A Numerical Analysis for the Performance Improvement of a Channel Heat Exchanger

Byung-Hyun Jang*, Byeong-Ha Jeon*, Kwon-Hee Lee*†
* Department of Mechanical Engineering
Dong-A University
Busan 604-714, KOREA
leekh@dau.ac.kr

Abstract: The shell and tube heat exchanger is used throughout various industries because of its inexpensive cost and handiness when it comes to maintenance. There are several thermal design factors that are to be taken into account when designing the tubes in the shell and tube heat exchangers. They are tube diameter, tube length, number of tubes, number of baffles, etc. The characteristics of flow and heat transfer within the shell are not simple. This paper conducted numerical analysis to predict the characteristics of difference in temperature and pressure drop, which are the performances of channel heat exchanger. In this study, the diameter of tube, the number of tubes and the number of baffles are considered as the design factors. Also, factors that affect the performances of channel heat exchanger were selected through design of experiment procedures.

Key-Words: Heat Exchanger, Fluid Analysis, Heat Transfer, Design of Experiment, Shell, Tube

1. Introduction

Heat exchanger is a generic term for all the devices that transfers heat from fluid of high temperature to fluid of cooler temperature. The heat exchanger is used from boiler for generator, car radiator and home refrigerators to air conditioners. In other words, heat exchanger is a device that transfers heat using the characteristics of conduction and convention, conducting heat exchange between fluids after separating fluids of different temperatures from solid wall.

As for the shell and tube exchanger, the structure is simple and easy to produce. Also, maintenance is easy and can be designed in various sizes. Moreover, it has the merit of being operable under a wide range of temperature and pressure. In general, shell and tube heat exchangers are used for high pressure facilities with pressures greater than 3,000 kPa and temperatures greater than 260 °C. The shell and tube exchanger among the total industrial heat exchangers represents by 60 % [1-2].

Several design features must be taken into account in the design process in design process of shell and tube exchanger. They are determined, considering the responses of difference in temperature and pressure drop. Thus, it is necessary to predict or calculate those responses in the design process.

There is limit in investigating the complex fluid and heat exchange phenomenon in the shell. In order to enhance the thermal capabilities of heat exchanger, it is crucial to increase the heat-transfer surface. However, the difference in temperature within heat exchanger prompts decrease in pressure, necessitating attention during design process. In the existing fields, simple theoretical and empirical formulas provided by TEMA (Tubular Exchanger Manufacturers Association)[3] Standard are used to predict capabilities of simple heat exchangers. However, it is impossible to apply such formulas to all types of heat exchangers currently under production.

In this research, through ANSYS CFX[4] based on FVM, using the shape function of FEM, heat transfer and fluid flow analysis of channel heat exchanger was conducted. In the existing numerical analysis for shell and tube heat exchanger using FLUNT [5], design variables were selected as sealing strip and then optimized model was suggested after trial and error using the CFD code. Moreover, Suk-jin Ou and Gwan-soo Lee [6] conducted shape optimization of parallel heat exchangers using RSM; Guo and Xu [7] conducted optimization using theoretical equation and DNA algorithms. On the other side, this research intends to evaluate the effects of key variables in the early phase of channel
heat exchanger, which is previous to the optimization phase.

In this paper, cooling heat exchanger of lubricants used for water pump bearings was looked into. First, preliminary design was complete then the temperature and pressure in the inlet and outlet were calculated using numerical analysis. Also, the number and the diameter of tubes and the number of baffles for channel shell and tube type heat exchanger were selected as design variables. And then evaluation was conducted on the effects of design variables in temperature difference and pressure drop. This process was performed based on the DOE (design of experiments) using orthogonal array. In this process, the magnitude of effects was calculated through ANOVA (analysis of variable) of temperature difference and pressure drop.

2. Preliminary design for oil cooler heat exchanger

The heat exchanger of this research is the oil cooler heat exchanger used for the sliding bearing for the feed water pumps in generators. Such heat exchanger is used to cool oil that served as lubricants by injecting coolants. In this heat exchanger, oil which serves as lubricant is injected into shell. On the contrary, cooling water is put into tube.

Shell and tube heat exchanger can be used under various environments and is not limited by length, number and diameter of tubes. The design of such exchanger is resolved into A, B, C, D type according to front end head type; E, F, G, H, J, K, X type according to different shell types; and L, M, N, P, S, T, U, W type according to rear end head type, all based on TEMA standard [3]. In the preliminary design, BEM type was selected. Here, B means bonnet type, E means single pass cell and M, fixed tube sheet.

Channel exchanger is suited for handling large quantity of low-middle pressured fluid. Unlike U-tube types, by securing space that allows inflow and outflow of fluids in tubes through channels, flow area of the tube is secured. The preliminary model of the oil cooler heat exchanger is depicted in Fig. 1.

The tube is made from aluminum with the outside diameter of 8mm and inside 7mm. The number of tube is 16, and in order to conserve time for numerical analysis the model has been simplified during the preliminary design phase. The shell was made from steel with diameter of 90mm with total length of 300mm. The diameter for both the inlet and outlet of the shell is 10mm inside the shell; there are 3 baffles to adjust the fluid flow of the shell. The material property of the tube is depicted in Table 1. It has been modeled that active heat exchange can take place by increasing the time when the fluid come contact into the tube using baffle.

2.1 Initial and boundary condition for heat flow analysis

As for the initial design of the heat exchanger, flow field was created into tetrahedron element using CFX mesh under ANSYS Workbench environment. Heat transfer and fluid flow analysis was conducted under steady state and incompressible and turbulent flow environments. Standard k-ε model installed in CFX was chosen for the turbulent model. The governing equations for the numerical analysis are continuity equation, Navier-Stokes equation and energy equation.

At the entry of tube of oil cooler heat exchanger, 305K of coolants flows in at 1.97kg/s and travels to the exit of the tube to cause heat exchange. On the other side, at the entry of shell, 338K of high-temperature lubricants flows in at 1.0kg/s and then flows out of the exit, causing heat exchange. In order to facilitate heat exchange through interaction between two fluids, the solid domain

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Table 1 Material properties of aluminum

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th>Specific Heat Capacity</th>
<th>Thermal Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell</td>
<td>2.702kg/m³</td>
<td>9.03×10³ J/kg·K</td>
<td>237W/mK</td>
</tr>
<tr>
<td>Tube</td>
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Table 2 Boundary and initial conditions

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<th>Tube</th>
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</thead>
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<tr>
<td>Inlet</td>
<td>Atmospheric</td>
<td>Atmospheric</td>
</tr>
<tr>
<td>(Temp)</td>
<td>Atmosphere</td>
<td>Pressure</td>
</tr>
<tr>
<td></td>
<td>1kg/s (338K)</td>
<td>1.97kg/s (305K)</td>
</tr>
<tr>
<td>Outlet</td>
<td></td>
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</tr>
</tbody>
</table>

Table 3 Material properties of VG20

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th>Specific Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>VG320</td>
<td>921 kg/m³</td>
<td>1800J/kg°C</td>
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</table>
and the gap of inside surface of the tube was given by the condition of INTERFACE supported by CFX. Also, by implementing INTERFACE condition between the outside surface and the fluid field of shell, interaction among heat exchanges was enabled. ANSYS CFX was used for heat transfer and fluid flow analysis and the initial and boundary conditions are listed in the Table 2. The material properties of lubricant VG20 is represented in Table 3.

2.2 Result of heat transfer and fluid flow analysis
For the assessment of thermal capabilities of shell and tube heat exchanger, the temperature difference and pressure drop of fluids must be considered. The results of temperature difference and pressure drop of fluids was visualized using the postprocessor of ANSYS CFX.

First, as for the analysis of the shell’s fluid flow, it was confirmed that turbulence occurred where the flow came into contact with baffle. There is a great difference between the free end and the fixed end of the baffle-this is a sudden shape change that caused by bottleneck effect at the contact point between the fluid and baffle; the turbulence is developed by a rapid change in speed.

The fluid flow affects the capabilities of heat exchanges. In the free end of the baffle, as there is no sudden change in the shape, flow is not relatively affected, so the speed of the fluid flow is remaining constant. As the result of such, there are no significant temperature differences in the free end of the baffle. However, in the fixed end of the baffle, the speed of the flow became dramatically fast. Thus, the contact surface with tube in the flow was increased under the effects of the turbulence at the fixed end of baffle; it has been confirmed that such causes significant temperature differences through the calculation.

According to the calculation done on the shell & tube heat exchanger, the temperature difference between the entry and the exit of the shell was approximately 12°C. Not only that but also the pressure drop was affected by the baffle. As the baffle caused bottleneck effect, such effect disrupted the flow of fluids in the free end of the baffle, causing the pressure to be high in the free end of the baffle and the pressure to be low in the fixed end of the baffle according to the calculation results. It has been calculated that the pressure difference between the entry and the exit of the shell to be 971Pa. The result of the analysis is listed in Fig. 2 and Fig.3

3. Evaluation on the effects of design variables using design of experiments
DOE means the planning direction of experiments. It is the design of any information-gathering exercises where variation exists, whether under the full control of the experimenter or not. Also it involves with designs regarding how the experiments will be conducted, how the data will be gathered and how should the data be statistically analyzed so as much information can be derived from the least number of experiments.

As for the design of experiments for the channel heat exchanger model used in this paper, design variables and levels were selected three each and also
an orthogonal array was utilized.

The variables and the levels are listed in Table 4. As for the factors, A represents the number of tubes, B the number of baffle and C the diameter of tube respectively.

### 3.1 DOE using orthogonal array

When the number of three design variables and levels selected three numbers respectively, it means $3^3$ factorial experiments leading to 27 experiments. But in order to decrease the number of experiments and gain the effect of full factorial experiment, experiments were conducted using $L_9(3^4)$ tables of orthogonal arrays.

Experiments can be conducted using discrete design value of interest in use of such table, enabling application in the discrete design space. Therefore, results can be derived conducting only 9 experiments by utilizing this table. The first and the second column of $L_9$ table are where independent variables can be placed. The third and the fourth column are the columns where interaction effects with the variables in the first and the second row will take place. Interaction among each variable is existent but it is not possible to judge that the interaction should be regarded or not before the experiment. Therefore, in this paper, the interaction among each variable was discounted, and the distribution of each design variable is depicted in Table 5.

### 3.2 Experiment result analysis and ANOVA

A total of 9 models were established based on the factors and levels decided by the table and the numerical analysis was conducted under the same aforementioned condition. As for the output data of the table, the result was deduced with focus on the temperature difference and pressure drop as the performance that influence the thermal capabilities of heat exchangers. The result is shown in the Table 6 and 7.

As it was difficult to make analysis of the effects the factors from the table have on the capabilities solely based on the result of numerical analysis data, ANOVA which numerically predicts such effects. The ANOVA for each data is listed in Table. 8 to 11. First, for the ANOVA on the temperature difference of shell, the factor that affect the temperature is significantly subject to the number of tubes but is not as affected by the number of the baffles and the diameter of the tubes.

With the pressure drop of shell, the number of the baffle heavily affects the pressure drop but the number of tubes doesn’t.

According to the ANOVA on the factors to tube temperature and pressure, it was confirmed that the

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**Table 4 Design variable and its level**

<table>
<thead>
<tr>
<th>Level</th>
<th>Number of Tube</th>
<th>Number of Baffle</th>
<th>Tube Diameter(mm)</th>
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<tr>
<td>1</td>
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<td>3</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>5</td>
<td>7</td>
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<tr>
<td>3</td>
<td>32</td>
<td>7</td>
<td>8</td>
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**Table 5 $L_9(3^4)$ Orthogonal Array**

<table>
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<tr>
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</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
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<td>2</td>
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<td>3</td>
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<td>8</td>
<td>3</td>
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<tr>
<td>9</td>
<td>3</td>
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</table>

**Table 6 Temperature difference in shell**

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Temperature Difference (°C)</th>
<th>Pressure Drop (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.0</td>
<td>2.7</td>
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<tr>
<td>2</td>
<td>13.2</td>
<td>4.0</td>
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<td>3</td>
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<td>16.8</td>
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<td>7</td>
<td>13.6</td>
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<tr>
<td>9</td>
<td>14.6</td>
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**Table 7 Temperature difference in tube**

<table>
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<tr>
<td>9</td>
<td>3.3</td>
<td>4.1</td>
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tube pressure and temperature are not affected by three factors.

4. Conclusion
In this paper, numerical analysis on shell and tube heat exchanger used as cooling device was performed. According to the numerical analysis, it was confirmed that the existence of baffle affected the pressure drop and the temperature difference dramatically. The DOE using L₉(3⁴) orthogonal array was performed to select the dominant design variable. Based on the experiment results, ANOVA table was made.

1) The factor that affects the temperature difference in shell is significantly subject to the number of tubes but is not as affected by the diameter of the tubes.
2) With the pressure drop of shell, the number of baffles heavily affects the pressure drop but the number of tubes doesn’t.
3) For future study, the optimized value of each design variable must be decided and the credibility of such values must be evaluated through verification experiments.

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References:

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<td>V</td>
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<td>(F(0.05))</td>
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