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Design optimization of shell and tube type heat exchanger of G.A Siwabessy multi-purpose reactor cooling system

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Abstract

G.A Siwabessy multi-purpose reactor is a nuclear reactor that utilizes a controlled fission reaction (a chain reaction of atomic fission). The heat exchanger in the reactor cooling system plays a vital role in transfering heat from the primary coolant side to the secondary coolant side. Heat transfer coefficient (U) and heat transfer area (Ao) are two variables that have a huge influence on the success of heat transfer in a heat exchanger. The aim of this research is to compare the U and A values in two different ways, namely the full factorial method and the use of Heat Transfer Research Inc. (HTRI) software. The novelty of this research is the use of two different methods to check the U and A0 values of heat exchangers in nuclear reactors. In the calculation using the full factorial method, 4 independent variables with 3 levels were made, so 81 calculations were obtained. The most optimal calculation results are then validated with HTRI software. From the calculation results, it is known that the largest overall heat transfer coefficient (U) is 6531.60 W/m^2 °C with a heat transfer area (Ao) of 584.47 m^2. The results of the validation with the HTRI software obtained an overall heat transfer coefficient (U) of 5045.10 W/m^2 °C with a heat transfer area (Ao) of 574.19 m^2. There is a difference in value between the results of manual calculations and the results of the validations of the HTRI software which is made possible by a decrease in the performance of the heat exchanger.

Keywords:
Full factorial, HTRI, optimization, heat exchanger, G.A Siwabessy reactor.

1 Introduction

A nuclear reactor is an installation that works based on a fission reaction or a chain reaction of atomic nuclear fission and is controlled. The nuclear fission reaction takes place in a section called the reactor core. The reactor core is composed of fuel, a moderator, reflector and a neutron source. Based on its use, nuclear reactors are divided into 2 types, namely research reactors (non-power reactors) and power reactors [1]. The research reactor is a reactor that utilizes newly generated neutrons and dissipates the heat. Research reactors typically have thermal power from a few watts to 50 MW [2]. Power reactors are used to generate energy and gen.

G.A. Siwabessy Multi-Purpose Reactor (RSG-GAS) is a non-power reactor used for research, serving irradiation activities, education, and training [3]. The RSG-GAS reactor is the first Material Testing Reactor (MTR) type research reactor in the world which is operated directly using low enriched uranium fuel, Low Enriched Uranium (LEU) Oxide type (U3O8-Al) with a density of Uranium in the meat of 2.96 gU/cm^3 and an enrichment of ^{235}U by 19.75%. Since 2002, RSG-GAS reactor fuel has been converted from Uranium-Oxide (U3O8-Al) to Uranium-Silicide (U3Si2-Al). The RSG-GAS reactor was built in the Center for the Development of Science and Technology/*Pusat Pengembangan Ilmu Pengetahuan dan Teknologi* (Puspiptek) in Setu District, South Tangerang City, Banten Province. The RSG-GAS reactor installation was built in 1983 and reached its critical point for the first time on July 29, 1987, and then inaugurated by the President of the Republic of Indonesia on August 20, 1987. On March 23, 1992, the operation was achieved at a nominal thermal power of 30 MW [4].

The main components of the RSG-GAS reactor are the reactor core and the cooling system consisting of the reactor pool, delay tank, primary cooling pump, heat exchanger, secondary cooling pump, and cooling tower. The heat exchanger in the reactor cooling system plays a vital role in transfering heat from the primary coolant side to the secondary coolant side, therefore its performance must always be ensured in good condition. The role of the heat exchanger in nuclear reactors determines the success of the reactor operation process [5]. The use of the reactor, which has been going on for 35 years, has caused a decrease in heat exchanger performance. There was thinning of the heat exchanger pipe walls of up to 10%, four pipes had dents of up to 10%, one pipe was blocked, and thirty-six pipes had fouling due to poor secondary cooling water quality [6]. Clogging can result in decreased efficiency due to reduced heat transfer area, increased flow velocity, and increased pressure loss [3].

One of the solutions to the heat exchanger problem in the G.A Siwabessy multi-purpose reactor cooling system is to redesign it using Heat Transfer Research Inch (HTRI) software and optimize performance with the full fractional method. HTRI is a company and software package that provides tools and methods of calculating heat transfer for the design and analysis of heat exchangers [7]. Firman *et al* optimized the condenser using the full factorial method and HTRI software and increased the effectiveness of the heat exchanger [8]. Heat exchanger optimization can be done by carrying out reverse engineering, the use of HTRI has been proven to improve the quality of heat transfer in the heat exchanger [9]. Subeno and Gaos optimized the heat exchanger design for chili sauce production using HTRI software and the full factorial method with four independent variables and 3 experimental levels. The four independent variables are pipe outer diameter, pipe length, tube pitch, and pipe arrangement [10].

The novelty of this research is the design optimization of the existing heat exchanger using 2 methods, namely the full factorial method and the HTRI software. The aim of this research is to optimize the heat exchanger design of the G.A Siwabessy multi-purpose reactor cooling system using the full factorial methode and HTRI software. The four design variables used are tube diameter, number of tubes, tube pitch, and tube length.

2 Research Methods/Materials and Methods

2.1 G.A Siwabessy Multi-Purpose Reactor Cooling System

Fig. 1 shows cooling system of reactor. The main cooling system of the reactor is composed of a primary cooling system, a secondary cooling system and a decay heat dissipation system. The function of the primary and secondary cooling systems is to guarantee the temperature inside the core and reflector according to the permissible operating limits as long as the reactor is operating until the thermal power of the design. As long as the reactor operates the heat that forms in the reactor core and around the reflector is taken up by the primary cooling water flowing to the bottom of the core, the heat from the primary cooling water is then transferred to the secondary cooling water inside the heat exchanger then the heat is discharged into the atmosphere through the cooling tower.

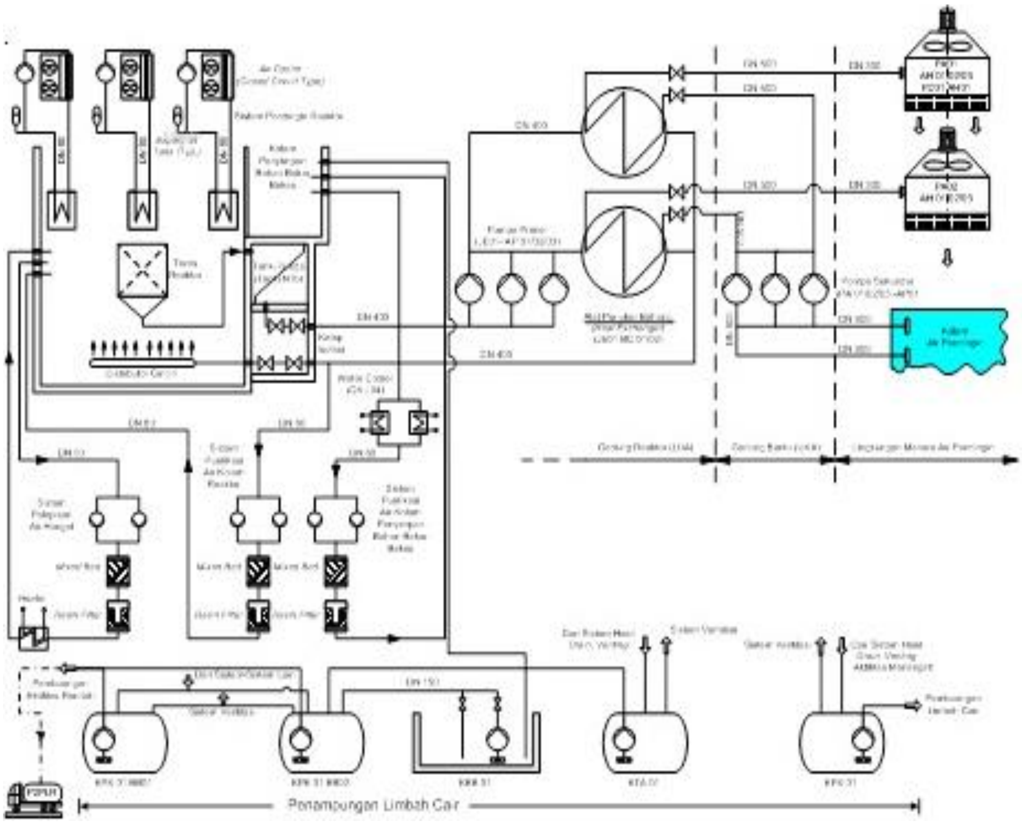
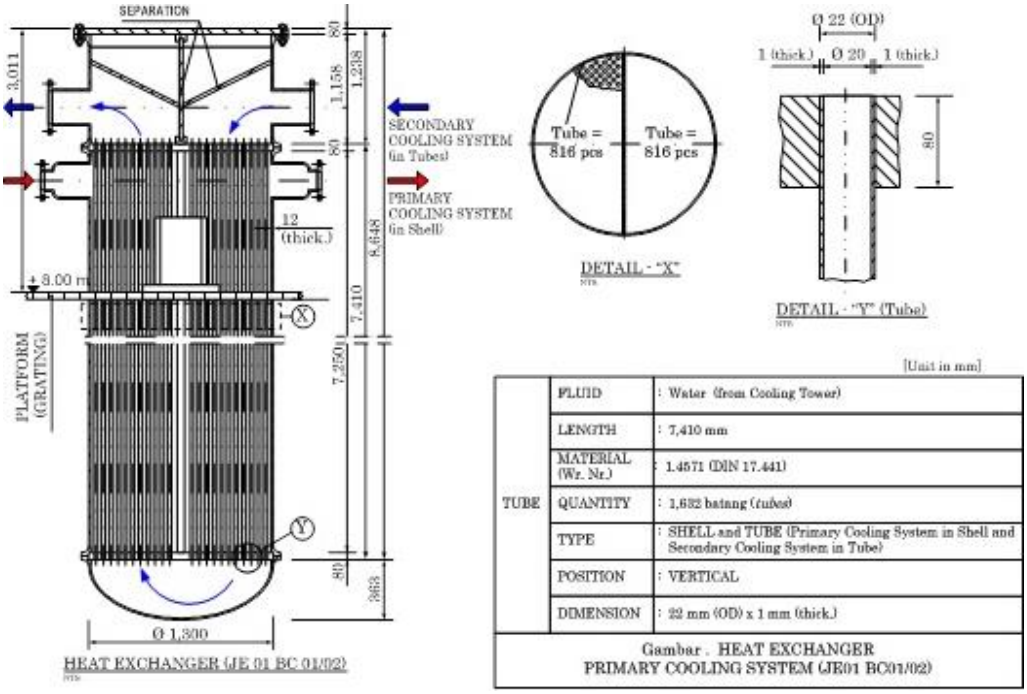


Fig. 1. The main cooling system of the G.A Siwabessy multi-purpose reactor [11].

The primary cooling system takes heat from the core and reflector of the reactor, then the heat is transferred to the secondary cooling system through two heat exchangers (shell and tube heat exchanger). The secondary cooling system is the last heat-taker for reactor installations. The heat from the primary cooling system is transferred through two heat exchangers (shell and tube heat exchangers) and discharged into the environment/atmosphere through the cooling tower.

G.A Siwabessy multi-purpose reactor cooling system (Fig. 2) has two heat exchanger units (JE-01 BC-01 and JE-01 BC-02). Both of heat exchanger units are connected to a parallel pipe on the press side of the primary coolant pump. Each of the heat exchanger units is prepared to move 50% of the total load of primary heat transfer at full power reactor operation. Two-pass cell and tube type heat exchangers both on the shell side and tube side (2/2), installed in a vertical position with primary cooling water flowing on the side of the shell and secondary cooling water flowing on the side of the tube with the opposite direction of flow. Technical specifications and operating limitations of G.A Siwabessy are presented in Table 1 and Table 2 respectively.



TUBE	FLUID	: Water (from Cooling Tower)
	LENGTH	: 7,410 mm
	MATERIAL (Wr. Nr.)	: 1.4571 (DIN 17.441)
	QUANTITY	: 1,632 batang (*tubes*)
	TYPE	: SHELL and TUBE (Primary Cooling System in Shell and Secondary Cooling System in Tube)
	POSITION	: VERTICAL
	DIMENSION	: 22 mm (OD) x 1 mm (thick.)
Gambar . HEAT EXCHANGER PRIMARY COOLING SYSTEM (JE01 BC01/02)		

Fig. 2. Heat exchanger of G.A Siwabessy multi-purpose reactor cooling system [11].

Table 1. Technical specifications of G.A Siwabessy multi-purpose reactor heat exchanger [12][11].

	Shell side (hot water)	Tube side (cold water)
Design pressure/test (bar)	10/13	10/13
Temperature (°C)	60	60
Tube O.D/I.D (mm)	-	22/20
Tube length (mm)	-	7.410
Number of tubes	-	1632 (816)
Tube pitch (mm)	-	28
Tube layout (triangle) (°)	-	30
Shell O.D (mm)	1.300	-
Shell thickness (mm)	12	-
Number of passes (multi-pass)	2	2
Orientation	Vertical	Vertical
Total length (mm)	9000	-
Material	1.4301 DIN 17440 stainless steel 304	Austenitic steel 1.4541 DIN 17440 AISI 321, stainless steel X6CrNiTi18-10

Table 2. Operating limitations of G.A Siwabessy multi-purpose reactor heat exchanger [12].

	Shell/primary (hot water)	Tube/secondary (cold water)
Fluid	Demineralized watter	Raw watter
Flow rate (kg/s)	430	485
In/out temperature (°C)	49/40	32/40
Working pressure in/out (bar)	1.4/0.9	0.4/0.0
Fouling resistance (m^2. K/W)	0.00009	0.00019
Heat exchanger capacity (kW)	16.200	
Allowable pressure drop (bar)	0.5	0.4
Allowable velocity (m/s)	3	3
Heat transfer area (m^2)		780

2.2 Calculation of Heat Exchanger Design Optimization

In this study, 4 free variables were made with 3 levels. Based on the experimental design of the full factorial method 4 free variables with 3 levels will be produced 81 ($3^4 = 81$) times the experiment with different combinations. It is expected that from the interaction of existing variables, the most optimal combination will be obtained (Table 3).

Table 3. Free variables and research levels

Code	Free variables	Level		
		1	2	3
A	Tube diameter, d_O (mm)	19	22	25
B	Number of tubes, Nt	1469 (-10%)	1632	1795 (+10%)
C	Tube pitch, Pt (mm)	25	28	32
D	Tube length, L (mm)	6669 (-10%)	7410	8151 (+10%)

Eq. 1-Eq. 8 are used in the calculation of the design optimization of shell and tube type heat exchangers [13] [14] [15].

Calculates the heat balance between a hot fluid and a cold fluid (Eq. 1).

$$q_h = \dot{m}_h C_{ph}(T_{h,\ in} - T_{h,\ out}) \tag{1}$$

where: q_h is the amount of heat in the hot fluid (J/s), $\dot{m}_h$ is the mass flow rate of the hot fluid (kg/s), C_{ph} is the specific heat of the hot fluid (J/kg °C), $T_{h,\ in}$ is the temperature of the hot fluid inlet of the heat exchanger (°C) and $T_{h,\ out}$ is the temperature of the heat fluid out of the heat exchanger (°C).

$$q_c = \dot{m}_c C_{pc}(T_{c,\ out} - T_{c,\ in}) \tag{2}$$

where: q_c is the amount of heat in the cold fluid (J/s), $\dot{m}_c$ is the mass flow rate of the cold fluid (kg/s), C_{pc} is the specific heat of the cold fluid (J/kg °C), $T_{c,\ in}$ is the temperature of the cold fluid in the heat exchanger (°C) and $T_{c,\ out}$ is the temperature of the cold fluid out of the heat exchanger (°C). Calculates the logarithmic mean temperature difference and an illustration of the heat exchanger in Fig. 3.

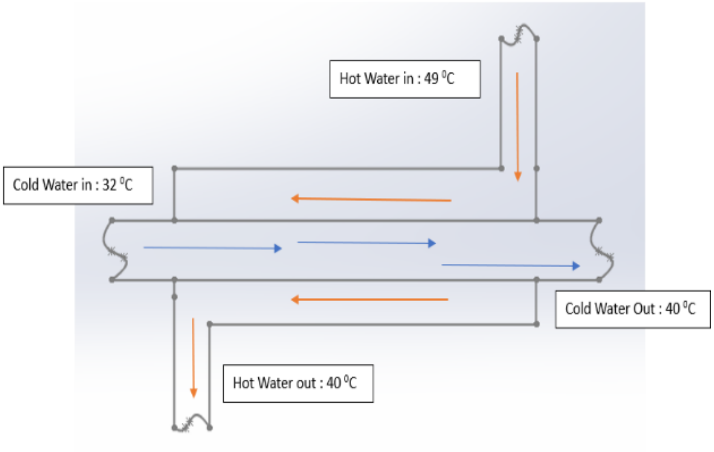


Fig. 3. Illustration of a heat exchanger and temperature.

Eq. 3 applies to heat exchangers with parallel flow and opposite flow. As for the shell and tube heat exchangers with cross-flow and multipasses, the Eq. 4 applies.

$$\Delta T_{LMTD,\ CF} = \frac{\Delta T_1 - \Delta T_2}{ln\,\dfrac{\Delta T_1}{\Delta T_2}} \tag{3}$$

where $\Delta T_1 = (T_{h,\ in} - T_{c,\ out})$ and $\Delta T_2 = (T_{h,\ out} - T_{c,\ in})$.

$$\Delta T_{LMTD} = F \times \Delta T_{LMTD,\ CF} \tag{4}$$

With F is a correction factor that depends on the geometry of the heat exchanger and the temperatures in and out of the flow of hot fluids and cold fluids. The F value is obtained from the correction factor graph for cross-flow shell and tube heat exchangers with first looking for the parameters P and R, where $P = \frac{t_2 - t_1}{T_1 - t_1}$ and $R = \frac{T_1 - T_2}{t_2 - t_1}$.

Calculates the total heat transfer surface area (Eq. 5).

$$A_o = \pi d_o L N_t \tag{5}$$

Where: A_o is the heat transfer area (m^2), d_o is the outer diameter of the tube (m), L is the tube length (m) and N_t is the number of tube.

Calculates the overall heat transfer coefficient (Eq. 6).

$$U = \frac{Q}{A_o\ \Delta T_{LMTD}} \tag{6}$$

Where: U is the overall heat transfer coefficient (W/m^2. °C), Q is the actual heat transfer rate (J/s).

Calculating the effectiveness of the heat exchanger (Eq. 7).

$$\varepsilon = \frac{Q}{Q_{max}} \times 100\% \tag{7}$$

where: $Q_{max} = C_{min}(T_{h,\ in} - T_{c,\ in}$. ε is the effectiveness of the heat exchanger (%), Q_{max} is the maximum possible heat transfer rate (J/s) and C_{min} is minimum heat capacity rate (J/s°C).

Calculate the number of transfer units (Eq. 8).

$$NTU = \frac{UA_o}{C_{min}} \quad (8)$$

2.3 Validation Using HTRI Software

Validation is carried out only for the most optimal design, that is, a design with a large value of the overall heat transfer coefficient (U) with a small of heat transfer area (Ao). Heat Transfer Research Inc. (HTRI) is a tool or software to perform calculations for the design of heat exchangers. The data report from the HTRI software is a reference in analyzing the design of the heat exchanger.

3 Results and Discussion

The four design variables that are optimized are tube diameter, number of tubes, tube pitch and length tube. Table 4 shows the 4 variables of optimization results with three levels.

There are similarities in diameter, number of tubes, and length of pipe but different in tube pitch. From the results of the calculations carried out, it is known that the optimal value or the largest value of the overall heat transfer coefficient (U) is 6531.60 W/m^2 °C with a heat transfer area (Ao) of 584.47 m^2. Meanwhile, the values of the overall heat transfer coefficient (U) and heat transfer area (Ao) for heat exchangers under existing conditions are 4569.77 W/m^2 °C and 835.39 m^2 based on the same calculation results. The design data with the most optimal values are no. 1, 4 and 7 (Fig. 4).

Subeno and Gaos obtained similar results, the use of the full factorial method successfully obtained the optimal thermal resistance coefficient value [10]. The U value greatly influences the effectiveness of heat exchange transfer in the heat exchanger, the greater the U value, the more efficient the heat transfer will be. While the A value is optimized as much as possible because it is to reduce production costs and will be a consideration of the fluid flow rate [5].

Based on the results of the HTRI software validation, the overdesign value is -0.03%, this is an indication of the reduced performance of the heat exchanger. Generally, overdesigns for heat exchangers range from 10% to 20%. Sukarman and Gaos succeeded in optimizing a heat exchanger for a degreaser water heater, obtaining an overdesign of 15% to 25% [16], while Subeno et al obtained an overdesign from the calculation of 10% to 25% [10].

Table 4. Heat exchanger calculation results

Parameters	No.41*	No.1	No.4	No.7
Performance:				
Heat transfer rate, Q (MJ/s)	16.38	16.38	16.38	16.38
Overall heat transfer coefficient, U (W/m^2 °C)	4569.77	6531.60	6531.60	6531.60
Heat transfer area, A_o (m^2)	835.39	584.47	584.47	584.47
Logaritmic mean temperature difference, ΔT_{LMTD} (°C)	4.29	4.29	4.29	4.29
Effectivity, ε (%)	69.23	69.23	69.23	69.23
NTU	2.10	2.10	2.10	2.10
Tube construction (free variables):				
Tube diameter, d_o (mm)	22	19	19	19
Number of tubes, N_t	1632	1469	1469	1469
Tube pitch, P_t (mm)	28	25	28	32
Tube length, L (mm)	7410	6669	6669	6669

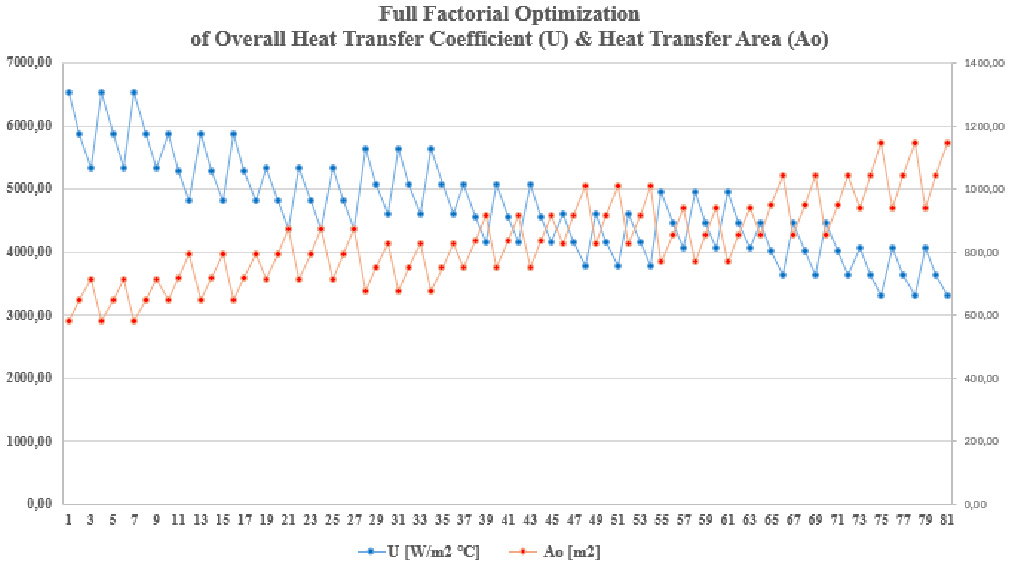


Fig. 4. Full factorial optimazation.

Fig. 5 shows the comparison of heat exchanger performance values in existing, optimization, and HTRI software simulation conditions. The LMTD value of HTRI results is 5.3°C, so the difference with the optimization results is 1°C. There is a difference in the optimal value of the calculation results with the validation results. The difference can be explained as the current condition of the heat exchanger has experienced a decrease in performance. Factors that affect the heat exchanger performance of the G.A Siwabessy reactor cooling system of the include the thinning of the walls in some tubes, basin defects (dent), plugged (clogged/closed) and the most dominant is the occurrence of fouling due to water quality on the secondary cooling side (raw water) which all of them affect the heat transfer area [5]. Fig. 6 shows the process of cleaning the heat exchanger in a nuclear reactor.

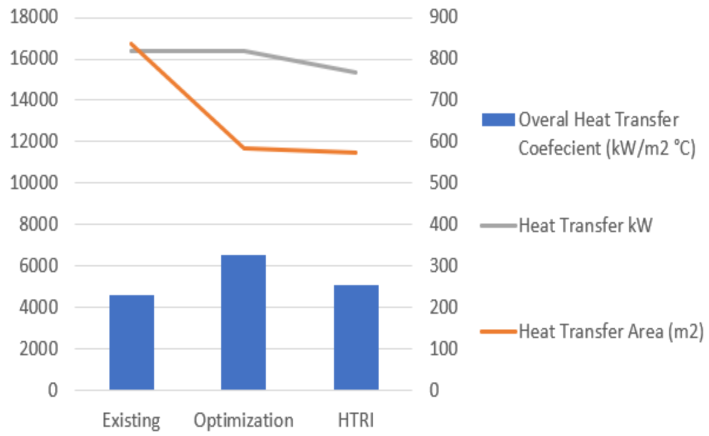


Fig. 5 comparison of optimization values and HTRI.

Fig. 6. Nuclear reactor heat exchanger cleaning activities.

4 Conclusion

Based on the calculation results, the optimal design was obtained in design data no. 4. The value of the overall heat transfer coefficient (U) is 6531.60 W/m^2 °C, the heat transfer area (Ao) is 584.47 m^2 and the heat transfer (Q) is a maximum of 16.38 MJ/s (16.38 MW). The validation results using HTRI software are known to have a overall heat transfer coeficent (U) is 5045.10 W/m^2 °C with a heat transfer area (Ao) of 574.19 m^2 and a maximum heat transfer (Q) of 15.34 MJ/s (15.34 MW). There is a difference in value between the results of manual calculations and the validation results of HTRI software which is possible by a decrease in the performance of the heat exchanger.

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