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Heat Transfer Characteristics in Vertical Tubular Baffle Internal Reboiler through Dimensional Analysis

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Abstract. Heat transfer in shell and tube heat exchangers is in general described in terms of the relationships of Nuselt, Prandtl, and Reynold dimensionless numbers. One of the parameters of heat exchanger performance is convective heat transfer coefficient (h), and mathematical model can predict it. This study aimed to find out the relationship of the parameters that affected the performance of vertical tubular baffle internal reboiler during ethanol distillation. The mathematical model was developed by a dimensional analysis with the π-Buckingham method. Several influencing parameters during the distillation process were identified to develop a mathematical model. The study was carried out on the distillation process of low-concentration ethanol, i.e., 10%, 20%, 30% using internal reboilers with different tube sizes, i.e., diameters of 1.27 cm, 2.54 cm, 3.81 cm and height of 4 cm, 6 cm, 8 cm, to obtain the value of h observation. Based on the results of the study, a heat transfer model was obtained, i.e., $\boldsymbol{Nu = 1452.29\, Re^{0.357} \left(\frac{D}{L}\right)^{0.023} \left(\frac{TC_p}{v^2}\right)^{-0.148} \left(\frac{D\rho C_p v}{k}\right)^{0.473}}$, where Nu, Re, D, L, T, C_p, v, ρ, and k, are respectively Nuselt, Reynold, tube diameter, tube height, temperature, heat capacity, velocity, mass density, and thermal conductivity of the fluid (material). This model can be used to determine h prediction, and the result is following h observation with equation y = 0.98x and R^2 = 0.99. Based on the results of the study, it is known that differences in material concentration, diameter, and height of the reboiler tube affect the value of h.

Keywords: Dimensional analysis; Internal reboiler; π-Buckingham method

1. Introduction

A distillation process is determined by the type of heat exchanger (reboiler) that serves to heat and evaporate the distilled solution. The temperature in the reboiler is determined by the types of the reboiler and it affects the distillation productivity (Bhanvase et al., 2007 and Foletto, 2015). In general, small-scale distillation uses an internal reboiler, i.e., a heat exchanger located in the bottom column of the distillation equipment and submerged in the distilled solution (Bell et al., 2011).

The types of heat exchangers used as internal reboilers include stub in U-tube bundle

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reboiler (Voigt & Nj, 2013), calandria (Bhanvase et al., 2007), and vertical helical coil (Ghorbani et al., 2010). A design and test of another type of heat exchanger with different shapes and directions of fluid flow were developed by (Susmiati et al., 2019) named vertical tubular baffle. This study showed that the geometry (diameter, height, and the number of tubes) in this type of heat exchanger affects the heat transfer coefficient. As explained by (Abd & Naji, 2017) the heat transfer coefficient in a heat exchanger can be increased by increasing the tube length. (Lei et al., 2017) also stated that different baffle shapes in a shell and tube heat exchanger produce different heat transfer coefficients, i.e., louver baffle is higher than segmental baffle.

A vertical tubular baffle heat exchanger as a reboiler in an ethanol distillation process has been carried out by (Susmiati et al., 2021) and it was found that different reboiler geometries produced different distillation ethanol concentrations. This shows that different geometries lead to other heat transfer coefficients, thus leading to different productivity of the distillation process. This is in line with (Parhi et al., 2019) and (Badi et al., 2021), who stated that increasing the productivity of distillation equipment can be carried out by optimizing reboiler heat input.

The characteristics of a heat exchanger's performance include heat transfer rate, heat transfer coefficient, pressure drop coefficient, and friction factor. The heat transfer coefficient in a heat exchanger can be determined based on the Nuselt number (Kim et al., 2017). A study on heat transfer in spiral heat exchangers with different impellers was done by (Rosa et al., 2017) showing that the overall heat transfer coefficient is a function of the Nusselt (Nu), Reynolds (Re), Prandtl (Pr) numbers, and wall temperature (Vi) i.e., $Nu = 0.81Re^{0.64}Pr^{0.33}Vi^{0.14}$ on a pitched blade turbine impeller and $Nu = 0.10Re^{0.83}Pr^{0.33}Vi^{0.14}$ on Ruston turbine impeller.

The relationship among the Nuselt, Prandtl, and Reynold dimensionless numbers can be used to predict the convective heat transfer coefficient in a heat exchanger. The heat transfer model of a heat exchanger can be developed by a dimensional analysis as conducted by (Lin et al., 2007) on the characteristics of heat transfer in corrugated channels of a plate heat exchanger. (Nakla, 2011) also developed a heat transfer model on film boiling using dimensional analysis to calculate the effect of diameter on heat transfer coefficient. Dimensional analysis is useful to explain a phenomenon that is found in a process and described as a mathematical model (Pexton, 2014).

Several parameters affect the performance of a vertical tubular baffle internal reboiler in an ethanol distillation process, i.e., fluid temperature (T), viscosity (μ), and mass density (ρ) of fluid, diameter (D), and height (L) of reboiler tube. For the development of the instrument, it is important to have a model that describes the heat transfer process and the relationship between the influencing parameters, thus helping the scale-up and engineering processes. The relationship among these parameters can be expressed in an equation of Nuselt, Prandtl, and Reynolds dimensionless numbers with dimensional analysis. This study aimed to develop a mathematical model of heat transfer in a vertical tubular baffle internal reboiler using dimensional analysis and the π-Buckingham method.

2. Methods

2.1. *Heat Transfer Model with a Dimensional Analysis and π-Buckingham Method*

The performance of the heat transfer in the internal reboiler was affected by several parameters, as listed in Table (1). If the convective heat transfer coefficient (h) was a function of performance, then the influencing parameters were the variables of the function as shown in the following equation.

$$h = f\left(\rho, \mu, C_p, k, v, T, D, L, t\right) \tag{1}$$

According to the dimensional analysis and the π-Buckingham method, the number of the dimensionless numbers formed was equal to the number of the process variables deducted by the number of the dimensions (Loubière et al., 2019). As shown in Table (1) there were four dimensions and ten variables identified during the process, so there were six dimensionless numbers (π) as follows:

$\pi_1 = \frac{Dh}{k}$ $\pi_4 = \frac{D}{L}$

$\pi_2 = \frac{\mu C_p}{k}$ $\pi_5 = \frac{TC_p}{v^2}$

$\pi_3 = \frac{D\rho v}{\mu}$ $\pi_6 = \frac{D\rho C_p v}{k}$

Table 1 Thermal processing variables in internal reboiler with the units and dimensions

No	Variable	Symbol	Unit	Dimension
	Process and instrument			
1.	Fluid temperature	T	°C	θ
2.	Reboiler tube diameter	D	m	L
3.	Reboiler tube height	L	m	L
4.	Mass density of fluid	ρ	kg/m^3	ML^{-3}
5.	Viscosity of fluid	μ	kg/ms	$ML^{-1}T^{-1}$
6.	Heat capacity of fluid	Cp	J/kg°C	$L^2T^{-2}\theta^{-1}$
7.	Thermal conductivity of the fluid	k	J/sm°C	$MLT^{-3}\theta^{-1}$
8.	Velocity of fluid	v	m/s	LT^{-1}
9.	Thermal processing time	t	s	T
	Output			
10.	Convective heat transfer coefficient	H	J/sm^2°C	$MT^{-3}\theta^{-1}$

Based on the dimensionless numbers, the convective heat transfer coefficient was included in dimensionless number π_1 so according to equation (1), it can be elaborated that π_1 served as the function of π_2 to π_6 and can be expressed in the following equation.

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6) \quad (2)$$

By entering the parameters, equation (2) is:

$$\frac{Dh}{k} = C\left(\frac{\mu C_p}{k}\right)^a \left(\frac{D\rho v}{\mu}\right)^b \left(\frac{D}{L}\right)^c \left(\frac{TC_p}{v^2}\right)^d \left(\frac{D\rho C_p v}{k}\right)^e \quad (3)$$

So, the value of h was determined using the equation below.

$$h = C\left(\frac{k}{D}\right)\left(\frac{\mu C_p}{k}\right)^a \left(\frac{D\rho v}{\mu}\right)^b \left(\frac{D}{L}\right)^c \left(\frac{TC_p}{v^2}\right)^d \left(\frac{D\rho C_p v}{k}\right)^e \quad (4)$$

The values of constant C, a, b, c, d, e were determined using a multiple linear regression analysis based on the experimental data, as has been done by Witdarko (2016) to determine the convection heat transfer coefficient in mechanical pneumatic drying of cassava flour.

2.2. Convective Heat Transfer Coefficient in an Internal Reboiler

In an ethanol distillation process, the heating of materials takes place in a reboiler and there is either conductive or convective heat transfer. Conductive heat transfer takes place in the internal plate that is used to make the reboiler tubes and the bottom as shown in Figure (1. b), while convective heat transfer takes place in two places, i.e., on the surface of the plate and on the reboiler tube that is in direct contact with the steam and on the surface of the plate and on the reboiler tube that is in direct contact with the materials. The comparison between internal conductive heat transfer and external convective heat transfer, which is called the resistance value (Biot number), can be neglected because the temperature in the reboiler (plate and tube) is almost uniform, so it can be called a lumped system. This is because the plate that makes up the reboiler has a high thermal conductivity value and it is placed in a medium with low conductivity (fluid), i.e., steam and water.

The convective heat received by the materials is the same as the heat that takes place on the surface of the tube and reboiler plate as expressed in the formula below (Demedeiros et al., 2009).

$$-\rho C_p V \frac{dT}{dt} = hA(T - T_\infty) \tag{5}$$

Where ρ and V are the mass density and volume of the material, respectively. The product of the two is the mass of the material, so the formula can be changed as follows.

$$-mC_p \frac{dT}{dt} = hA(T - T_\infty) \tag{6}$$

$$\int_{T_0}^{T} \frac{dT}{(T-T_\infty)} = -\frac{hA}{mC_p}\int_{t_0}^{t} dt \tag{7}$$

$$\ln\left(\frac{T_0-T_\infty}{T-T_\infty}\right) = -\frac{hA}{mC_p}t \tag{8}$$

Equation (8) is identical to the Cartesian equation of a straight line with t as the value of x and $\ln\left(\frac{T_0-T_\infty}{T-T_\infty}\right)$ as the ordinate (y-axis), gradient b is the value of $\frac{hA}{mC_p}$. Therefore, the value of h (convective heat transfer coefficient) of observation is determined as follows.

$$h = \frac{bmC_p}{A} \tag{9}$$

The value of the convective heat transfer coefficient (h observation) was used as data to determine the values of the constants in the mathematical equations obtained from the dimensional analysis. The mathematical model was used to determine the value of the h prediction. The mathematical model was validated by plotting h observation and h prediction on a Cartesian graph. Statistical analysis using SPSS 25 was done to determine the effect of the experimental variations on the value of h and determine which experimental variation produced the best h value.

2.3. Laboratory Experiment

Vertical tubular baffle internal reboilers with different tube diameters and heights were used in laboratory-scale rectification distillation equipment as shown in Figure (1. a). Distillation equipment consisted of a condenser that was 32 cm in length and 6.35 cm in diameter, a distillation column was 76 cm in height and 5.08 cm in diameter, a reboiler column was 30 cm in height and 20 cm in diameter, and a boiler was 30 cm in height and 20 cm in diameter. The size variations of the internal reboilers were 1.27, 2.54, and 3.81 cm in diameter as well as 4, 6, and 8 cm in height whose shape and dimensions were shown by Figures (1. c and 1.d). The material used in the distillation process was a low-concentration ethanol solution, i.e., 10%, 20%, and 30%. Before being placed into the distillation equipment, the mass density of the material (ρ) was first measured using a 10 ml pycnometer with a gravimetric method (Zhang et al., 2018). An empty and dry 10 ml pycnometer was weighed using an analytical balance with an accuracy of 0.01 gr with a maximum capacity of 200 gr and the pycnometer mass (m_P) was obtained. The empty pycnometer is filled with water or material, then dried and weighed in the same manner and temperature as the empty pycnometer so that the weight of the pycnometer and water (m_W) or the weight of the pycnometer and materials (m_M) is obtained. The density of the material is determined by the following equation.

$$\rho_M = \rho_W \frac{m_M - m_P}{m_W - m_P} \tag{10}$$

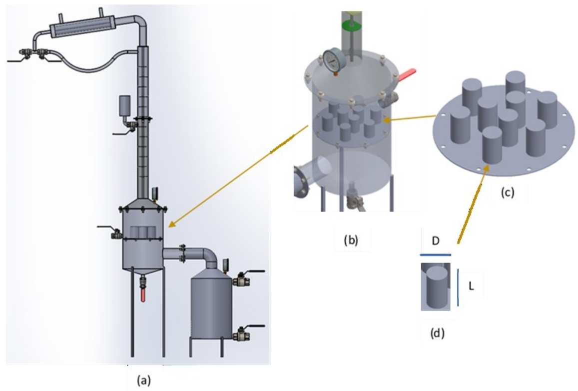

Figure 1 (a) Ethanol distillation instrument, (b) Bottom column, (c) Internal Reboiler Vertical Tubullar Baffle, (d) Reboiler tube dimension

The distillation process was carried out in batches with a material volume of 3500 ml, assuming that the internal reboiler tube was completely submerged in the liquid material. The change in the temperature of the material in the reboiler during the process was measured by a thermocouple once every five minutes. The processing time was also recorded from the beginning to the end of the distillation process (Susmiati et al., 2021).

Some of the influencing parameters were determined based on the literature, i.e., the value of k and μ on the saturated ethanol table (Perry et al., 1997). The value of ρ measured during the experiment was used to calculate the value of material C_p, while the value of v was the velocity of the fluid (material) of which the value was the amount of material placed into the reboiler per unit area and unit time.

3. Results and Discussion

3.1. Convective Heat Transfer Coefficient (h observation) in Internal Reboiler

The convective heat transfer coefficient (h) was obtained based on the data of the material temperature in the reboiler and calculated using equations (8) and (9). An example of a Cartesian graph to calculate the value of h is shown in Figure (2). The calculation results of the value of h observation in all the experiments are shown in Table (2). Calculating the value of h using the Lump system formula was also done by (Witdarko et al., 2016) to determine the convective heat transfer coefficient during the process of drying cassava flour. (Siswantoro et al., 2012) also used this formula to determine the value of h observation during the process of frying crackers with sand media.

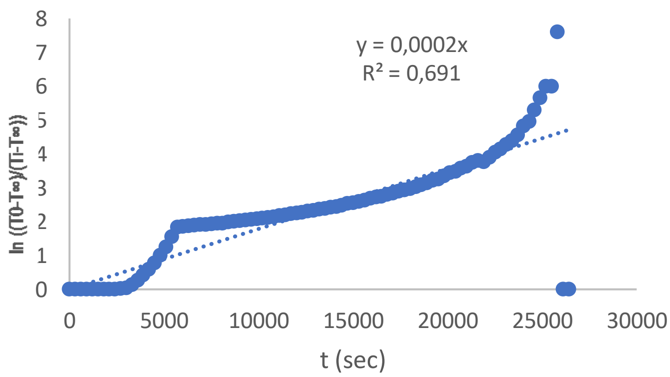

Figure 2 Cartesien graph to determine the value of h in the experiment using a diameter of 0.5 inch, a tube height of 4 cm, and an ethanol concentration of 30%

In addition to the value of h observation, Table (2) also shows that the temperature of the material in the reboiler during the distillation process with each experimental variation varied. In all the concentrations, the temperature of the material increased with an increasing tube reboiler diameter; according to (Wicaksono et al., 2019) the temperature inside the heat exchanger increased with increasing heat exchanger surface area. However, the temperature difference in this study was not significant because the distillation equipment was set up at the same temperature. At this temperature, there was a difference in the value of *h* at different concentrations, i.e., the lower the concentration of the material, the higher the value of *h*. The difference in the concentration of the material led to a difference in the specific heat of the material, leading to a difference in the heat transfer rate. The lower the concentration of the material, the higher the water content, the higher the mass density (ρ) and specific heat (Cp) of the material, the higher the heat transfer rate, the higher the convective heat transfer coefficient.

Table 2 Temperature and convective heat transfer coefficient in experimental variations

D (cm)	L (cm)	D/L	n tube	T (°C)			h obs (J/m²s°C)		
				F10%	F20%	F30%	F10%	F 20%	F30%
1.27	4	0.32	17	94.37	94.23	94.37	194.87	91.66	85.80
	6	0.21	12	93.97	93.57	93.90	146.90	138.24	85.80
	8	0.16	9	93.73	93.57	93.80	196.19	138.22	85.94
2.54	4	0.64	9	95.80	95.57	95.77	147.92	92.18	85.94
	6	0.42	6	95.67	95.77	95.83	147.17	92.00	85.79
	8	0.32	4	95.17	95.17	95.20	147.89	92.73	85.79
3.81	4	0.95	6	96.27	95.53	96.10	147.64	93.07	85.98
	6	0.64	4	96.17	96.00	95.80	148.59	92.68	87.65
	8	0.48	3	95.97	95.93	95.83	149.14	92.12	87.51

The differences in the value of *h* were caused not only by a difference in the temperature and concentration of the materials but also by a difference in the number of tubes in the reboiler. The composition of the tube significantly determines the heat transfer in fluids (materials). At the same surface area, the higher the number of tubes in the reboiler, the faster the heat is evenly transferred in to the fluid. This is because the distance between one tube and the other is not too far, leading to a faster heat transfer rate although the temperature is not too high. This is the following (Fouda et al., 2018), showing that increasing the overall heat transfer coefficient in a heat transfer coil can be done by increasing the coil diameter and the number of tubes in it. A high number of tubes means a small tube diameter. The smaller the tube diameter, the higher the convection heat transfer coefficient. Choi and Oh (2011) also proved that in the investigation of two-phase flow boiling heat transfer of R-410A and R-134A in small horizontal tubes.

3.2. Mathematical Model of Heat Transfer in Internal Reboiler during Ethanol Distillation Process

The convective heat transfer coefficient of the observation was one of the data entered into equation (3) along with the value of other parameters, thus obtaining constant C = 1452.29, a = 0, b = 0.357, c = 0.023, d = -0.148, and e = 0.473. The values of the constants were substituted into equation (3), thus obtaining a new equation with constants as follows.

$$\frac{Dh}{k} = 1452.29\left(\frac{D\rho v}{\mu}\right)^{0.357}\left(\frac{D}{L}\right)^{0.023}\left(\frac{TC_p}{v^2}\right)^{-0.148}\left(\frac{D\rho C_p v}{k}\right)^{0.473} \quad (11)$$

Equation (11) is the relationship of the Nuselt and Reynolds dimensionless numbers which can be expressed in equation (12).

$$Nu = 1452.29 Re^{0.357} \left(\frac{D}{L}\right)^{0.023} \left(\frac{TC_p}{v^2}\right)^{-0.148} \left(\frac{D\rho C_p v}{k}\right)^{0.473} \quad (12)$$

Equation (11) was used as the basis for predicting the value of h following equation (4). The validation of the mathematical model was shown by comparing *h* observation and *h* prediction as shown in Figure (3). Based on the result of the validation, it can be seen that the value of h prediction was closed to the value of h observation with equation y = 0.9832x, and $R^2 = 0.99$. This shows that the model can be used to predict the value of *h* and the result was similar to the actual phenomenon (99% similarity). The same technique was done by (Loubière et al., 2019) to compare the calculation results of the prediction and observation in a study on the performance of stromal cell bioreactor with dimensional analysis. (Kim et al., 2017) also performed the same thing, i.e., comparing the theoretical Nuselt number with the experimental Nuselt number in a study on the characteristics of heat exchanger performance with internal turbulence generators under varied blade configurations and operational conditions.

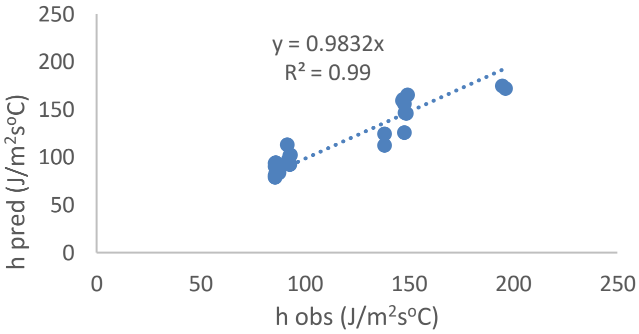

Figure 3 Comparison between h observation and h prediction

3.3. Effect of Differences in Diameter, Tube Height, and Concentration of Materials on Convective Heat Transfer Coefficient (h)

The statistical analysis results of the convective heat transfer coefficient with SPSS 25 showed that there was a highly significant effect of variations in diameters and concentrations on the value of *h*, but variations in height did not have any effect on the value of *h*. The experimental variation that produced the highest value of *h* according to Duncan's test was 1.27 cm in diameter, 8 cm in height, and 10% in concentration with the value of *h* of 196.19 J/m^2s^oC.

A change in the diameter of the reboiler tube changed the Nuselt and Reynold numbers according to equation (9). Figure (4) presents the relationship between the Nuselt and Reynold numbers during the process, i.e., the higher the Reynold number, the higher the Nuselt number. This is in line with several other studies on heat exchangers that there was a significant relationship between the Nuselt and Reynold numbers, where the higher the Reynold number, the higher the Nuselt number (Putra et al., 2013; Kim et al., 2017; Liaw et al., 2021; and Fouda et al., 2018). An increase in the tube reboiler diameter, increased Reynold and Nuselt number.

It is shown in Figure (5) that there was a difference in the value of h at each material concentration and an increase in the *D/L* ratio, in general, decreased the value of h. The lower the material concentration, the higher the value of h. The 10% concentration produced the highest value of h, while the value of h was the lowest at the concentration of 30%. This is in line with several previous studies, showing that the *L/D* ratio in the internal reboiler had an effect on the ethanol concentration and ethanol yield in the distillation process. The higher the L/D value, the lower the D/L value, the higher the ethanol concentration (Susmiati et al., 2021). High mass density at low material concentration caused high heat capacity, while low D/L means low tube pitch, and this caused high h.

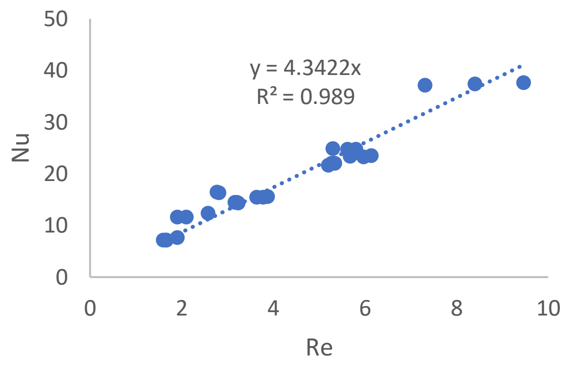

Figure 4 Relationship between Nuselt and Reynold number

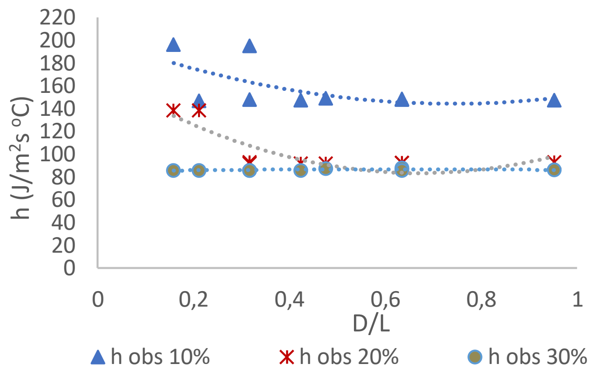

Figure 5 Relationship between D/L and h observation

Based on the mathematical model formed, i.e., equation (12), it was known that Prantld number did not influence the heat transfer in the vertical tubular baffle internal reboiler because the process was carried out at the same temperature. As stated by (Alimoradi, 2017), the viscosity and thermal conductivity of fluid are influenced by temperature. In addition, a difference in the tube diameter and mass density of the material brought a significant difference in the convective heat transfer coefficient. This is because of a change in the Reynold number. An increase in the Reynold number can increase the overall heat transfer coefficient (Putra et al., 2013 and Fouda, et.al., 2018). An increase in the heat transfer coefficient in a heat exchanger is related to geometric parameters and Reynold number (Ghorbani et al., 2010 and Alimoradi, 2017). An addition of twisted tape in the heat transfer tube (Padmanabhan et al., 2021) and fins on a helical coil (Tuncer et al., 2021) can also increase the heat transfer coefficient.

4. Conclusions

The heat transfer in the vertical tubular baffle internal reboiler during the ethanol distillation process can be described in the form of a relationship of various influencing parameters and $Nu = 1452.29\, Re^{0.357} \left(\frac{D}{L}\right)^{0.023} \left(\frac{TC_p}{v^2}\right)^{-0.148} \left(\frac{D\rho C_p v}{k}\right)^{0.473}$ was obtained, where $Nu, Re, D, L, T, Cp, v, \rho,$ and k, are respectively Nuselt, Reynold, tube diameter, tube height, temperature, heat capacity, velocity, mass density, and thermal conductivity of the fluid (material). The mathematical model can be used to determine the convective heat transfer coefficient (h) and its validity reaches 99%. The highest convective heat transfer coefficient was obtained in the experiment with a reboiler that was 1.27 cm in diameter and 8 cm in height, and a 10% material concentration, i.e., 196.19 J/m^{2}s^{o}C.

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References

Abd, A.A., Naji, S.Z., 2017. Case Studies in Thermal Engineering Analysis Study of Shell and Tube Heat Exchanger for Clough Company with Reselect Different Parameters to Improve the Design. *Case Studies in Thermal Engineering*, Volume 10, pp. 455–467

Alimoradi, A., 2017. Case Studies in Thermal Engineering Study of Thermal Effectiveness and its Relation with NTU in Shell and Helically Coiled Tube Heat Exchangers. *Case Studies in Thermal Engineering*, Volume 9, pp. 100–107

Badi, D., Al Helal, A., Lagat, C., Phan, C., Barifcani, A., 2021. Evaluation of Reboiler Temperature Retention Time in MEG Degradation Products at Varying MEG Concentrations. *Journal of Petroleum Science and Engineering*, Volume 196, p. 107735

Bell, J.A., Bouck, D., Farone, J.P., Flowers, J., Grave, E., Kister, H.Z., Marut, T., Morehead, P., Olsson, R., Parker, J., Summers, D.R., De Villiers, W.E., Wilder, L., Xu, S., Yeoman, N., 2011. Reboiler Circuits for Trayed Columns. *Chemical Engineering*, Volume 118(1)

Bhanvase, B.A., Deosarkar, M.P., Shirsath, S.R., Gaikwad, R.W., 2007. Internal Reboiler in the Distillation Column. *Chemical Engineering World*, Volume 42(6), pp. 86–88

Choi, K., Oh, J., 2011. Two-Phase Flow Boiling Heat Transfer of R-410A and R-134A in Horizontal Small Tubes. *International Journal of Technology*, Volume 2(2), pp. 139–146

Demedeiros, A., Ferguson, R., Powers, B., 2009. Transient Response Characteristics and Lumped System Analysis of Geometrically Similar Objects. Available online at https://studylib.net/doc/18343208/transient-response-characteristics-and-lumped-system-anal

Foletto, E.L., 2015. Operation Parameters of a Small-Scale Batch Distillation Column for Hydrous Ethanol Fuel (HEF) Production. *Ingeniería e Investigación*, Volume 35(1), pp. 31–35

Fouda, A., Nada, S.A., Elattar, H.F., Refaey, H.A., Bin-mahfouz, A.S., 2018. International Journal of Mechanical Sciences Thermal Performance Modeling of Turbulent Flow in Multi-Tube in Tube Helically Coiled Heat Exchangers. *International Journal of Mechanical Sciences*, Volume 135, pp. 621–638

Ghorbani, N., Taherian, H., Gorji, M., Mirgolbabaei, H., 2010. Experimental Study of Mixed Convection Heat Transfer in Vertical Helically Coiled Tube Heat Exchangers. *Experimental Thermal and Fluid Science*, Volume 34(7), pp. 900–905

Kim, D., Joshua, E., Pialago, T., Shin, J., Kyung, O., Kim, M., Woo, C., 2017. Performance Characteristics of Heat Exchanger with Internal Turbulence Generators under Various Blade Configurations and Operating Conditions. *Applied Thermal Engineering*, Volume 123, pp. 562–572

Lei, Y., Li, Y., Jing, S., Song, C., Lyu, Y., Wang, F., 2017. Design and Performance Analysis of the Novel Shell-and-Tube Heat Exchangers with Louver Baffles. *Applied Thermal Engineering*, Voluem 125, pp. 870–879

Liaw, K.L., Kurnia, J.C., Sasmito, A.P., 2021. Turbulent Convective Heat Transfer in the Helical Tube with Twisted Tape Insert. *International Journal of Heat and Mass Transfer*, Volume 169, p. 120918

Lin, J.H., Huang, C.Y., Su, C.C., 2007. Dimensional Analysis for the Heat Transfer Characteristics in the Corrugated Channels of Plate Heat Exchangers. International Communications in Heat and Mass Transfer, Voluem 34(3), pp. 304–312

Loubière, C., Delafosse, A., Guedon, E., Chevalot, I., Toye, D., Olmos, E., 2019. Dimensional Analysis and CFD Simulations of Microcarrier Just Suspended State In Mesenchymal Stromal Cells Bioreactors. *Chemical Engineering Science*, Volume 203, pp. 464–474

Nakla, M. El. 2011. International Journal of Multiphase Flow on Fluid-To-Fluid Modeling of Film Boiling Heat Transfer using Dimensional Analysis. *International Journal of Multiphase Flow*, Volume 37(2), pp. 229–234

Padmanabhan, S., Reddy, O.Y., Yadav, K.V.A.K., Raja, V.K.B., Palanikumar, K., 2021. Heat Transfer Analysis of Double Tube Heat Exchanger with Helical Inserts. *Materials Today: Proceedings*, Volume 46(part 9), pp. 3588–3595

Parhi, S.S., Rangaiah, G.P., Jana, A.K., 2019. Optimizing Reboiler Duty and Reflux Ratio Profiles of Vapor Recompressed Batch Distillation. *Separation and Purification Technology*, Volume 213, pp. 553–570

Perry, R.H., Green, D.W., Maloney, J.O., 1997. *Chemical Engineers' Handbook Seventh*. McGraw-Hill, USA

Pexton, M., 2014. How Dimensional Analysis Can Explain. *Synthese*, Volume 191(10), pp. 2333–2351

Putra, N., Septiadi, W.N., Julian, G., Maulana, A., Irwansyah, R., 2013. An Experimental Study on Thermal Performance of Nanofluids in Microchannel Heat Exchangers. *International Journal of Technology*, Volume 4(2), pp. 167–177

Rosa, S., Elena, M., Taqueda, S., Luis, J., Paiva, D., Silva, M., Moraes, D., 2017. Nusselt's Correlations in Agitated Tanks using the Spiral Coil with Rushton Turbine and PBT 45° Impeller. Comparison With Tanks Containing Vertical Tube Baffles. *Applied Thermal Engineering*, Volume 110, pp. 1331–1342

Siswantoro, Rahardjo, B., Bintoro, N., Hastuti, P., 2012. Mathematical Modeling of Heat and Mass Transfer on Frying by using Sand as a Medium for Transferring Heat. *Agritech*, Volume 32(1), pp. 87–97

Susmiati, Y., Purwantana, B., Bintoro, N., Rahayoe, S., 2019. Design and Testing of the Vertical Tubular Baffle Heat Exchanger as an Internal Reboiler in the Distillation Device. *IOP Conference Series: Earth and Environmental Science*, Volume 355(1), 012001

Susmiati, Y., Purwantana, B., Bintoro, N., Rahayoe, S., 2021. Kinerja Internal Reboiler Tipe Vertical Tubular Baffle pada Proses Distilasi Etanol secara Batch (*Internal Performance of Vertical Tubular Baffle Reboiler in Batch Ethanol Distillation Process*). *Jurnal Rekayasa Proses*, Volume 15(1), p. 59

Tuncer, A.D., Sözen, A., Khanlari, A., Gürbüz, E.Y., Variyenli, H.İ., 2021. Upgrading the Performance of a New Shell and Helically Coiled Heat Exchanger by using Longitudinal Fins. *Applied Thermal Engineering*, Volume 191, p. 116876

Voigt, I., Nj, D.U.P., 2013. Modular Evaporators. *International Sugar Journal,* Volume 116(1382), pp. 119–123

Wicaksono, R.P.S., Fathia, S.H., Kolang, I.F., Riadi, A., Nirbito, W., Muharam, Y., Nugroho, Y.S., 2019. Effect of the Heat Transfer Surface on Prevention of Spontaneous Combustion of Coal. *International Journal of Technology*, Volume 10(6), pp. 1220–1227

Witdarko, Y., Bintoro, N., Suratmo, B., Rahardjo, B., 2016. Pemodelan pada Pengeringan Pneumatik Mekanis Tepung Kasava: Hubungan Koefisien Pindah Panas dengan Variabel Pengeringan (*Modelling on Mechanical Cassava Flour Pneumatic Drying: Correlation of Heat Transfer Coefficient and Drying Variables*). *Agritech*, Volume 36(3), pp. 362–368

Zhang, T., Hu, J., Tang, S., 2018. Densities and Surface Tensions of Ionic Liquids/Sulfuric Acid Binary Mixtures. *Chinese Journal of Chemical Engineering*, Volume 26(7), pp. 1513–1521