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Optimizing Plate Heat Exchanger Design for Steam Condensate Recovery Systems

[1] Lupi Abdul Malik, [2,3] Dessy Agustina Sari*

[1,2]Chemical Engineering Program, Faculty of Engineering, Universitas Singaperbangsa Karawang
Jalan HS Ronggowaluyo Telukjambe Timur, Karawang, Jawa Barat, Indonesia 41361
[3]Chemical Engineering Doctoral Degree, Faculty of Engineering, Universitas Diponegoro
Jalan Prof. H. Soedarto, SH, Kampus Tembalang, Kota Semarang - Jawa Tengah, Indonesia 50275

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***e-mail the corresponding author :**
dessy.agustina8@staff.unsika.ac.id

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ABSTRACT

Condensate water is typically generated as a by-product during the use of steam as a medium for heat transfer. In order to optimize the transfer area, the chemical industry often employs heat exchangers, such as the plate heat exchanger (PHE), which provides flexibility in adjusting the space area for heat transfer. This case study examines the optimization of plate geometry dimensions to enhance the heat transfer process of PHE equipment design. The optimization process involves mathematical equations and a literature review of the design of this type of heat exchanger. Improving the dimensional aspect of the plate geometry results in an increase in the overall heat transfer coefficient (U) and a reduction in the number of design requirements used. The study's estimation results suggest that the PHE design has a limitation on plate dimensions, which should be less than 0.3×0.6 m. Additionally, it is important to consider the pressure drop value, which should not exceed 29.07 kPa. A review of the chemical industry field provided estimated options for plate size and quantity, both of which support the optimization of heat transfer rate and design constraint thresholds. The implementation of the design has been found to enhance the performance of the planning process for recovering steam condensate water.

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1. INTRODUCTION

Utilization of steam condensate as a heat source in heat exchangers is a strategy to improve energy efficiency and minimize industrial process waste. Post-condensation steam condensate has the potential to be a valuable heat source in a variety of applications, ranging from heating to evaporation [1]. The relatively high temperature of steam condensate affects its utilization and regular management. In this case, to maximize utilization, a heat exchanger that has optimal performance and is suitable for the desired placement area is required. In the design of heat exchangers, determining the right geometry and configuration depends on the type of fluid, placement area, temperature, and other factors. This requires optimization to provide the right design suitability for implementation. Optimization methods can use mathematics or simulation to minimize the problem [2].

It is worth noting that various industries commonly use heat exchangers such as shell and tube, double pipe, plate, and other types [3],[4],[5]. In order to facilitate the management of the steam condensate recovery system, plate heat exchangers (PHE) present certain advantages and fulfill the requirement for a broad range of flexibility in conducting heat transfer processes. Another advantage of PHE is its ease of maintenance, applicability to processes with small heat transfer and approach temperatures as low as 1°C, lower fouling factors resulting in lower process costs, and more flexible design compared to shell and tube heat exchangers [6], [7]. The chemical, food and beverage, and water treatment industries are some examples where PHE has been implemented [6], [8], [9].

The performance of PHE is monitored through various parameters such as geometric parameters, heat transfer coefficients, thin plate heat transfer coefficients, and equipment design pressure drop limits [10]. Previous researchers have conducted optimization studies of PHE using both mathematical equations and computer simulations. Algorithm implementation has been used by researchers [11] to optimize PHE design, taking into consideration the use of plate numbers. Moreover, a related topic has been addressed by researchers [12] concerning the segment of zig-zag flow geometry to assess the efficiency and pressure drop in PHE design. Additionally, other aspects of PHE have been investigated by various researchers, including the estimation of plate distance, corrugation geometry, chevron type, as well as flow type or path on pressure drop parameters and heat transfer simulation [13], [14], [15], [16]. As suggested by the researcher [10], this was achieved by selecting the plate geometry and the quantity of flow paths with the aim of minimizing the pressure drop during the heat transfer process in the PHE. The proposed changes to the PHE design for that segment were evaluated with consideration for the pressure drop limitation while prioritizing the optimization of the heat transfer process.

A review of previous research by PHE researchers presents an opportunity to discuss the optimization of plate geometry design in the steam condensate recovery system (20–35% of the potential unutilized reactor output steam is to be recovered as condensate). The analysis aims to obtain a geometry that is suitable for the predetermined process area for placement, as specified by the industry. This area is an empty space, either planned or unplanned, in the design of the heat transfer unit requirements of the factory process flowsheet. The use of plate heat exchangers (PHE) necessitates the evaluation of design alternatives and an assessment of the effect of plate geometry on both the overall heat transfer coefficient and the allowable design pressure drop. As such, it is crucial to optimize the PHE design by maximizing the available process equipment area while minimizing operating costs.

2. RESEARCH METHODS

This study conducted a PHE design from the results of the assessment of condensate water in the process circuit in the HAI industry. The HAI industry is one of the factories that produces liquid chemicals for bleaching agents and its products are intended for industry. Figure 1 is an illustration of the research design in this industry and Figure 2 is the process flow in the unit studied.

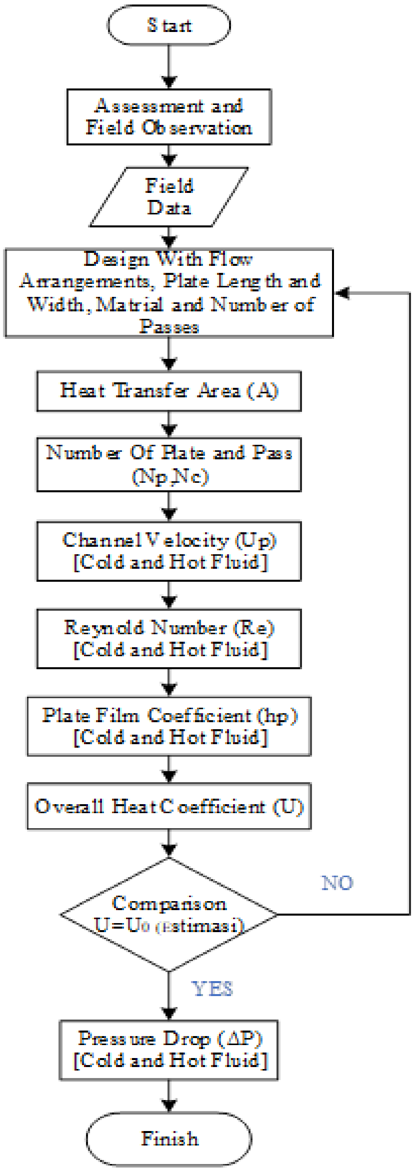

Figure 1. Design flowchart for PHE in steam condensate recovery

The use of steam as a heating medium in the reactor produces condensate water and some unutilised steam. The residue continues to undergo a condensation process with the addition of water as the medium. It is worth noting that a relatively high amount of water is required for this process. The reuse of high-temperature air condensate steam as a heating medium for products in the STHE (Shell and Tube Heat Exchanger) unit is possible. Therefore, the use of heat exchanger equipment is necessary to lower the temperature of the remaining steam and condensate water, which can then be reused in the STHE. The purpose of the PHE equipment design is to recirculate the condensate steam water that was previously discarded or unused. Figure 2 shows the process scheme for PHE's equipment design using CCW (Chilled Cooling Water). The placement location is in the steam recovery process.

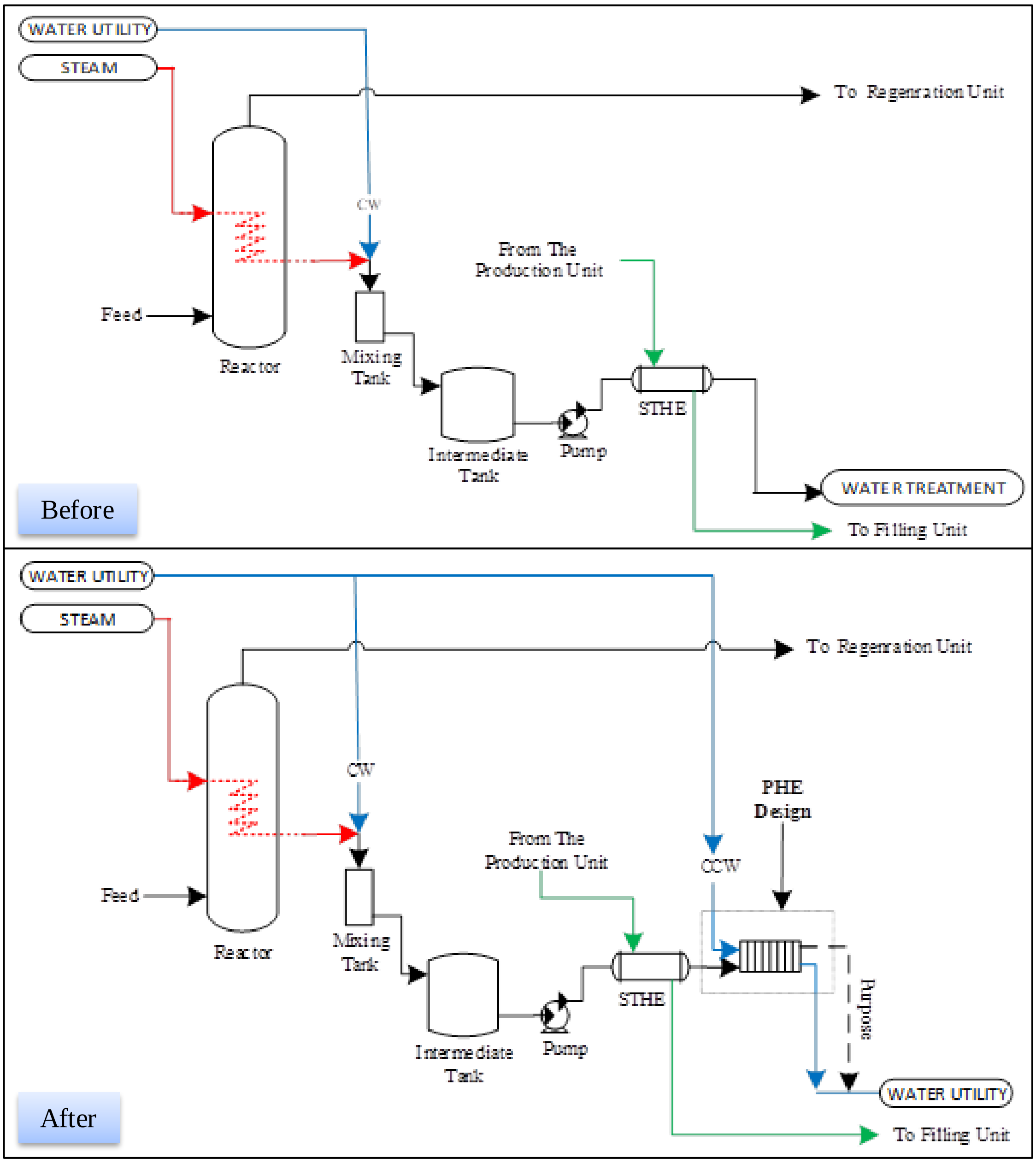

Figure 2. Process section in the HAI industry for PHE design placement

Data Collections

Data collection is an essential requirement for the design of PHE equipment. Supporting data can be obtained from literature sources such as books and articles on fluid property values and constants for equipment design calculations. The necessary data includes a comprehensive review of the process area, target operating conditions, and measurements of the PHE equipment layout. The design of PHE is presented in Table 1, with variations in plate geometry (L-length and W-width) through planning steps as a form of preliminary or initial prediction.

Tabel 1. Plate frame heat exchanger in industry HAI

Process Variables	Hot Fluid	Cold Fluid	Design	
Fluid type	Steam condensate	CCW	Number per pass	1:1
T inlet, ^{o}C	48	18	Flow arrangement	Counter-current
T outlet, ^{o}C	28 (purpose)	-	Thickness of plate, *s*, mm	0.5
Volumetric rate, $\dot{V}$, m^3/h	1.8		Plate geometry, m (variable, W×L)	A = 0.15×0.3 B = 0.2×0.4 C = 0.3×0.6 D = 0.4×0.8
			$s_{plate\ spacing}$, mm	1.5
			Diameter port, d_{pt}, mm	100

The placement layout of PHE equipment was subject to a measurement process to identify design limitations, including the impact of environmental factors and worker mobility. The placement area measures 2×1.5 m and follows predetermined points, as shown in Figure 3, based on the empty location map of the HAI industry.

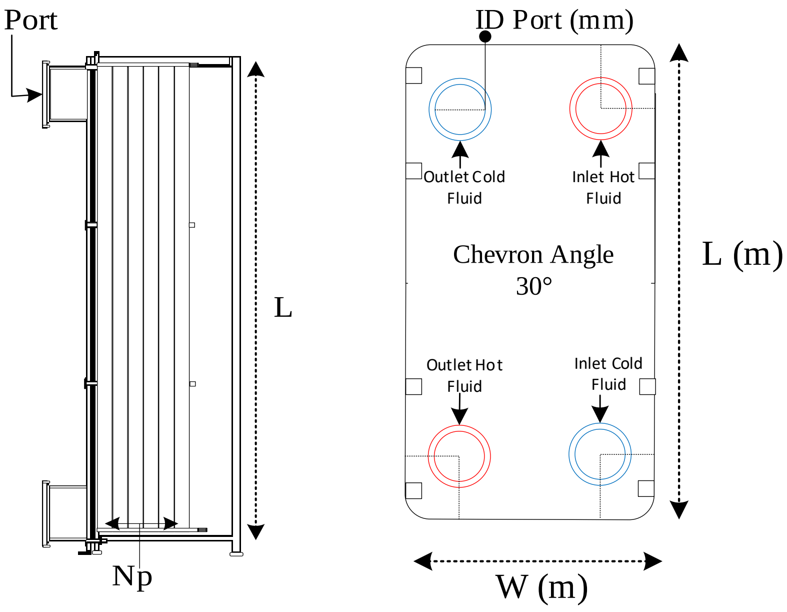

Figure 3. The geometric model and dimensions of the plate

Design Procedures

The design procedure for the PHE equipment involves using mathematical equations to process operating conditions data and supporting data from the heat transfer process literature [6], [17], [18], [19], [20], [21]. The design estimation steps consist of obtaining the heat transfer area value (equations 1–8), overall heat transfer coefficient (equation 9), and pressure drop (equations 10–12). These steps are performed to determine the suitability of the PHE design results.

Heat transfer area, A_{PHE}

$$A_{PHE} = \frac{Q_{hot\ fluid}}{U \times\ F_t\ \ \times \Delta T_{LMTD}} \tag{1}$$

$$Q_{hot\ fluid} = \{\dot{m}\ \times\ C_p\ \times (T_1 - T_2)\}_{hot\ fluid}$$

$$\Delta T_{LMTD} = \frac{\Delta T_1\ - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} = \frac{(T_1\ - t_2\,) - (T_2\ - t_1\,)}{\ln\left(\frac{T_1\ - T_2}{t_2\ - t_1}\right)}$$

$$NTU = \ \frac{T_1\ - t_2}{\Delta T_{LMTD}}$$

The calculation of the heat transfer area in a plate heat exchanger (PHE) involves several factors, including the heat load data (Q), the logarithmic mean temperature difference (ΔT_{LMTD}), and the temperature correction factor (F_t) acquired from a graph using the NTU (Number Thermal Unit) value or obtained from a journal. Finally, the value (U_0) represents the overall heat transfer coefficient assumption, determined through a thorough review of relevant literature and dependent on the specific type of heating and cooling fluid used in the PHE design. The heat transfer area value (A or A_{PHE}) is then calculated using the plate dimensions or area of one plate (A_{1p}), number of plates (N_p), and number of channels per pass (N_C) to apply equations (2) and (3).

$$N_p = \frac{A_{PHE}}{A_{1p}} \tag{2}$$

$$A_{1p} = W \times L$$

$$Nc = \ \frac{N_P - 1}{2} \tag{3}$$

Equation (3) provides information on the number of plates and channels per pass (N_C) in the design. This data is then utilized to calculate the channel velocity (u_p) for both fluid sides inside the PHE using equations (4) and (5).

$$G_{p_{cold\ or\ hot\ fluid}} = \frac{\dot{m}_{cold\ or\ hot\ fluid}}{A_0} = \frac{\dot{m}_{cold\ or\ hot\ fluid}}{W\ s\ N_C} \tag{4}$$

$$u_{p\ cold\ or\ hot\ fluid} = \frac{G_{p_{cold\ or\ hot\ fluid}}}{\rho_{cold\ or\ hot\ fluid}} = \ \frac{\dot{m}_{cold\ or\ hot\ fluid}}{\rho_{cold\ or\ hot\ fluid} \times A_f \times N_C} \tag{5}$$

$$A_f = W \times\ s_{plate\ spacing}$$

Equations (4) and (5) require operational and supporting data such as mass velocity (G_p), fluid density (ρ), and channel cross-sectional area (A_f). The flow type of the design can be determined by obtaining the Reynolds number (Re) value in equation (6), which is calculated using the results of both equations. This approach allows for the classification of the flow as laminar, transitional, or turbulent.

$$Re_{cold\ or\ hot\ fluid} = d_e \times \left(\frac{G_p}{\mu}\right)_{cold\ or\ hot\ fluid} \tag{6}$$

$$d_e = 2 \times s_{plate\ spacing}$$

The Reynolds number (Re) is calculated using the mass velocity (G_p), hydraulic mean diameter (d_e), fluid viscosity (μ), and plate spacing thickness (splate spacing). Equation (7) can be used to determine the Nusselt number (Nu) and plate film coefficient (h_p) by taking into account Re and d_e.

$$Nu_{cold\ or\ hot\ fluid} = 0.26 \times (Re^{0.65})_{cold\ or\ hot\ fluid} \times (Pr^{0.4})_{cold\ or\ hot\ fluid} \tag{7}$$

$$h_{p\ cold\ ot\ hot\ fluid} = Nu_{cold\ or\ hot\ fluid} \times \left(\frac{k_{cold\ or\ hot\ fluid}}{d_e}\right) \tag{8}$$

The value of h_p represents the heat transfer coefficient that occurs during the formation of a thin fluid layer on the plate. It is worth noting that Equation (8) requires data on the thermal conductivity of the fluid (k).

Overall heat transfer coefficient, *U*

The U value represents the heat capacity exchanged during the heat transfer process in PHE equipment. The U value represents the heat capacity exchanged during the heat transfer process in PHE equipment. The U-value design serves as the initial reference to determine the suitability of the mathematical design calculation. The value of U obtained from Equation (9) is compared with the assumed value of the overall heat transfer coefficient (U_0, depending on the property and type of fluid).

$$\frac{1}{U} = \frac{1}{h_{p\ hot\ fluid}} + \frac{1}{F_{h\ hot\ fluid}} + \frac{s}{k_p} + \frac{1}{h_{p\ cold\ fluid}} + \frac{1}{F_{h\ cold\ fluid}} \tag{9}$$

Equation (9) is determined by several factors, including the plate thickness (s), thermal conductivity (k_p) based on the construction material used as outlined in Table 4.1 (stainless steels) and Table 4.2 [18], and the fouling factor coefficient (F_h) based on the fluid type as referenced in Table 12.9 in [4].

Pressure Drop, Δ*P*

Pressure drop is a parameter used to determine the amount of pressure loss due to heat transfer processes that occur in plate heat exchanger (PHE) equipment. The overall pressure drop value (ΔP) in PHE consists of the plate pressure drop (ΔP_p) and the pressure loss through the port (ΔP_{pt}), as shown in equations (10) to (12). The first and second aspects of pressure drop are used to determine the pressure drop on the plate and the pressure loss in the flow or port channel, respectively.

$$\Delta P_{p\ cold\ or\ hot\ fluid} = 8 \times j_{f\ cold\ or\ hot\ fluid} \times \left(\frac{L_p}{d_e}\right)\left(\frac{\rho \times u_p{}^2}{2}\right)_{cold\ or\ hot\ fluid} \quad (10)$$

$$j_{f\ cold\ or\ hot\ fluid} = 0.6 \times (Re^{-0.3})_{cold\ or\ hot\ fluid}$$

$$L_p = L \times number\ of\ pass$$

$$\Delta P_{pt\ cold\ or\ hot\ fluid} = 1.3\left(\frac{\rho \times u_{pt}}{2}\right)_{cold\ or\ hot\ fluid} \times N_p \quad (11)$$

$$u_{pt\ cold\ or\ hot\ fluid} = \frac{4\dot{m}_{cold\ or\ hot\ fluid}}{\rho_{cold\ or\ hot\ fluid} \times \left(\pi d_{pt}{}^2\right)}$$

$$A_{port} = \frac{1}{4}\pi d_{pt}{}^2$$

$$\Delta P_{cold\ or\ hot\ fluid} = \left(\Delta P_p + \Delta P_{pt}\right)_{cold\ or\ hot\ fluid} \quad (12)$$

Equation (10) for (ΔP_p) requires the friction factor (j_f) and length of path (L_p). Equation (11) for ΔP_{pt} involves the role of the velocity through the port (u_{pt}) by first calculating the area of the port using the diameter of the port (d_{pt}).

3. RESULT AND DISCUSSIONS

The design calculations for PHE have been modified to align with the operational conditions outlined in the case study installation plan. As indicated in Table 2, the heat load from the design and the required CCW flow rate of 3.6 m^3/h, which serves as a cooling medium for the condensate of the steam, have been provided.

The results presented in Table 2 indicate that the fluid mass flow rate parameter (u_p) and plate film coefficient (h_p) increase during the heat transfer process from both sides as the plate dimensions increase (from variable A to D, 0.15×0.3–0.4×0.8 m). Moreover, the larger plate dimensions demonstrate a decrease in the friction factor (j_f) with an increase in the Reynolds number. It is worth noting that the friction value is one of the factors that can contribute to a decrease in pressure (ΔP) in the design of PHE equipment when the fluid flow rate decreases [22]. As with other types of heat exchangers, minimizing the pressure drop value is an important design consideration in order to achieve an optimal heat transfer rate.

Table 2. The results of the heat load and design parameters of the PHE equipment

Parameter	A		B		C		D	
	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold
Mass velocity, G_p, kg/m^2.s	379.05	752.45	383.92	762.13	400.06	794.15	408.64	811.20
Channel velocity, u_p, m/s	0.3767	0.7277	0.3815	0.7371	0.3976	0.7681	0.4061	0.7846
Plate film coefficient, h_p, W/m^2.^{o}C	13021	16773	13129	16913	13486	17372	13673	17613
Friction factor, j_f	0.0614	0.0605	0.0612	0.0603	0.0604	0.0596	0.0600	0.0592
Heat load, Q, kJ/s			43.7		LMTD	14.42		
Volumetric rate in cold side, $\dot{V}$, m^3/h			3.6		NTU	1.38		

Note: corrugation angle is in 30^o.

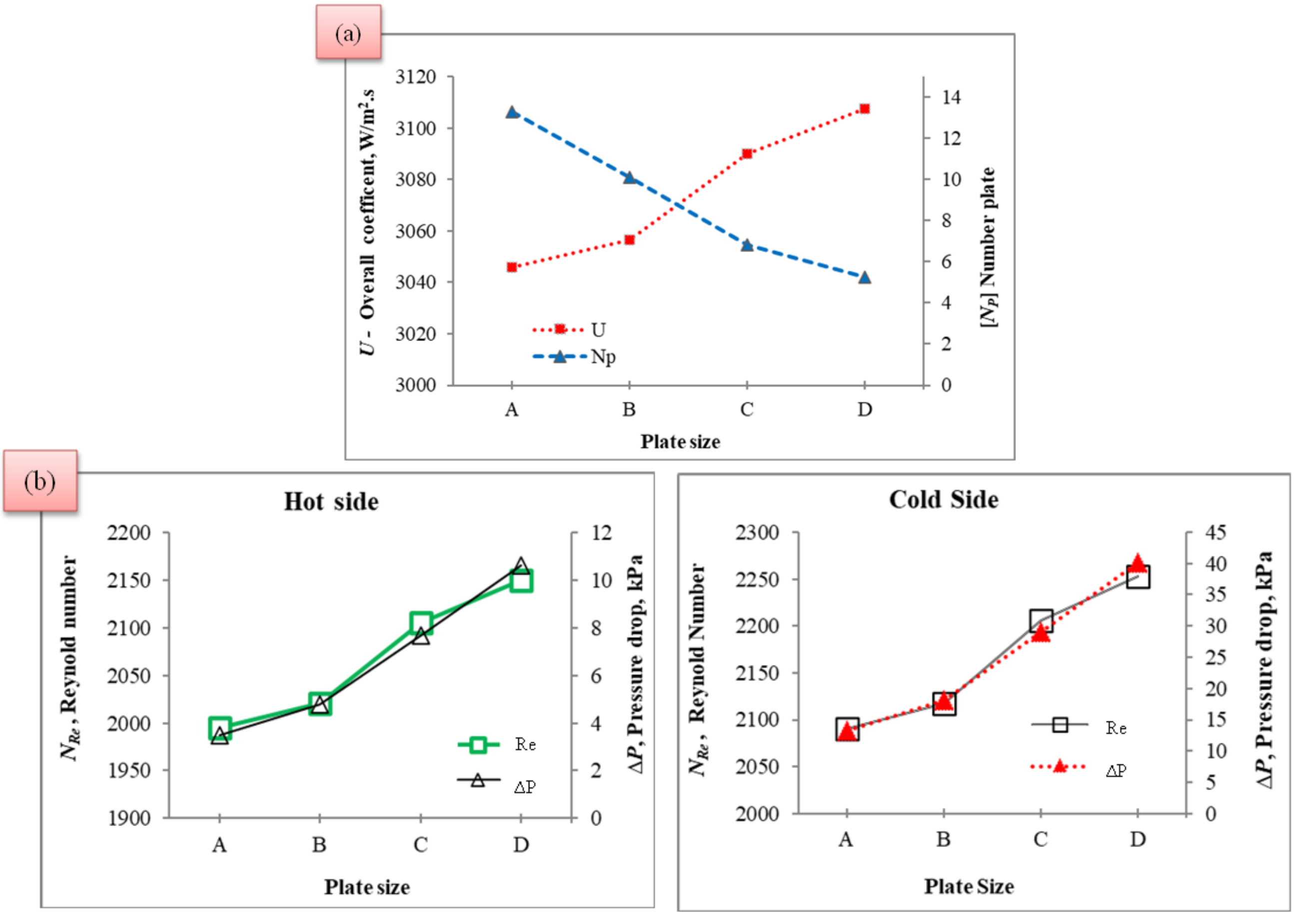

Figure 4. The impact of plate size on: (a) the number plate (N_p) and the overall coefficient of heat transfer design value (U); (b) Re and ΔP on both sides of the heat exchanger.

Figure 4 (a) shows the results of the PHE design in the HAI industry, indicating that increasing the plate dimensions improves the overall heat transfer coefficient (U). However, the number of plates used in the design decreases as the plate geometry increases (from variable A to D). The actual value of U was obtained after adjusting the design to the available space in the HAI industry. The condition was adjusted to ensure that the second U value did not differ by more than 10% from the estimated U_0 value. If the U value is outside the range, adding or reducing the number of plates can address the impact [6]. Research conducted in the HAI industry showed an increase in the overall heat transfer coefficient due to an increase in plate dimensions (variable D, 0.4×0.8 m). This condition has led to a reduction in the quantity of PHE plates from the previous design. Additionally, this decision also re-evaluates the number of plates and the distance between them applied in the PHE design. The number of plates has been adjusted while considering the limitations of the design in the HAI industry and its commercial suitability in the market. This limit can affect the heat transfer rate, overall heat transfer coefficient, and pressure drop value during the heat transfer process from both the cold and hot fluid sides [23], [24].

Figure 4 (b) shows the results of research conducted at HAI industry on the pressure drop (ΔP_p) reduction on both sides of PHE plate for each plate size (i.e., 0.15×0.3; 0.2×0.4; 0.3×0.6; and 0.4×0.8 m). Both sides of the plate have equivalent Reynolds numbers with respect to the pressure drop values. The hot fluid side of the PHE provides the highest pressure drop value, which is 10.62 kPa. On the other side, it reaches 40.18 kPa. Both pressure drops were obtained using a 0.4×0.8 m geometry plate design (variable D). Increasing the fluid flow velocity, or Reynolds number, can cause an increase in the ΔP_p value in the PHE design in the HAI industry. This achievement is similar to that of [15], where high Reynolds numbers can affect the pressure drop value. The PHE design in this industry has the limitation that the allowed pressure drop value is in the range of 30-35 kPa. This limit is also applied by [17], [25]. Therefore, the ΔP_p value obtained on the cooler side of the PHE has the highest value and exceeds the maximum limit. Indirectly, the PHE design in the case study at HAI Industry has a limitation for plate size of 0.3×0.6 m with a ΔP_p value of 29.07 kPa. If the ΔP_p value exceeds the design ΔP_p value, the HAI industry will experience a decrease in PHE equipment efficiency. In addition, the management also experiences an increase in design and operational costs [26]. The improved performance of the heat exchanger equipment enables low energy consumption and easy maintenance if regular maintenance processes are carried out [27].

The pressure drop resulting from the PHE equipment design can be taken into consideration by adjusting the HAI industry process management towards the selection of the plate spacing and chevron angle values used in the design (in this study, 30^{o}). The greater use of chevron angle values (i.e., 45 and 60) is able to provide an increase in pressure drop and continues to decrease the efficiency of PHE performance. The involvement of mathematical equations (1) to (12) relates to the heat transfer area of PHE (A_{PHE}), overall heat transfer coefficient (U), and pressure drop (ΔP). These can be compared using simulation programs such as HTRI (Heat Transfer Research Inc.), Aspen Hysis, and similar software. The purpose of using such software is to compare and predict the suitability of the optimal geometry before installation [28] [29] in the process area. The hypothesis was supported by the presence of practitioners [30] who aimed to achieve the performance of PHE equipment that meets the target of the HAI industry [31], [32] while considering aspects of occupational health and safety, cost-effectiveness, and optimization of operating conditions towards the target of operating the plant in reusing steam condensate water.

4. CONCLUSIONS

The study conducted research on the design of PHE equipment in the HAI industry with empty space for condensate water recirculation from the reactor steam output. The design results show that the applicable geometric dimension is the third plate (0.3×0.6 m). The use of variable C resulted in an overall coefficient heat transfer (U) value of 3090.144 $W/m^2.°C$ with a good mass flow rate compared to other plate geometries. In addition, plate C has a pressure drop below the maximum pressure drop limit set in the literature (i.e., 30–35 kPa). However, equipment design research for PHE in the HAI industry still requires development processes for other factors that can increase design pressure drop. In the future, this research will undergo a comparison process with the size of commercial plate geometry to determine the suitability of process needs. This sustainability will lead to material considerations, performance analysis, and the design suitability of the PHE tool after its installation.

5. NOTATIONS

A	: heat transfer area, m^2
A_f	: channel cross section area, m^2
A_{ip}	: effective area of one plate, m^2
A_{port}	: area port, m^2
C_P	: heat capacity, kJ/kg.K
d_e	: hydraulic mean diameter, m
d_{pt}	: diameter port, mm
F_t	: correction factor value from the graph based on NTU value
F_h	: fouling factor coefficient, kg/m.s
G_p	: mass velocity, $kg/m^2.s$
h_p	: plate film coefficient, $W/m^2.^oC$
j_f	: friction factor
k	: thermal conductivity of fluid, kg/m.s
k_p	: thermal conductivity of the plate construction used, $W/m.^oC$
L	: length of plate – plate geometry, m
L_p	: path length, m
$\dot{m}$	: mass flow rate of fluid, kg/s
N_C	: number of channels per pass
N_P	: number of plates
NTU	: number thermal unit
Nu	: Nusselt number
Pr	: Prandtl number
Q	: beban panas, kJ/s
Re	: Reynolds number
s	: s = thickness of plate, m : $s_{plate\ spacing}$ = thickness of plate spacing, m
T, t	: T_1 = inlet temperature in hot fluid, ^oC : T_2 = outlet temperature in hot fluid, ^oC : t_1 = inlet temperature in cold fluid, ^oC : t_2 = outlet temperature in cold fluid, ^oC
U	: overall heat transfer coefficient, $W/m^2.^oC$
u_p	: channel velocity, m/s
$\dot{V}$	: volumetric rate of fluid, m^3/h
u_{pt}	: velocity through port, m/s
W	: width of plate – plate geometry, m
ρ	: density of fluid, kg/m^3
μ	: viscocity of fluid, kg/m.s
ΔT_{LMTD}	: log mean temperature difference
ΔP	: total pressure drop, N/m^2
ΔP_p	: pressure drop plate, N/m^2
ΔP_{pt}	: pressure loss through port, N/m^2

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