Design optimization of a heat exchanger in PCCS using LMTD method

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1. Introduction

After the Fukushima accident, next generation nuclear power plants use passive safety systems. The passive system represents that it does not rely on external electric power and uses natural force only when the nuclear power plant accidents occur. APR+ adopts both active and passive safety systems, so it is called as a hybrid nuclear power plant. A safety injection system, a shutdown system and a containment spray system are included in the active safety system. For the passive safety system, a passive fluidic device, a passive autocatalytic ignitor and a passive auxiliary feed water system are considered. One of the important passive safety systems is a passive containment cooling system (PCCS). In order to prevent release of the radioactive material into the environment, the containment has to be efficiently cooled to decrease the pressure and temperature. Heat exchangers can be used to remove decay heat in the containment without external power. A shell and tube type heat exchanger is considered and the heat exchanger is connected to the passive containment cooling tank (PCCT). The PCCT is located in the auxiliary building and the heat exchanger is in the containment as shown in Fig.1. Decay heat is transferred to the PCCT from the containment. As the passive safety system does not use external power, natural convection is dominant to cool the containment. Therefore, the heat removal ability is depend on the design of the heat exchanger. In this paper, a design optimization algorithm of the heat exchanger is proposed.

2. Methods and Results

In this section, a design optimization procedure is described. For the heat exchanger optimization, length, diameter, number of tubes, et al. can be considered as design variables. Based on the prototype of the PCCS heat exchanger [1], the variation of the variables are defined.

2.1 Heat exchanger model description

Fig.1 shows configurations of the vertical type heat exchanger. Sizes of the heat exchanger components are obtained from [1]. In [1], one bundle has 252 tubes which are connected to a header. Length of tubes is 5000-6000mm and the outer diameter and the thickness of the tube are 31.8mm and 3.05mm, respectively. Area of tubes is dominant over the area of other components. We assume the heat transfer takes place only through tubes.

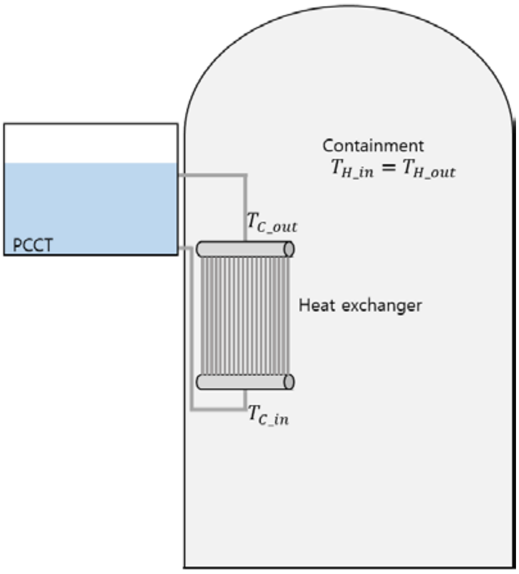

Fig. 1. A shell and tube type heat exchanger in the containment

2.2 Heat exchanger analysis

The heat exchanger is analyzed with the Logarithmic Mean Temperature Difference (LMTD) method. In order to simplify the heat transfer analysis, following assumptions are considered. There are no phase changes in both tubes and a shell. The heat exchanger has a steady state condition. Flow and thermal conditions are fully developed. Each tube has equal water distribution. Material properties are obtained from the NIST Reference Fluid Thermodynamic and Transport Property (REFPROP). Hot fluid exists on the shell side which is a containment. Cold fluid passes tubes. The total heat transfer rate is given by

$$\dot{Q} = \dot{m} c_p \Delta T \qquad [1]$$

The inlet and outlet temperature of the shell is almost same. The heat transfer occurs in a combined mode including inner convection, conduction and outer convection. For this combined mode, the overall heat transfer coefficient can be represented as follows:

$$UA = \frac{n}{\frac{1}{h_i A_i} + \frac{1}{2\pi K L}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_o A_o}} \qquad [2]$$

where

h_i : convective heat transfer coefficient for the tube interior
h_o : convective heat transfer coefficient for the tube exterior
r_i : inner radius of the tube
r_o : outer radius of the tube
A_i : inner area of the tube
A_o : outer area of the tube
K : thermal conductivity of the tube
L : tube length
n : number of the tubes for one module

The total heat transfer rate also can be obtained from the LMTD method. The heat transfer rate also can be written as follows using the overall heat transfer rate

$$\dot{Q} = UA\Delta T_m \qquad [3]$$

where

$$\Delta T_m \equiv \frac{(T_{H\_out} - T_{C\_out}) - (T_{H\_in} - T_{C\_in})}{\ln[(T_{H\ out} - T_{C\ out})/(T_{H\ in} - T_{C\ in})]}$$

The outlet temperature of the tube can be predicted by solving the nonlinear equation with iterative procedures.

2.3 Design optimization procedure

As the heat exchanger has many design variables, various combinations with design variables can be produced. All different models can not be made practically. Optimization schemes are needed to obtain the optimized design efficiently. At first, number of tubes, entrance temperature of the cooling water and tubes length are considered as design variables. Each variable has two levels. Sample points for the surrogate model can be obtained from the orthogonal array table. For the optimization tool, the genetic algorithm (GA) is used for the surrogate model. Table.1 shows arrangement of three parameters.

Table 1: Orthogonal array table

Experiment number	Num. of tubes	$T_{C\ in}$	Tube length
1	252	58.3	6000
2	252	56	6100
3	258	58.3	6100
4	258	56	6000

The optimization result is that the number of tubes is 252, $T_{C\ in}$ is 56℃ and the tube length is 6100mm. In order to verify the optimization result, all combination experiments are calculated. The result is the same as the previous optimization result.

3. Conclusions

The PCCS heat exchanger requires high heat removal performance to prevent the pressurization of the containment when the nuclear power plant accidents occur. As the heat exchanger has a big size and is composed of various components, it is difficult to do experiments for all the design cases. In this paper, the design optimization scheme for the PCCS heat exchanger is introduced and verified with simple examples.

REFERENCES

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