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〈Technical Note〉

Parametric Study on Design Factors of the Shutdown Cooling Heat Exchanger Using the Taguchi Method

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Abstract

The Taguchi method was applied to investigate the effect of design factors on the performance of the shutdown cooling heat exchanger in the SMART-P. This method provided the simulation matrix for the KDESCENT program and an efficient tool for analyzing the simulation results. Levels of the design factors were selected by the effectiveness-NTU method. From 18 runs with the KDESCENT program, it was found that the performance of the system was greatly influenced by the inlet temperature at the shell side and the mass flow rate of the reactor coolant at the tube side. After applying the Taguchi method, we identified the important design factor that should be controlled and designed carefully. This method provides an efficient way to estimate the influence of each design factor on a system performance.

Key Words : taguchi method, shutdown cooling system, heat exchanger, design factor, KDESCENT

1. Introduction

The shutdown cooling system (SCS) of SMART-P (System-integrated Modular Advanced ReacTor - Prototype) reduces the temperature of the reactor coolant from the hot shutdown temperature to the refueling temperature and afterwards maintains the refueling temperature. The shutdown cooling system has a shell-and-tube heat exchanger. In the heat exchanger, the reactor coolant flows through the tubes and cools down by transferring heat to the cooling water at the shell side.

The shutdown cooling heat exchanger (SDCHX) has design parameters that are determined to meet operational requirements of the SCS. Each design parameter has a different degree of influence on the system performance and it is difficult to measure the magnitude of influence because of interactions between design parameters of the system that is nonlinear and multivariable. The effect of the design parameters on the system performance may be investigated with the full factorial combinations of all factors. This approach needs a lot of time and costs, and is sometimes impossible to carry out. To overcome this difficulty and to analyze the SDCHX systematically, the Taguchi method was applied to this study.

The Taguchi method [1,2] has been applied to various industries, such as electronics and mechanics, after Dr. Genichi Taguchi utilized his method to improve Japan' s telecommunications system in 1949. In diverse industries, his method was proved to be so effective in reducing cycle time and rework in process optimizations and system designs. In addition, this method provides a systematic and efficient way to design an experimental study. For example, Wang and Pan [3] applied this method to a study on the two-phase natural circulation loop, which is a complex multivariable system with high nonlinearity, and found the condition that improves the stability of the system.

The Taguchi method uses the mathematical tool called the orthogonal array to study a complex system with a relatively small number of experiments. The introduction of the orthogonal array is a major factor for the reduction of the number of experiments. The orthogonal array is a method of organizing experiments with a fraction of the full combinations. The orthogonal array is constructed so that each factor is given the same weight in the experiment. As a result, the effect of it can be assessed independently of the effects of the other factors. Examples of the standard orthogonal array are given in Phadke' s book [4].

To select the orthogonal array among the standard orthogonal array, it is required to choose design factors and their levels in the shutdown cooling heat exchanger. The seven design factors are chosen from the parameters that are related to the performance of SDCHX. The level of some design factors is determined by applying the effectiveness-NTU method to the refueling operation period. To evaluate the effect of the design factors on the system performance, the value considered is the elapsed time from the beginning of the shutdown operation to the time when the temperature of the reactor coolant become 50℃. The short elapsed time means a high performance of SDCHX for a certain condition. This value is obtained by the KDESCENT code, which simulates the shutdown cooling operation. The simulation matrix is provided by the orthogonal array. In Chapter 2, the application of the effectiveness-NTU method, which determines the level of design factors, will be discussed and analysis of the contribution of design factors on the SDCHX performance will be provided in Chapter 3. Conclusion will be made in Chapter 4.

2. Effectiveness-NTU Method

The operating condition for the shutdown cooling heat exchanger of SMART-P is estimated by the Effectiveness-NTU method. This condition is the basis for the input conditions of the Taguchi method, which will be performed with the KDESCENT code, in the next chapter.

2.1. Computational Condition

The SDCHX of SMART-P reduces the temperature of the reactor coolant from the hot shutdown temperature to the refueling temperature and maintains the refueling temperature. The second function of SDCHX is considered in this chapter. The operating conditions of SDCHX are assumed to be in the steady state after the reactor coolant is cooled down to the refueling temperature. During the refueling operation, the SDCHX removes decay heat and sensible heat. According to the decay curve, the decay fraction is 0.40% after 100,000 seconds and 0.19% after 1,000,000 seconds. The decay heat, Q_{decay}, is calculated from the fact that

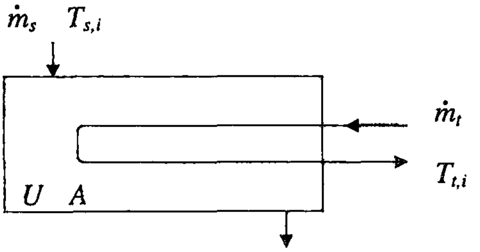


Fig. 1. Schematic Diagram of the Shutdown Cooling Heat Exchanger

the fraction after 5 days is 0.25%.

$$Q_{decay} = 65MWt \times 0.25\% = 0.16 \times 10^6 Wt \tag{1}$$

The amount of heat to be removed by the heat exchanger is assumed to be 0.18MWt, which included a 10% margin for the pump heat and the sensible heat of the reactor vessel.

Figure 1 is schematic diagram of the shutdown cooling heat exchanger. The reactor coolant flows through the tube side and the cooling water from the component cooling system through to the shell side. The inlet temperature of the shell side, $T_{s,i}$, and the inlet temperature of the tubes, $T_{t,i}$, are 35 and 50℃, respectively. The overall heat transfer coefficient of SDCHX was assumed to be 2000 W/m^2 · ℃. The overall heat transfer coefficients of the exchangers in commercial nuclear power plants are in the range of 1500~2200 W/ m^2 · ℃. Working fluids are treated as water at both sides of the heat exchanger. The density and the specific heat are assumed as 1000 kg/m^3 and 4200 J/kg · ℃, respectively.

2.2. The Effectiveness -NTU Method

Under the given condition, the required heat transfer area to remove the heat of 0.18MWt for various flow rates at the tube side and the shell side of SDCHX is calculated by the effectiveness-NTU method. Heat exchangers are easily analyzed by the LMTD (Log Mean Temperature Difference) method when the temperatures of the inlet and the outlet are known. When only inlet temperatures are given, LMTD requires iterations. In this study, the known temperature conditions are only given at the inlet. We choose an alternate approach: the effectiveness-NTU (Number of transfer units) method.

In this method, the heat transfer rate is determined from the expression

$$Q = \varepsilon C_{min}(T_{h,i} - T_{c,i}) \tag{2}$$

where ε is the effectiveness, and $T_{h,i}$ and $T_{c,i}$ are the inlet temperatures of hot and cold flows, respectively. The minimum heat capacity rate, C_{min}, is the smaller of the hot and the cold fluids. We assume that the specific heats at both sides are the same. Under this assumption, Eq. (2) is rewritten as follows:

$$Q = \varepsilon C_{min}(T_{h,i} - T_{c,i}) \approx \varepsilon \dot{m}_{min} C_p (T_{t,i} - T_{s,i}) \tag{3}$$

$$Q = \varepsilon \dot{m}_{min} \times 4200 \times (50-35) = 0.063 \times 10^6 \times \varepsilon \dot{m}_{min} \tag{4}$$

$$\varepsilon \dot{m}_{min} = \frac{0.18 \times 10^6}{0.063 \times 10^6} = 2.86 \tag{5}$$

where $\dot{m}_{min}$ is the minimum value between the flow rate at the tubes, $\dot{m}_t$, and at the shell, $\dot{m}_s$. The effectiveness of a shell-tube type heat exchanger that has one shell and two tubes is given as[5]:

$$\varepsilon = 2\left(1 + C_r + \sqrt{1+C_r^2} \times \frac{1+\exp\left(-NTU\sqrt{1+C_r^2}\right)}{1-\exp\left(-NTU\sqrt{1+C_r^2}\right)}\right)^{-1} \tag{6}$$

In Eq. (6), C_r and NTU are given as follows:

$$C_r = \frac{C_{min}}{C_{max}} \tag{7}$$

$$NTU = \frac{UA}{C_{min}} \approx \frac{UA}{\dot{m}_{min} C_p} = \frac{2.0\times10^3 A}{4200\,\dot{m}_{min}} \approx 0.476\frac{A}{\dot{m}_{min}} \tag{8}$$

where the heat transfer area is computed from Eqs. (5) and (6) with the specified $\dot{m}_t$ and $\dot{m}_s$.

Figure 2 shows the required heat transfer area for the given flow rates at the tube and shell side. The required area decreases as the flow rate from the component cooling system increases. The rate of decrease reduces as the flow rate at the shell increases, and the area remains the same above 15kg/s of the shell side flow rate. As the flow rate at the tubes increases, the required area tends to decreases. In Figure 2 two distinctive regions are shown: less than 6 kg/s of the tube side flow rate and the above. In the first region, a small change of tube side flow rate results in a large variation of the required heat transfer area while in the second region the required area shows a negligible change. The second region is a favored design point because, in the first region, SDCHX may become incapable of removing heat with the slight reduction of tube side flow rate.

In addition to heat transfer, corrosion should be considered in the determination of the flow rates. To prevent corrosion, the velocity is limited to 3~4m/s when the inner diameter is 50mm, which is the main pipe of the system. Water flow at 4m/s of the area averaged velocity is corresponding to 7.8kg/s of mass flow rate.

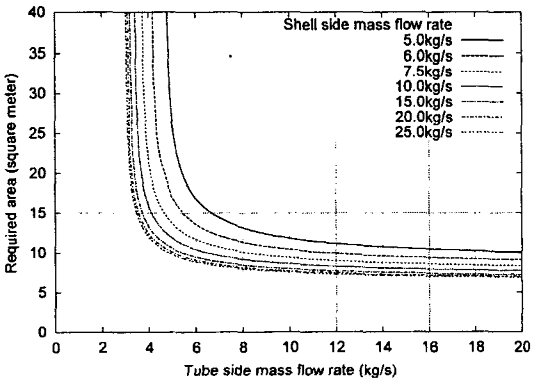


Fig. 2. Heat Transfer Area to Remove Heat of 0.18MWt at a Given Tube Side Mass Flow Rate

The effectiveness-NTU method and the limitation established by the pipe corrosion determine the levels of flow rates and the heat transfer area of the shutdown cooling heat exchanger. As a preliminary design point for the Taguchi method, 5kg/s and 7.5kg/s of the mass flow rates at the tube side and the shell side and, 15m^2 of the heat transfer area are selected.

3. Comparisons the Effect of Design Factors by the Taguchi Method

3.1. KDESCENT Program

In the previous chapter, the heat transfer area that is required to meet the system requirements at the final stage of the SCS operation was calculated. Another requirement of the system operation is the limitation on the elapsed time of the shutdown cooling operation before the reactor coolant temperature reaches the refueling temperature. Using the KDESCENT[6] code the simulation was conducted to calculate the elapsed time.

The computer code KDESCENT analyzes the shutdown cooling operation. This code calculates the heat removal rate of SDCHX by the LMTD method. According to the operation mode of SDCHX, the code adjusts the bypass flow of SDCHX and the cooldown rate of the reactor coolant. At the beginning of the operation, the high temperature difference between the tube side and the shell side may cause higher cooldown rate than the limited value, which is 41.7℃/hr for commercial reactors. In the program, the specified cooldown rate is accommodated by the adjustment of the rate of flow that bypasses the heat exchanger. Once all the reactor coolant flows through the tubes without bypass flow, the cooldown rate of the reactor coolant is calculated from the heat balance. The SCS of SMART-P consists of two trains, and each train has 100% heat removal capacity. In this study, it is assumed that only one train of the system is operating during the shutdown cooling operation.

3.2. Simulation Matrix

In the present study, we choose seven parameters as the design factors of SDCHX: The flow rate at the tube side and the shell side ($\dot{m}_t$, $\dot{m}_s$), the reactor coolant temperature at the beginning of the shutdown cooling operation ($T_{t,i}$), the inlet temperature of the cooling water at the shell side ($T_{s,i}$), the overall heat transfer coefficient (U), the heat transfer area (A), and the maximum cooldown rate of the reactor coolant system. These factors and their chosen levels are listed in Table 1.

The levels of the design factors are selected as follows. The two levels of the maximum cool down rate, 41.7 and 100°C/hr, are obtained from the limited value of 41.7°C/hr in the commercial reactors, and 100°C/hr in the design of SMART. The levels for the initial temperature of the tube side flow are 180, 200 and 220°C. The first two levels are for commercial reactors and SMART-P, and the last level is chosen to observe system behavior when the operation is started at a higher temperature than normal. The temperature levels of the component cooling water are 30, 35, and 40°C. It is assumed that the component cooling water is supplied at a constant temperature throughout the operation. The levels of the overall heat transfer coefficients are 1500, 1750, and 2000 W/m^2 · °C. The overall heat transfer coefficients may vary because of heat exchanger type and fouling effect, which is caused by the undesired accumulation of material on the heat exchanger surface, and the tube thickness. Considering the preliminary design point in Chapter 2, the levels of the heat transfer area and flow rates at both sides of the SDCHX are determined.

The L18 orthogonal array is selected for simulations to investigate the effect of the seven design factors on the operation of the shutdown cooling system. Table 2 is constructed from the L18 orthogonal array, on the basis of the levels shown in Table 1. Among the standard orthogonal

Table 1. Design Factors and Their Levels

Design Factors		Level		
		1	2	3
A	Cool down rate(°C/hr)	41.7	100	
B	Tube side initial inlet temperature (°C)	180	200	220
C	Tube side mass flow rate (kg/s)	2.5	5.0	7.5
D	Shell side inlet temperature (°C)	30	35	40
E	Shell side mass flow rate (kg/s)	5.0	7.5	10.0
F	Overall heat transfer coefficient (W/m^2 · °C)	1500	1750	2000
G	Heat transfer area (m^2)	10	15	20

Table 2. Simulation Matrix and Results

	A	B	C	D	E	F	G	t_{90}	t_{50}
1	41.7	180	2.5	30	5.0	1500	10	7.6	210.0
2	41.7	180	5.0	35	7.5	1750	15	2.5	86.3
3	41.7	180	7.5	40	10.0	2000	20	2.2	92.7
4	41.7	200	2.5	30	7.5	1750	20	4.2	97.7
5	41.7	200	5.0	35	10.0	2000	10	3.2	103.7
6	41.7	200	7.5	40	5.0	1500	15	3.4	313.7
7	41.7	220	2.5	35	5.0	2000	15	6.5	296.2
8	41.7	220	5.0	40	7.5	1500	20	3.5	259.1
9	41.7	220	7.5	30	10.0	1750	10	3.3	38.0
10	100	180	2.5	40	10.0	1750	15	5.8	473.2
11	100	180	5.0	30	5.0	2000	20	1.9	37.0
12	100	180	7.5	35	7.5	1500	10	3.0	146.3
13	100	200	2.5	35	10.0	1500	20	4.5	219.8
14	100	200	5.0	40	5.0	1750	10	4.9	434.0
15	100	200	7.5	30	7.5	2000	15	1.5	18.6
16	100	220	2.5	40	7.5	2000	10	8.0	552.1
17	100	220	5.0	30	10.0	1500	15	2.2	35.8
18	100	220	7.5	35	5.0	1750	20	2.1	64.4

arrays that are provided by Phadke[4], the L18 orthogonal array is suitable for the simulations. To conduct the full factorial simulations for this case, it is required to run about 4000 times. The orthogonal array is constructed in order that a level of a design factor experiences each level of the other design factors at the same rate. For this reason, the average effect of each level on the system can be examined.

3.3. Analysis of the Simulation Result

Eighteen cases of SCS operating conditions were simulated by KDESENT with the conditions listed in Table 2. The last two columns of the table list the results of the simulations: the elapsed time until the reactor coolant temperature reaches the temperature of cool shutdown condition 90℃ (t_{90}), and the temperature of the refueling condition 50℃ (t_{50}).

It was observed that the elapsed time t_{90} was distributed between 1.5 and 8.0 hours and t_{50} between 18.6 and 552.1 hours. Figure 3 shows an average of t_{90} for each level of the design factors. The average for each level was obtained by taking an average of the elapsed time that corresponds with the factor levels. As the inlet temperatures of the tube side and shell side of heat exchanger decrease, and as the flow rates of both sides increase, the elapsed time t_{90} decreases. As the cool down rate and the heat transfer area increase, the elapsed time decreases. It is clearly shown in the Figure 3 that the overall heat transfer coefficient has little effect on the system performance.

In the case of t_{90}, the most dominant design factor is the tube side flow rate, and the second is the heat transfer area. When the tube side flow rate is low, the entire coolant flows through the heat exchanger without bypassing it even before the reactor coolant temperature decreases considerably. As a result, the elapsed time to 90℃

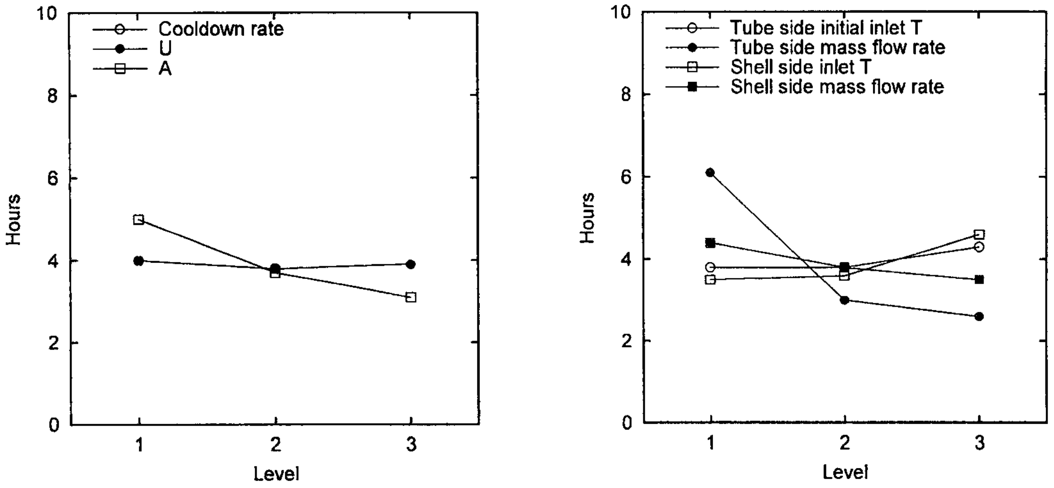
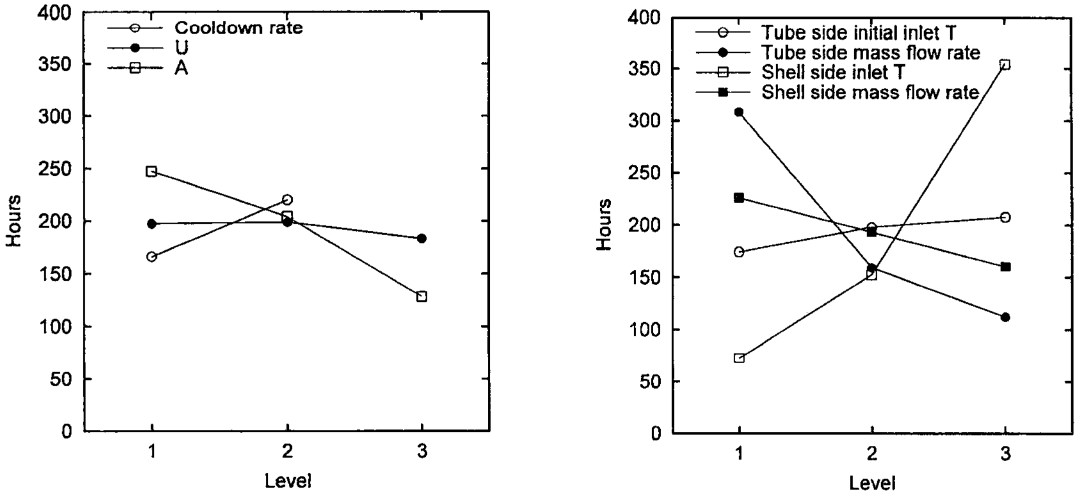


Fig. 3. The Average of the Elapsed Time to 90 ℃
(The lines for U and cooldown rate are overlapped.)



a) The temperature at the shell side

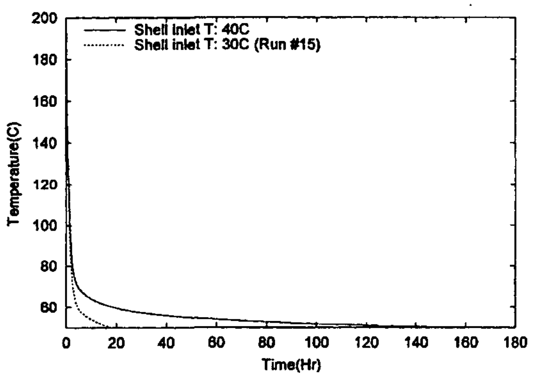
b) The overall heat transfer coefficient

Fig. 4. The Average of the Elapsed Time to 50 ℃

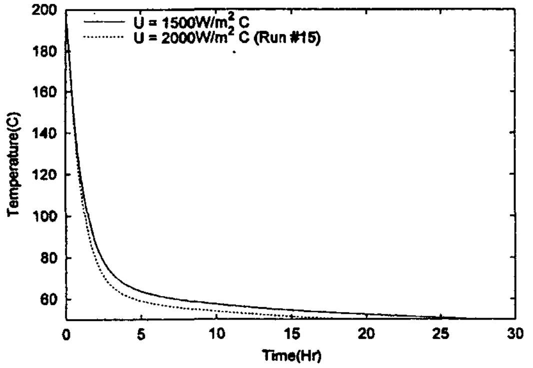
increases as $\dot{m}_t$ is at the lower levels. The other design factors show relatively small effect on the elapsed time to 90℃.

The average of the elapsed time to 50℃, which is the main concern in the design of SDCHX, is shown in Figure 4. The design factors show resembling trends for the case of t_{90}. As the flow rates at both sides and the overall heat transfer coefficient decrease, the elapsed time t_{50} increases. The elapsed time increases with the higher inlet temperatures and the larger heat transfer area. The most effective design factor for t_{50} is the inlet temperature at the shell side. The tube side flow rate and the heat transfer area of the exchanger follow it, in importance. The cool down rate, the initial inlet temperature at the tubes, and the overall heat transfer coefficient show little effect on the elapsed time to 50℃. It is a surprising result that the overall heat transfer coefficient is the least significant design factor.

To verify this fact, two extra simulations were conducted with the change of level of the cooling water temperature and the overall heat transfer coefficient of simulation No. 15. The results of the extra simulations are shown in Figure 5. It is observed that when the cooling water temperature is changed from 30 to 40℃, t_{50} increased to 165.8 hours from 18.6 hours. And, when the overall heat transfer coefficients are decreased from 2000 to 1500W/m^2 · ℃, t_{50} increases to 28.6 hours only. These results can be explained as follows: The lower cooling water temperature means the higher temperature potential of the heat exchanger when the temperature at the tube side is near 50℃. As the cooling water temperature is increased from 30 to 40℃, the temperature difference is reduced by half. In the case of the overall heat transfer coefficient, the decrease from 2000 to 1500 induces 25% decrease of *NTU* and leads to 12% decrease of the effectiveness. The accumulation of this reduction during the operation may generate the difference in the increment of the elapsed time.



a) The temperature at the shell side



b) The overall heat transfer coefficient

Fig. 5. The Results of the Verification Simulations

4. Concluding Remarks

Using the Taguchi method, the effect of the design factors of the shutdown cooling heat exchanger on the elapsed time of the shutdown cooling operation was investigated. It is possible to understand the influence of each design factor on the shutdown cooling heat exchangers with only 18 runs of simulations, which is very efficient with respect to analysis using the full factorial combination. It is found that, in the chosen levels, the inlet shell side temperature is the most effective design factor for controlling the system operation. The tube side flow rate and the heat transfer area are also important factors. These three factors should be managed carefully to meet the system requirements during design and operation. Other factors have insignificant effect on the performance, so they can be controlled to enhance other features of the heat exchanger, for example reducing construction costs. In this manner, the findings of the study can be applied to the design and operation of SDCHX. This method can be widely applied to other complex systems to understand and analyze the effect of design parameters on the system.

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