTC with flow rate and (b) Temperature distribution with the distance from top position at 3000 height of Radiator

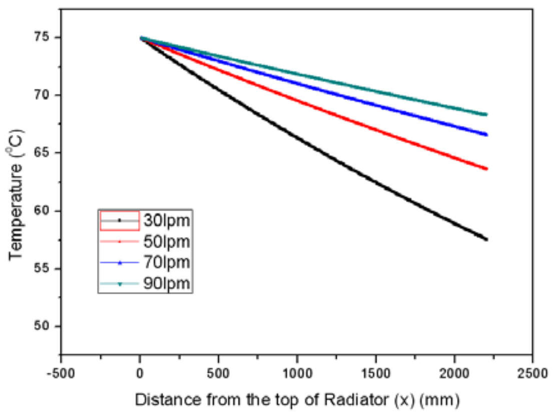
between hot fins will be decreased along the height of them.

Fig.3 (b) shows the temperature distribution along x position (height) of 1st, 20th fin when it flows at 50 LPM. In spite of bigger HTC, the temperature range of 1st fin is slightly higher than 20th, because the flow into each entrance of the fin differs. At the first fin, 1.73 LPM flows while 1.19 LPM enters at 20th fin.

3.2 Temperature distribution

Fig.4 shows the temperature distribution of oil flowing at 30,50,70,90 LPM on the 1st fin of 2200 mm(a) and 3500 mm(b) height. At (a), when flow rate is 30 LPM, temperature difference of top-bottom is 16℃ while 6℃ at 90 LPM. In case of (b), at the same flow rate of the former, each deviation was 21 ℃ and 8.5 ℃. It was shown that when the flow rate increase three times temperature difference of top-bottom decrease 40%. Although the temperature difference reduces with increase of flow rate, natural cooling effect slightly increases following the flow rate due to the increase of mean film temperature as shown in Fig.3(a). This

(a)



(b)

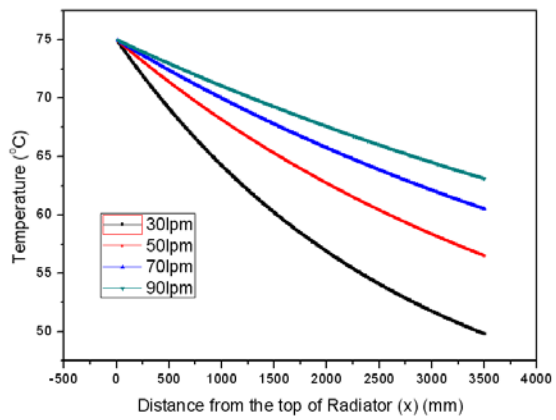


Figure 4: Temperature distribution of first fin with the distance from top position at (a)2200 , (b)3500 height

tendency is shown more clearly when the inlet oil temperature is higher.

As per similar reason, temperature distribution along the direction of height presents a parabola descending sharply on the upper side of radiator compared to lower position. It implies that a long radiator is not efficient when the deviation of mean oil temperature and ambient temperature is small.

3.3 Heat release rate of radiator

In order to evaluate radiator efficiency, limit of oil temperature rise has to be considered. Every transformer oil is confined by their limits and generally, 55℃ is used as standard rise in Korea. Reflecting such limit, inlet temperature was assumed to be 75℃, where ambient temperature is 20℃. But we need to clarify that the radiator efficiency can be increased if inlet temperature increases. Fig.5 shows the heat release rates of radiators according to changes of their heights and flow rates. Total heat release rate can be obtained by summing up the heat transfer rate at each element, as follows.

$$P_{total} = \sum_{n=1}^{fin\_n} \sum_{x=1}^{L} \rho C_p \dot{V}_{fin}(n) \cdot \{T(x) - T(x+1)\} \qquad (8)$$

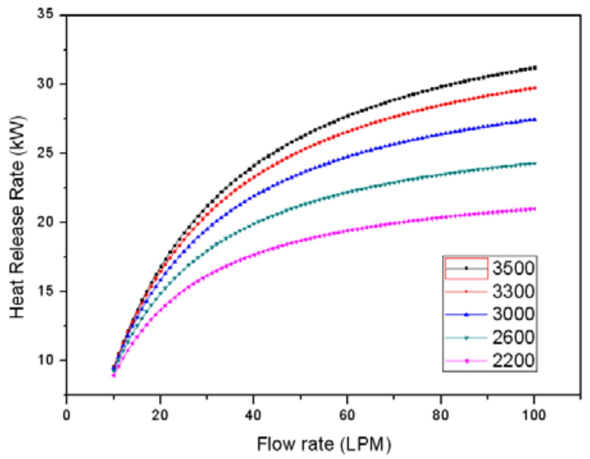


Figure 5: Heat transfer rate with Flow rate and Height of a Radiator

When flow rates change from 10 LPM to 100 LPM, heat transfer rate increase 1.6~ 2 times and their differences seem to be diverged as radiator height becomes higher. It is notable that the efficiencies don't change much with flow rate over 35 LPM.

The results were a little lower than experimental values based on real site. There are many possible reasons that can explain the low values. For example, wind around transformer, excepting generated one by natural convection, can help heat transfer and radiation loss, which is not considered here, can be another factor.

3.4 Compare to CFD result

To compare the results, CFD (Computational Fluid Dynamics) analysis was conducted by using commercial tool, Fluent (ver 6.3) in the case of 50 LPM flow rate, 3000 mm height radiator, while other conditions were same as the former calculation. For computation, about 6 million hexahedron cells have been generated and most of them have been used for air grid. Boundary conditions for the computation were given in Table.2.

Table 2: Conditions for CFD

Air	Boussinesq model	β =0.0032(1/K)
	Boundary	Pressure outlet
		20℃
Oil	Same as the classical calculation	

The simulation results are presented in Fig.6. From (a), it is generally found that convective HTC of 1st fin is much higher than that of 20th fin. This tendency is correspond to result of classical approach, but the values are pretty different as follows: mean HTC = 7.4 W/m^2K at 1st fin, 3.7 W/m^2K at 20th fin.

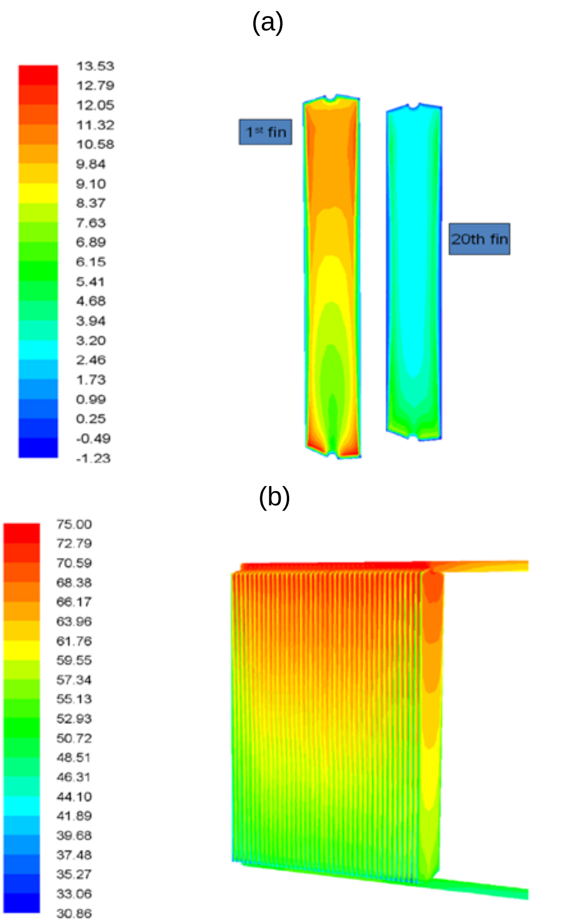


Figure 6: Result of CFD analysis :
(a)Contour of surface Heat Transfer Coef (W/m^2K)
(b)Temperature distribution (℃)

Fig.6 (b) shows the temperature distribution of radiator surface. Comparing to the result of classical calculation, overall heat release rate was 11% larger as follows: CFD = 26.2 kW, while classical calculation = 23.6 kW. But if consider the characteristic of CFD that is varying with both grid quality and analysis scheme, it is difficult to conclude which result is more close to real case. So an additional experiment for real model is needed to use or modify classical formula.

3.5 Experimental result & future work

Test set shown in Fig.7 (a) was developed for estimating performance of cooling system for power transformer. Since an experiment is not main focus in this study, it will not be dealt minutely with here. To sum up shortly about test, all equipment excepting radiators were thermally insulated and located in large room with little air movement to keep the ambient temperature constant. From Fig.7 (b) it was found that cooling capacity of test radiator is slightly bigger than the values of classical calculation, but a little bit small compared to those of CFD simulation.

This equipment is still in operation to test not only radiators, but fans, coolers and so on. So after

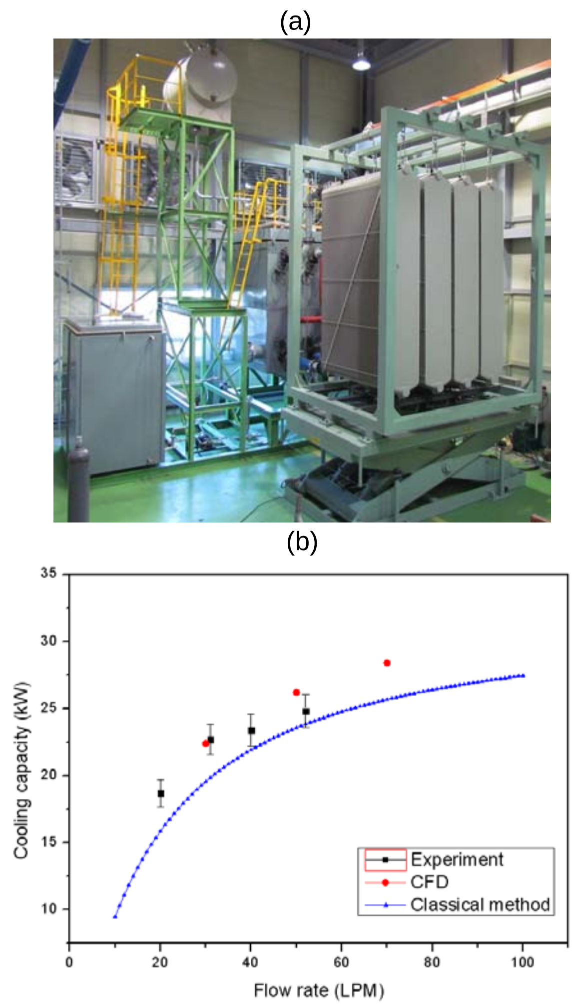


Figure 7: Experiment
(a) Test setup , (b) Comparison with other results

additional test for various cooling system, building up the thermally integrated program for power transformer is afoot through the modification of old formula.

4 CONCLUSION

The results showed that the heat release rate of radiator increased by increasing the oil flow rate and their height but didn't change much at a certain flow rate above. It was also shown that the rate of heat transfer at each end fins has 1.5 times higher value compared to those of other fins. The overall efficiencies in each classical case were 9~12% lower than CFD result with a different radiator size and both results were lower than what we expected. Some experiments in a few cases, which are not done yet completely, showed slightly higher efficiencies than calculation results but less then those of CFD simulation. These deviations can be explained by the heat loss that occurred through the tank and pipe and by the radiation effect. This study will be helpful in understanding heat transfer phenomena in radiators and can also be used to design optimum cooling system of power transformer.

5 REFERENCES

[1] Z. Radakovic and M. Sorgic, "Basics of detailed thermal-hydraulic model for thermal design of oil power transformers," IEEE Trans. Power Del., vol. 25, no. 2, pp. 790–802, Apr. 2010

[2] Churchill, S. W., and H. H. S. Chu, "Correlating Equations for Laminar and Turbulent Free Convection from a Vertical Plate," *International, Journal of Heat Mass Transfer,*vol 18.1323p , 1975.

[3] Elenbaas, W., "Heat Dissipation of Parrallel Plates by Free Convection," *Physica* ,9,1 ,1942.

[4] Bar-Cohen, A., and W. M. Rohsenow "Thermally Optimum Spacing of Vertical Natural Convection Cooled, Parallel Plates, " *Journal of Heat transfer,*106,116 , 1984.

[5] Oliver, A. J., 1980, "Estimation of transformer winding temperatures and coolant flows using a general network method", *IEE Proc., Part C*, vol. 127, no. 6, pp. 395-405, 1980.

[6] FLUENT 6.3 Tutorial Guide Volume, Fluent Incorporated, Centerra Resource Park, 10, Cavendish Court, Lebanon, NH 03766, 2006.