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CFD ANALYSIS OF GAS-INSULATED TRANSFORMERS

D.J. Lee, S.S. Seol, I.S. Park, J.H. Kim, S.B. Shin, and J.H. Woo
Hyundai Heavy Industries Co. Ltd.
1, Cheonha-dong, Dong-ku, Ulsan, 682-792 ,Republic of Korea
Tel. 82-52-230-6188, Fax. 82-52-250-9578
einstein@hhi.co.kr

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ABSTRACT

A thermal design of transformers has been performed using an empirical formula. In order to reduce the developing cost and time, CFD analysis is used in thermal design process for gas-insulated transformers. We calculated the pressure loss of coolant and the temperature rise of winding with empirical formulas and CFD analysis. Also, we constructed some real machines and compared the analytic results with the experimental data. The comparison shows a good agreement between the CFD calculations and experimental results.

INTRODUCTION

Today, electric power demand in cities has been continually increased. To save the transmission cost of electricity, transformer substations have been built in urban regions. But it is difficult to find areas to install a transformer substation in urban region, because of the people's hatred for those dangerous electric plants. So transformer substations have usually being installed inside a building or a basement.

Because an oil type transformer has possibilities bringing to a big disaster such as fire or explosion, it is inappropriate as an urban transformer. Therefore, gas-insulated transformers using SF_6 gas with non-flammable and non-explosive natures were developed.

Gas type transformers also have other advantages such as compact installation space and simplification of facilities. On the other hand, gas type transformers have a poorer cooling performance than oil type due to its small heat capacity and thermal conductivity. To compensate for these defects, various studies have being conducted in the fields of gas type transformers in recent years[1].

Under all circumstances, the temperature of windings must be kept below the maximum permissible temperature to maintain reliability and prolonged durability of the gas type transformer. In the design process, the accurate prediction for the winding temperature is very important in the face of determining the adequate capacity of cooling system[2].

HHI gas type transformers have been designed using the empirical formula set and manufactured after the validation through an experimental model test. The model test process is required to guarantee a reliability of product but very expensive and laborious. In this study, we try to reduce the cost of the iterative trial and error course by adding the CFD analysis process between the design and model test processes. For this purpose we established the CFD model for gas type transformer and compared the simulated and hand-calculated (empirical formula) results to experimental data.

In this paper, the results for the flow rate distribution of coolant into each channel (magnetic core, TV, LV, HV, and Tap) of gas-insulated transformer and the temperature rise of windings under the given pressure loss conditions are obtained by empirical formula and CFD analysis. Also, the tested results for two real transformers (development type and commercial type) are included. The comparisons for each result are discussed.

NOMENCLATURE

A : surface area [m^2]
Cv : specific heat capacity of SF_6 gas [J/kg·K]
De : equivalent diameter of cooling duct section [m]
f : friction factor [-]
h : heat transfer coefficient, [$W/m^2 \cdot K$]
Nu : Nusselt number [-]
P : power loss at winding, [W]

Pr : Prandtl number [-]
$\triangle$p : pressure drop [Pa]
q : heat flux surface density [W/m^2]
Q : SF$_6$ gas flow rate [m^3/hr]
Re : Reynolds number [-]
V : velocity [m/s]

Greek Letters

ρ : SF$_6$ gas density [kg/m^3]
δ : insulation thickness [mm]
λ : heat conductivity [W/m·K]

Subscripts

gas : SF$_6$ gas
w : winding
i : coolant channel

EXPERIMENTS AND NUMERICAL METHODS

The configuration of gas-insulated transformer is shown in Fig. 1. The transformer consists of the main part that changes voltage, and heat exchanger that controls the coolant temperature. The main part is composed of magnetic cores, windings, and insulations, etc. The coolant, SF$_6$ gas, makes the temperature in the transformer stay below a specific value by removing heat generated at the magnetic cores and windings.

The coolant of the transformer flows through magnetic cores, TV winding, LV winding, HV winding and TAP winding, respectively. The geometry of the coolant channel and the coolant flow passage in the transformer are shown in Fig. 2. Empirical formulas applied to find out the pressure loss of coolant channels and the temperature rise of the winding are

$$Q = \frac{P}{C_v \rho \, \Delta t_{gas}} \tag{1}$$

$$\Delta P_i = f \, \frac{\rho V_i^{\,2}}{2} = f \left(\frac{\rho}{2 A_i^{\,2}} \right) Q_i^{\,2} \tag{2}$$

$$Q = \sum Q_i \tag{3}$$

$$\Delta t_w = \frac{q \delta \times 10^{-3}}{2 \lambda} \tag{4}$$

$$Nu = 0.021 \mathrm{Re}^{0.8} \, \mathrm{Pr}^{0.43} = \frac{h_{gas} De}{\lambda} \tag{5}$$

Experiments are carried out on the transformers. The temperatures of coolant at the inlet and outlet of the transformer are measured by K-type thermocouple with 0.05 °C precision. The total flow rate of coolant is governed by the performance of the fan installed. The flow rates of coolant in each channel cannot be measured because the flow meter cannot be installed due to the complicated structure of transformer. The heat losses at each winding are calculated by measuring electric power loss of the transformer.

Numerical analysis of flow field is performed using a commercial CFD package, Fluent. All simulations are performed using a three-dimensional, structured grid with Cartesian coordinates. The flow fields for the steady state, three-dimensional, incompressible, and turbulent flow are analyzed. In order to solve the flow fields, the conservation equations for mass, momentum, energy, and turbulent properties are selected as the governing equations. The standard k-ε model is applied to simulate the turbulent flow.

The computational domain of the transformer used in this study is modeled as shown in Fig. 3. The computational domain, a quarter of whole flow field, is sufficient to investigate the flow characteristics due to its symmetry. Two million cells are used in whole domain.

RESULTS AND DISCUSSIONS

The total coolant flow rate is calculated by equation (1). The coolant inlet and outlet temperatures are given in table 1 as the design conditions. The heat losses of the windings are tabulated in table 2. In this case, the required flow rate of coolant is 1806 m^3/hr. Table 3 shows the properties of the coolant and insulation applied to the empirical formula and CFD analysis.

We can express the pressure losses in each coolant channel as equation (6).

$$\Delta P = \Delta P_m = \Delta P_{TV} = \Delta P_{LV} = \Delta P_{HV} = \Delta P_{m1} = \Delta P_{m2} \tag{6}$$

For calculating the pressure losses and flow rates of each coolant channel, the pressure losses are assumed.

From equation (2), we can obtain the coolant flow rates through magnetic cores, TV winding, LV winding, HV winding and TAP winding, respectively. A friction factor, *f*, in equation (2) follows the HHI's design standard.

The flow rates vs. the pressure losses of the coolant at each channel are shown in Fig. 4.

The total coolant flow rate is the sum of all coolant flow rates. In order to adjust the sum of all coolant flow rates to 1806 m^3/hr, we calculate equation (2) iteratively for the various pressure drops. The results are summarized in table 4. The pressure drop, 1735 Pa is suitable to this case.

The parts of magnetic core with complex coolant paths are excluded in CFD analysis. Since the magnetic core parts generate much less thermal energy than others and are completely insulated by insulation, they can be assumed to be thermally independent components. The coolant flow rate, 1618.5 m^3/hr, except the flow rates through the magnetic cores in table 4 is applied to CFD analysis.

The flow rate distribution through each coolant path calculated by empirical formula and CFD analysis is shown in table 5. The result shows a large different flow rate for TV winding. It can be considered due to the assumption of same pressure drop at each coolant channel in the empirical formula. In real facility, the coolant is provided to each channel from a main pipe, and the pressures at the inlet of each channel have different values.

The measuring data of the temperature rise at each winding are compared with the results from the empirical formula and CFD analysis in table 6. The permissible winding temperature is 160 ^oC and all results satisfy that condition. The temperature rises predicted by CFD analysis are closer to the experimental results than the results using the empirical formula. The differences in the temperature rise between experimental and CFD analysis results are less 10 %.

CONCLUSIONS

For a gas-insulated transformer, we calculated the flow rate distribution of coolant into each channel for the given pressure loss and the temperature rises of windings using empirical formulas. CFD analysis was simultaneously conducted to get the coolant flow rate distributions, the pressure drops, and the temperature rises at each winding. The test results of real facilities were compared with the results calculated using the CFD analysis and the empirical formula. The empirical formula predicted very large flow rate at TV winding compared to CFD analysis. Although we could not measure the flow rates at each channel, the temperature rises were gauged with highly accurate thermometry. The results of CFD analysis showed good agreement with the measuring data.

By analyzing the thermal flow fields of transformer with CFD before the model test process, we could predict more accurately the cooling performance of transformer. Through the feedback of the results to design stage and the appropriate design change, we could improve the thermal performance of transformer.

REFERENCES

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[2] Nakadate, M., Toda, K., Sato, K., Biswas, D., Nakagawa, C., and Yanari, T., 1996, "Gas Cooling Performance in Disc Winding of Large-Capacity Gas-Insulated Transformer", IEEE Transactions on Power Delivery, **11**, pp. 903-908.

Table 1 Coolant and cooling water design temperature

	Temperature [^oC]
Coolant inlet	74.8
Coolant outlet	91
Cooling water	35

Table 2 Heat losses of windings

	Heat loss of winding	
	KW	kW/m^3
TV	9.7	134.2
LV	20.9	200.5
	27.1	226.2
HV	76.5	173.0
TAP	11.2	157.5

Table 3 Properties of coolant and insulation

Coolant, SF_6	Density [kg/m^3]	22.3
	Heat capacity [J/kg ^oC]	756.2
	Heat conductivity [W/m ^oC]	1.780×10^{-2}
	Viscosity [kg/m s]	1.886×10^{-5}
Insulation	Heat conductivity [W/m ^oC]	0.24
	Thickness [mm]	0.6~1.2

Table 4 Coolant flow rates through each channel at various pressure drops

Pressure drop [Pa]	Coolant flow rate [m^3/hr]						
	Q_m	Q_{TV}	Q_{LV}	Q_{HV}	Q_{m1}	Q_{m2}	Q_{Total}
1400	89	115	575	765	40	40	1624
1735	99.5	127.5	643	848	44	44	1806
1800	102	130	657	862	45	45	1841

Table 5 Flow rate distribution in the transformer

	Empirical Formula [m^3/hr]	CFD analysis [m^3/hr]	Error [%]
TV	127.5	92.3	27.6
LV	643	598.3	7
HV	848	927.9	8.6
Total	1618.5	1618.5	-

Table 6 Comparison of winding temperature rise data in the transformer

	Winding temperature rise [^{o}C]			
	Experiment (Development)	Experiment (Commercial)	Empirical Formula	CFD analysis
TV	129	127	105	119.7
LV	141	149	113	129.3
HV	119	126	107	112.3

Figure 1 Gas-insulated transformer

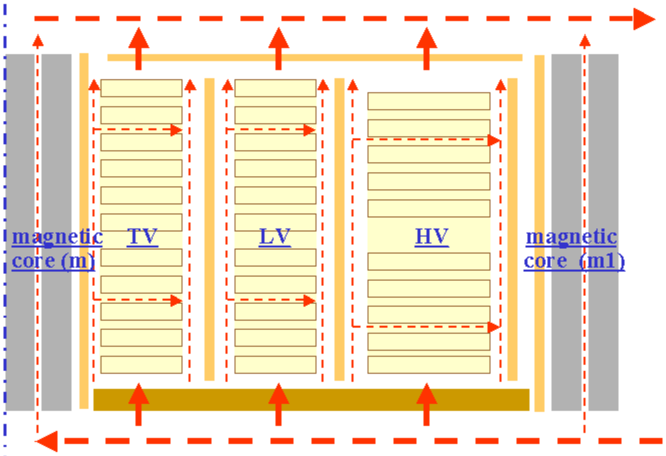

Figure 2 Geometry of the coolant channel and the flow passage in the transformer

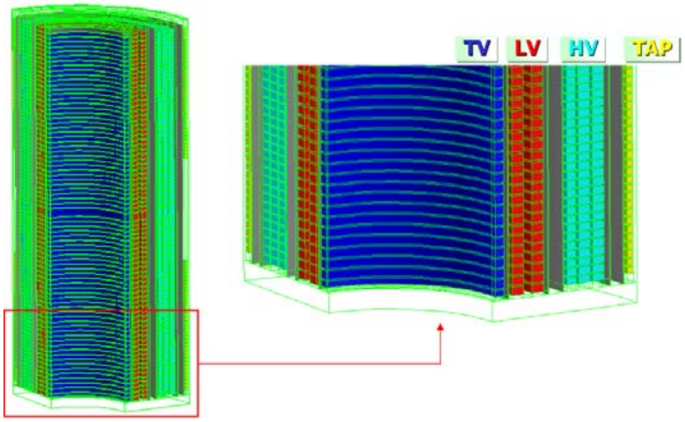

Figure 3 Computational domain of gas-insulated transformer

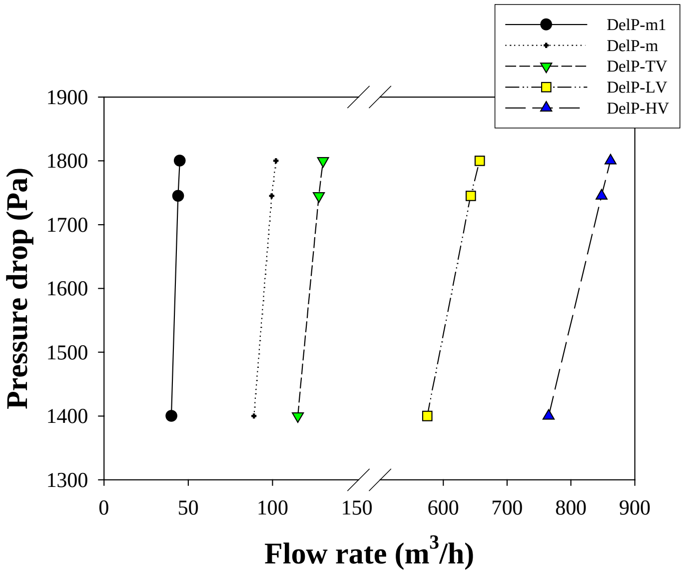

Figure 4 Distribution of coolant flow rates to TV, LV, HV windings and magnetic cores