ABSTRACT

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Performance of an Air-Cooled Heat Exchanger in a Separation Unit Based on Fouling Factor and Pressure Drop

(Evaluasi Kinerja Air-Cooled Heat Exchanger Pada Unit Pemisahan Berdasarkan Fouling Factor dan Pressure Drop)

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This is an open access article under the **Creative Commons Attribution-ShareAlike 4.0 International License**. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. CC–BY-SA Heat exchangers transfer heat from a high temperature to a low temperature in a fluid. Air-cooled heat exchangers are one of the most widely used types of heat exchangers, after shell and tube heat exchangers. Its performance is determined by calculating the fouling factor value and the pressure drop. The purpose of this case study is to evaluate the performance of a water-cooled heat exchanger in a plant that produces a thickening agent (CMC, or carboxymethylcellulose), which affects the amount of ethanol produced. Ethanol will cool from 79.347 to 54.133 °C, and air will cool from 31.333 to 59.667 °C as the cold fluid. The calculation results show that both reviews exceed the design threshold of 0.007056 h.ft².°F/Btu. These heat exchangers require maintenance and repair. These results differ from the pressure drop values on the air side and pipe section, which are $1.2.10^{-3}$ inH_2O and 0.647 psia, respectively. Both values remain outside the allowable limits. The performance evaluation of process equipment in the separation unit was aided by field data. The review of the data was able to predict a plant shut-down. This action was able to effect a partial or total plant shut-down due to fouling and scale exceeding design data thresholds.

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1. INTRODUCTION

A heat exchanger, also known as heat transfer equipment, is a device that moves heat from a hot fluid to a colder one. This instrument can be used as a warmer as well as to cool the fluid between liquids or convert gaseous phases to liquids [1]. Air-cooled heat exchangers, shell and tube heat exchangers, double pipe heat exchangers, and plate heat exchangers are among the heat exchanger types that are frequently employed in industry. Only air-cooled heat exchangers, out of the five types, use ambient air as cooling media to condense or cool hot fluids [2]. In four of them, the heat transfer medium is steam or water. Selecting the appropriate heat exchanger type can reduce ongoing running expenses and streamline the maintenance procedure [3].

An air-cooled forced draft heat exchanger is a type of heat exchanger used by CMCproducing plants to cool the top product in distillation. This tool consists of two fans located at the bottom of the tool. The working principle of this tool is to circulate the surrounding air using a fan so that heat transfer between ethanol and air occurs. Long-term use of an air-cooled heat exchanger will affect the performance of the device. As a result, the heat transfer between the fluid (in the form of ethanol) and the air is not maximized, so the ethanol output temperature is less than optimal. In addition, the fan workload also increases and will have an impact on plant operating costs.

Decreased performance on the tool can be caused by several things, such as the formation of scale, corrosion, leakage, or fluid flow that causes friction on the tool wall [4]. Fouling is the formation of a deposit (crust) on the surface of the device so that it can inhibit heat transfer and increase fluid flow resistance in the heat exchanger [5]. This scale is caused by the accumulation (deposition) of material and the flow passing through the heat exchanger [6]. The value of impurities that are close to saturation or exceed the design limit will have an impact on the increased pressure drop value as well [7]. Pressure drops occur due to the frictional force on the fluid flowing through the tube [8]. A small pressure drop value indicates reduced turbulence in the flow in the heat transfer system, so that the amount of heat transferred is reduced, which can increase the work efficiency of the heat exchanger [9]. The decline in heat exchanger performance can be seen from the pressure drop and dirt factor (R_D) values that have exceeded the permissible limits [4]. Analysis of tool performance is useful to prevent losses incurred if the heat exchanger performance is that it can result in the tool stopping operating [10].

Research on heat exchanger performance evaluation based on the value of fouling factor (R_D) and/or pressure drop (ΔP) has been widely conducted. The evaluation of shelland tube-type condensers has been carried out by [5]. His research used the Kern method and obtained a fouling factor value of 0.03851 h.ft².°F/Btu, which exceeded the design limit of 0.00059 h.ft².°F/Btu. The air-cooled heat exchanger at Minarak Brantas Gas, Inc. has also been evaluated for its performance based on the R_D value and obtained a result of 0.003 h.ft².°F/Btu, which exceeds the design data of 0.001 h.ft².°F/Btu [11]. Another review of the effectiveness of shell and tube heat exchangers through pressure drop values has been carried out by [6]. Its performance involves the role of the Aspen Hysys simulator and provides an actual value on the shell side of 0.58 kg/cm² (already exceeding the design limit of 0.46 kg/cm²). While the pressure drop value on the tube side of 0.0185 kg/cm² is still below the permissible value of 0.21 kg/cm².

Based on this background, the purpose of this study is to analyze the performance of the air-cooled heat exchanger at the CMC plant. The method used is the evaluation of fouling factor and pressure drop performance by involving design and actual data on the separation unit. The estimation also uses the Heat Transfer Research Inc. HTRI simulation program as a form of evaluation consideration for the application of mathematical equations (PM).

2. RESEARCH METHODS

Data Collection

The processes and stages carried out in the research are:

- 1) Reference study regarding water-cooled heat exchanger units
- 2) Collection of design data and equipment operating conditions
- 3) Data processing to obtain the performance of the air-cooled heat exchanger equipment, which is reviewed and compared with design data
- 4) Follow-up action from the results of the analysis in step (3) on the part of the company

The materials used to support the four research steps were the collection of primary data and secondary data related to air-cooled heat exchangers. Primary data is in the form of operating conditions and tool design, which are presented in Table 1. Meanwhile, secondary data is data obtained from the results of primary data calculations. Data collection was carried out for one month at one of the factories in Bekasi district. Then, the method used to complete this case study is an analysis activity based on heat transfer using design data and operating conditions when the heat exchanger is working.

Tube Side	2	Air Side	
Outside diameter	1 in	Inlet air pressure	1 bar
Inside diameter	0.87 in	Outlet air pressure	1 bar
Tube length	11 m	Pressure drop allowance	8.19 inH ₂ O
Number of tubes	186	Fin	
Number of tube passes	1	Fin height	5/8 in
Number of tube rows	4	Fin thickness	0.401 mm
Tube bundle length	11.5 m	Number of fins per 1 in	10
Pressure drop allowance	1.0515 psia		
Fouling factor allowance	2.888 x 10 ⁻⁴ h.ft ² .°F/Btu		

Table 1.	Air-cooled	heat	exchanger	design	data
I able I.	mi coolcu	ncat	CACHanger	ucoign	uata

Performance of An Air-Cooled Heat Exchanger

The determination of fouling factor and pressure drop values requires fluid property data such as heat capacity, density, viscosity, heat conductivity, and others. The value of these properties for ethanol is obtained through reference [12], and air comes from [2]. Mathematical equations (1) to (14) are a series of steps to evaluate the value of the fouling factor and pressure drop in the separation unit of the CMC plant.

The energy balance is estimated using the following equation (1):

$$Q_{\text{ethanol}} = Q_{\text{air}}$$
(1)
$$(\dot{m} \times Cp \times \Delta T)_{\text{ethanol}} = (\dot{m} \times Cp \times \Delta T)_{\text{air}}$$

Log Mean Temperature Difference (LMTD) is the average temperature difference between two fluids. Equation (2) presents the LMTD value:

$$\Delta T_{\rm LMTD} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)}$$
(2)

The heat transfer area requires the value of the LMTD correction factor (F), which can be helped by Figure 1 through the involvement of equation (3). The curve used depends on the type of flow, number of tube rows, and number of tube passes of the heat exchanger.

$$R = \frac{T_1 - T_2}{t_1 - t_2} \qquad S = \frac{T_1 - T_2}{t_1 - t_2} \qquad \Delta T_m = F \times \Delta T_{LMTD} \qquad (3)$$



Figure 1. LMTD correction factor LMTD correction factor [2]

The Reynolds number value is estimated through equation (4) to be forwarded to the calculation of the tube-side heat transfer coefficient and the air-side heat transfer coefficient in equations (5–6), respectively.

$$N_{\rm Re} = \frac{4\dot{m}_{\rm ethanol}}{\pi \times D_{\rm i} \times \mu} \tag{4}$$

$$h_{i} = (k/D_{i}) \times 0.023 N_{Re}^{0.8} \times Pr^{1/3}(\mu/\mu_{w}^{0.14})$$
(5)

$$\mathbf{h}_{o} = (\mathbf{k}/\mathbf{D}_{r}) \times \mathbf{N}\mathbf{u} \tag{6}$$

Equation (7) is used to calculate the air-side pressure drop value:

$$\Delta P_{\rm f} = \frac{9,22 \times 10^{-10} \,\mathrm{f} \,\mathrm{N}_{\rm Re} \mathrm{G}^2}{\rho_{\rm air}} \tag{7}$$
$$\Delta P_{\rm o} \cong 1,1\Delta P_{\rm f}$$

The tube-side pressure drop is shown in equation (8) below.

$$\Delta P_{f} = \frac{f n_{p} L G^{2}}{7,50 \times 10^{12} D_{i} s \phi}$$

$$\Delta P_{r} = 1,334 \times 10^{-13} (3,25 n_{p} - 1,5) G^{2}/s$$

$$\Delta P_{n} = 4,0 \times 10^{-13} G_{n}^{2}/s$$

$$\Delta P_{i} = \Delta P_{f} + \Delta P_{r} + \Delta P_{n}$$
(8)

Equations (9) to (10) are used to calculate the fin efficiency value and heat transfer area:

$$\eta_{\rm w} = \left(A_{\rm prime}/A_{\rm tot}\right) + \eta_{\rm f}(A_{\rm fins}/A_{\rm tot}) \tag{9}$$

$$A = n_t \times L \times A_{tot} / L \tag{10}$$

Persamaan (11) hingga (13) digunakan untuk menghitung nilai required overall coefficient (U_{req}) , clean overall coefficient (U_C) , dan design overall coefficient (U_D) :

$$U_{req} = \frac{Q}{A \,\Delta T_m} \tag{11}$$

$$U_{\rm C} = \left[\frac{(A_{\rm tot}/A_{\rm i})}{h_{\rm i}} + \frac{(A_{\rm tot}/L)\ln(D_{\rm r}/D_{\rm i})}{2\pi k_{\rm tube}} + \frac{1}{\eta_{\rm w} h_{\rm o}}\right]^{-1}$$
(12)

$$U_{\rm D} = \left[\frac{(A_{\rm tot}/A_{\rm i})}{h_{\rm i}} + \frac{R_{\rm Di}A_{\rm tot}}{A_{\rm i}} + \frac{(A_{\rm tot}/L)\ln(D_{\rm r}/D_{\rm i})}{2\pi k_{\rm tube}} + \frac{1}{\eta_{\rm w}h_{\rm o}} + \frac{R_{\rm Do}}{\eta_{\rm w}}\right]^{-1}$$
(13)

The fouling factor value on the air-cooled heat exchanger can be calculated using equation (14).

$$R_{\rm D} = \frac{U_{\rm C} - U_{\rm D}}{U_{\rm C} \times U_{\rm D}} \tag{14}$$

Simulation Using The HTRI Program

HTRI is a program used for rating, checking, designing, and/or simulating various types of heat exchangers, such as shell and tube, non-tubular exchangers, air coolers and economizers, and fired heaters [13]. The appearance of the input data in the HTRI simulation program is shown in Figure 2 below. Then, the case mode used in this study is rating because its role is to evaluate the performance of the tool. The data required to start the simulation are the design data of the air-cooled heat exchanger (presented in Table 1) and the operating condition data (mass flow rate, input and output temperatures of the cold and hot fluids).

🔜 Xace - [Input] - Simulasi air cooled 3 - I	nput Summary					
Input Summary	Case Mode					
Process	Rating	Simulation		ssic design (Grid design	
Hot Fluid Properties	- Process Condition	s				
Unit	Flow rate	Hot Inside	9.3764	1000-lb/hr	Cold Outsid	de 22.5839 1000-lb/hr
·····• Fans	Inlet/outlet Y	0 /	0	wt. frac. vapor	Altitude	0 ft
Optional Bundle	Inlet/outlet T	174.83 /	129.44	F	88.39	/ 139.4 F
Tube Types	Inlet P/Allow dP	1		psia / psi	i i	/ psia / inH2O
Bundle Layout	Unit Geometry			-		
Design	Unit type	Air-cooled he	at exchanger	~	Number of bays in	n parallel per unit 1 🗸
± ↓ Control	Orientation	Horizontal		~	Number of bundle	es in parallel per bay 1 🗸
	Hot fluid	Inside tubes	\sim		Number of tubepa	asses per bundle
			1.			
	Apex angle		deg			
	- Tube and Bundle	Geometry				
	Туре	High Fin		<i>y</i> -	Wall thickness	0.065 V inch
	Length	36.089	ft		No. of tuberows	4
	00	1 ~	inch		No. of tubes in	47 / 46
			1		odd/even rows	
	Transverse pitch	3	inch		Tube form	Straight 🗸
	Longitudinal pitch	3	inch		Tube layout	○ Staggered ● Inline
<< Previous Next >>						
Input Reports C Graphs CD D	rawinos www.Multir	le Services 🛄 I	Design	Session		··
Test unbor all reports and oraphis and o	ionings withink					Xace 7.3

Figure 2. Layout of field data input on HTRI

3. RESULTS AND DISCUSSIONS

Each heat exchanger has a different performance that depends on the design of the device and the operating conditions when the device is used. The performance of an air-cooled heat exchanger can be determined based on the fouling factor and pressure drop values. In calculating these two parameters, the design data and operating conditions of the air-cooled heat exchanger [2] are presented in Table 1 previously. The evaluation results from the application of mathematical equations (1-14) and the use of the HTRI program are presented in Figure 3 and Table 2 below.

Parameter			PM	HTRI
Heat transfer rate	Q	Btu/h	277,573.9327	296,400.000
Mass flow rate	m	lb/h		
Air side			22,583.5109	22,584
Tube side			9,736.28002	9,376
Temperature difference	ΔT	°F	32.8203	32.800
Heat transfer coefficient		Btu/h.ft ² .°F		
Air side	$\mathbf{h}_{\mathbf{i}}$		0.7732	0.340
Tube side	ho		15.0406	36.870
Overall coefficient		Btu/h.ft ² .°F		
Cleam	U _C		0.3390	0.279
Design	U_D		0.3382	0.278
Fouling factor	R_{D}	h.ft ² .ºF/Btu	0.007056	0.01289
Pressure drop	ΔP			
Air side		inH ₂ O	0.0012	0.0009470
Tube side		psia	0.6479	0.6200

Table 2. Performance evaluation of an air-cooled heat exchanger at the CMC Bekasi plant

TTTT	Output	Summar	y			Page 1	
Released to the following company:							
Vere 7.9.9.44/94/9099.40:09.5N: 48899.							
Xabe 7.3.2 11/21/2023 12.2	5 SN. 40035-					05 Units	
Rating-Horizontal air-cooled h	1eat exchanger	forced draft	cocurrent to a	crossflow			
No Data Check Messages.							
See Runtime Message Repo	rt for Warning I	Messages.					
Process Co	nditions		Outsi	ide	Tubeside		
Fluid name		Udara			Ethanol		
Fluid condition				Sens. Gas		Sens. Liquid	
Total flow rate	(1000-lb/hr)			22.584		9.376	
Weight fraction vapor, In/Out			1.0000	1.0000	0.0000	0.0000	
Temperature, In/Out	(Deg F)		88.39	139.40	174.83	129.44	
Skin temperature, Min/Max	(Deg F)		112.00	168.80	112.12	168.92	
Pressure, Inlet/Outlet	(psia)		14.697	14.697	0.000	0.000	
Pressure drop, Total/Allow	(inH2O)	(psi)	9.47e-4	0.000	0.620	0.000	
Midpoint velocity	(ft/sec)			0.29		6.82e-2	
- In/Out	(ft/sec)				6.94e-2	6.75e-2	
Heat transfer safety factor	()			1.0000		1.0000	
Fouling	(ft2-hr-F/Btu)			0.00000		0.00028	
Exchanger Performance							
Outside film coef	(Btu/ft2-hr-F)		0.34	Actual U	(Btu/ft2-hr-F)	0.278	
Tubeside film coef	(Btu/ft2-hr-F)		36.87	Required U	(Btu/ft2-hr-F)	0.244	
Clean coef	(Btu/ft2-hr-F)		0.279	Area	(ft2)	37102	
Hot regime		Se	ens. Liquid	Overdesign	(%)	14.25	
Cold regime			Sens. Gas		Tube Geomet	ry .	
EMTD	(Deg F)		32.8	Tube type		High-finned	
Duty	(MM Btu/hr)		0.296	Tube OD	(inch)	1.0000	
	Unit Geor	metry		Tube ID	(inch)	0.8700	
Bays in parallel per unit			1	Length	(ft)	36.089	
Bundles parallel per bay			1	Area ratio(o	ut/in) ()	24.724	
Extended area	(ft2)		37102	Layout		Inline	
Bare area	(ft2)		1724.9	Trans pitch	(inch)	3.0000	
Bundle width	(ft)		14.764	Long pitch	(inch)	3.0000	
Nozzle		Inlet	Outlet	Number of p	passes ()	1	
Number	()	1	1	Number of r	rows ()	4	
Diameter	(inch)	1.0490	1.0490	Tubecount	()	186	

Figure 3. Layout of the estimated evaluation results of an air-cooled heat exchanger through HTRI

This case study was completed through direct observation of the separation process unit and air-cooled heat exchanger equipment. This equipment plays an important role in the purification process because more ethanol is fed back (recycled). This reduces the production cost of the plant. Unlike other types of heat exchangers that use water as a cooling medium, this tool uses air as a cooling medium. The air is circulated using two fans, each of which has 10 blades. The motor drives each fan. The contacted air has the same temperature as the ambient temperature of $28-35^{\circ}$ C. The air cools the ethanol with a temperature of $\sim 80^{\circ}$ C in the tube so that its temperature drops to $\sim 54^{\circ}$ C. For the process of taking data on operating conditions in the air-cooled heat exchanger tool, it is done three times and becomes the average value.

Table 2 shows an insignificant difference in calculation results between the application of mathematical equations and the HTRI program. This achievement is due to differences in data processing such as viscosity and heat conductivity values that affect the values of heat transfer rate (Q), design overall coefficient (U_D), and clean overall coefficient (U_C) [14]. In addition to these results, Table 2 also shows the actual pressure drop value on the tube side is below the design data of 0.647 < 1.0515 psia. The air side pressure drop also shows the same result, which is below the design data of $1.2.10^{-3} < 8.15$ inH2O. Meanwhile, the actual fouling factor value has exceeded the design data (~7.1.10⁻³ > 0.000288 h.ft².°F/Btu). This result is influenced by the overall heat transfer value when the equipment is fouled (U_D) and also when there is no fouling or cleanliness (U_C) [9]. The increase in the fouling factor value is due to the fairly long use of the tool. The use is able to present deposits from the fluid flowing in the tube and have an impact on the formation of corrosion [11]. In addition, the presence of fouling can also be caused by crystallization, biological processes, corrosion, chemical reactions, and freezing or solidification [15].

Simulation calculations that have been carried out by [16] at an air flow speed of 2.39 m/s produce a pressure drop value of 177 Pa and form an impurity thickness of 0.4 mm. Operating conditions in the form of fluid flow velocity affect the fouling factor value, where the value will decrease as the flow rate increases [17]. In addition, tube material, fluid type, and temperature increase also affect the fouling factor value. A review of heat exchanger equipment for the desalination industry that has been carried out by [18] shows that an increase in temperature above 60°C on Cu-Ni 90/10 material passed by synthetic seawater can cause fouling formation to become unstable, and as a result, the degradation and corrosion process on the tool becomes faster. Simulation results that have been carried out by researchers [19] using Aspen EDR show that the lower the fluid flow rate, the lower the resulting pressure drop. Factors that affect the pressure drop value are the fluid flow rate through the tube, tube length, number of passes, and cleanliness of the cooling medium entering the condenser [20].

Fouling can cause back pressure, which can increase pumping power [21]. Cleaning of these heat exchanger parts is an option to reduce the value of the fouling factor, which can be in the form of using chemicals or replacing parts [22]. Routine maintenance activities can reduce heat and energy losses and result in a longer service life for process equipment

[23]. The action is also aimed at reducing the possibility of shut-downs in the event of part replacement because the company does not have a spare heat exchanger at the factory site.

Calculations through empirical equations can be accompanied by simulation programs (for example, HTRI, Heat Transfer Research Inc., and the like) to help cross-check and reduce problem-solving time [19-20]. In addition, the involvement of industry and practitioners in the company will help handle follow-up and optimization of operating conditions in the operating field after theoretical lectures in universities can be implemented in practice [24–28], which is simple for internship students [29] as a practical activity [30]. The possibility of further activities, such as the re-design of air-cooled heat transfer process equipment in the future, is an alternative as a form of down- or up-capacity through the feed mass flow rate. Similarly, similar research on process equipment has been applied to the petroleum fluid lifting industry sector [31].

4. CONCLUSIONS

Performance evaluation review of the air-cooled heat exchanger has been completed at the CMC plant in Bekasi district. A comparison of results between calculations and design data shows that cleaning of the exchanger is required. This is supported by the fouling factor of 0.007056 h.ft².°F/Btu, which is above the permissible limit (0.000288 h.ft².°F/Btu), although the pressure drop values on the air ($1.2.10^{-3} < 8.19$ inH2O) and tube (0.647 < 1.0515 psia) sides are not. Routine supervision of process equipment work evaluation through field data is one indicator of periodic inspection to reduce the presence of fouling and scale in preventing the possibility of partial or total plant shut-down.

5. DECLARATIONS

The authors declare no competing interests.

6. ACKNOWLEDGEMENTS

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7. NOTATIONS

A	: heat transfer surface area
A _{fins}	: fin surface area
Ai	: inner surface area of the tube
Ao	: the outer surface area of the root tube
A _{tot}	: total surface area of the finned tube
Ср	: heat capacity
Di	: inner diameter

- n_p : number of tube passes
- Pr : Prandtl number
- Q : heat transfer rate
- R_D : fouling factor
- R_{Di} : tube-side fouling factor
- s : spesific gravity
- U_D : design the overall heat transfer coefficient

D _r	: outer diameter	ΔP_{f}	: pressure drop*
F	: LMTD correction factor	ΔPi	: total pressure drop for tube-side fluid
f	: friction factor	ΔP_n	: pressure loss in tube-side nozzles
G	: flux mass	ΔP_o	: total air-side pressure loss
G _n	: the mass of flux in the nozzle	ΔP_r	: tube-side pressure drop**
k	: heat conductivity	ΔT	: temperature difference
L	: tube length	η_{f}	: fin efficiency
ṁ	: mass flow rate	η_w	: weighted efficiency of finned surface
N _{Re}	: Reynolds number	μ	: fluid viscosity
Nu	: Nusselt number	μ_w	: fluid viscosity***
Nr	: number of tube rows	ρ	: fluid density
n _f	: number of fins per unit length	ø	: viscosity correction factor
*001100	d by fluid friction on the straight part of the	tubo c	or in the flow across the tube bundle

*caused by fluid friction on the straight part of the tube or in the flow across the tube bundle. ** Tube side pressure drops due to tube entrance, exit, and return losses.

***, which is evaluated at the average tube wall temperature.

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