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Pitch ratio effect on the effectiveness of condenser for essential oil distillation

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Abstract

This research is focused in the usage of the helical coil pipe to shorten the distillation time which then aimed to obtain a helical coil pipe condenser configuration with an effective pitch ratio to shorten the distillation time. The pitch ratio value is varied from 2.10 to 4.20. The experimental results show that the effectiveness of the condenser decreases as the pitch ratio increases, where the maximum effectiveness at the pitch ratio of 2.10 is 74.13%, while the minimum pitch ratio of 4.20 is 67.19%. The maximum effectiveness is obtained at a pitch ratio of 2.10 due to a larger heat transfer contact area which results in an increase in the actual heat transfer as well. The experimental results with a pitch ratio of 2.10 obtained a condensate temperature of 37.29 ℃ which is 22.71 ℃ and a distillation time of only 2 hours compared to the results of the straight pipe condenser used by the SME group. The effect of the helical coil pipe pitch ratio obtained from the experimental results with a mean deviation value of 2.81% compared to the numerical study. It is concluded that the maximum condenser effectiveness is at the minimum pitch ratio value and then the pitch ratio of 2.10 can be used for clove essential oil distillation process.

***Keywords**: Pitch ratio; helical coil pipe; condenser; effectiveness; clove essential oil*

1. INTRODUCTION

The distillation process of essential oil derived from clove plants using the steamed method, where the main components of distillation consist of a boiler, condenser (cooling pipe), cooling tank, separator, and oil reservoir [1]. Clove oil is a business product that revives SMEs scattered in Indonesia, because it is needed in various industries such as the cosmetic industry [2], pharmacy [3-5], food and drink [6], and fuel oil additives [7]. The author's initial study is that the condenser model in the clove essential oil distillation system by SMEs still uses a straight pipe condenser with a high condensate temperature of 60-70 C and a distillation time of 5-6 hours. This shows that the process of refining clove essential oil with a straight pipe condenser is not optimal.

Several previous studies have been carried out to optimize the effectiveness of heat exchangers, by comparing helical coil pipes and straight pipes. Helical coil pipe is a very effective device for heat exchange because of the large heat transfer area and heat transfer coefficient compared to straight pipe if placed in the same dimensional space [8-9]. Efforts to increase the effectiveness of the coil-shell and pipe-in-pipe helical pipe configuration heat exchangers are influenced by the curvature ratio (d/D), mass flow rate, type of flow interaction (parallel and counter flow), flow pattern (laminar and turbulent) which have an impact on increasing the convection heat transfer coefficient, The overall heat transfer coefficient and the effectiveness of the helical coil pipe heat exchanger are more favorable than the straight pipe [9–12].

To optimize the effectiveness of the helical coil heat exchanger, experimental and numerical studies have been carried out on natural, turbulent, and mixed convection heat transfer mechanisms. Research on the natural convection phenomenon of helical pipe heat exchangers with vertical and horizontal positions, where the effectiveness of the heat exchanger is affected by the parameters; mass flow rate, helical radius ratio (D/d), pitch ratio (p/d) and tube length ratio (L/d) [13], experimental study of mixed convection heat transfer in a vertical helical coil pipe heat exchanger, it is concluded that the effect of coil pipe diameter is negligible and the coil surface area has a negative effect on the shell side convection heat transfer coefficient [14], numerical study of the effectiveness of helical pipe heat exchangers and validation with experimental data [15], a study of the calculation of the rate of heat transfer and entropy generation for forced convection heat transfer in helical pipes, where the critical value and optimal value are sought to increase the COP value (heat transfer rate per entropy generated) [16], The theoretical analysis of the heat transfer mechanism of the helical pipe heat exchanger, the results show that the effectiveness of the helical pipe heat exchanger is very high because the secondary flow movement is perpendicular to the main flow caused by the centrifugal force of the fluid. [17], numerical analysis of the effectiveness of the helical pipe heat exchanger by varying the pitch distance and tube diameter on the effectiveness of the heat exchanger [18], analysis of the effectiveness of helical pipe heat exchanger for eucalyptus essential oil distillation numerically by varying the pitch ratio. The results obtained that the greater the pitch ratio of the effectiveness of the heat exchanger the lower the effectiveness where the maximum effectiveness is at a pitch ratio of 2.1 of 75.9% [19].

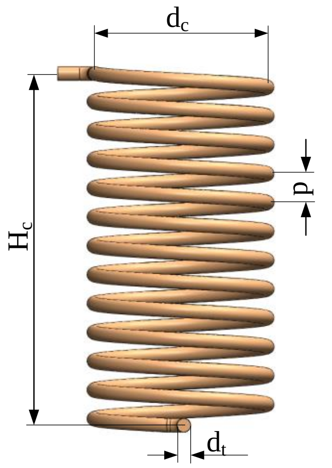
Although many studies on the helical pipe coil and shell side of the heat exchanger correlate with the convection heat transfer coefficient and the effectiveness of the heat exchanger, but there is not much information regarding the introduction of the helical coil pipe in the condenser of the essential oil distillation system. The new innovation carried out in this research is the introduction of helical coil pipes to shorten the distillation time, because the convection transfer coefficient in helical coils is greater than straight pipes due to secondary flow movement caused by the effect of curvature and centrifugal force [20].

The main focus of this research is to obtain a helical coil condenser configuration with an effective pitch ratio to shorten the distillation time. The research was carried out theoretically based on experimental data and validated the results of experimental studies on effectiveness calculations with numerical effectiveness to examine the natural convection heat transfer coefficient on the helical coil pipe side and the forced convection transfer coefficient on the shell side which leads to the calculation of effectiveness for various dimensionless pitch ratio.

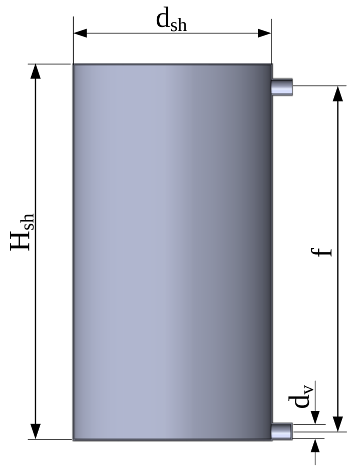
2. METHODS

2.1 Characteristics of coil helical pipe condenser

The type of clove essential oil distillation condenser consists of two main parts, namely; condenser shell and condenser coil helical pipe are presented in Figure 1. The coil helical pipe has an inner diameter, $d_{t,i}$ and outside diameter, $d_{t,o}$. Coil helical diameter, d_c (measured between the centre of the pipe), while the distance between two adjacent cycles, called pitch, p. The ratio of pipe diameter to coil diameter is called curvature ratio [21]. The ratio of pitch distance to pipe diameter is called pitch ratio, $p/d_{t,o}$, while the ratio of the coil diameter to the pipe diameter is called the diameter ratio, $d_c/d_{t,o}$ and the ratio of the length of the pipe to the diameter of the pipe is called the ratio of length, $L/d_{t,o}$ [22].



a) Condenser coil helical pipe



b) Condenser shell

Figure 1. Type of condenser and geometric parameters.

Distance between shell inlet and shell outlet, *f*. Shell inlet diameter, d_v. While the shell height and shell width are H_{sh} and d_{sh}. The angle made by the projection of one turn of the coil with the plane perpendicular to the axis is called the helical angle. Read more Table 1 presents the geometric characteristics of the condenser.

Table 1. Geometrical characteristics of the condenser.

Parameters	$d_{t,i}$	$d_{t,o}$	H_c	D_c	d_{sh}	H_{sh}	d_v	f
Value (m)	0.01580	0.01905	0.5	0.24	0.3	0.57	0.03	0.52

Many studies have identified that in a helical coil pipe the flow pattern is very complex due to the increase in the convection heat transfer coefficient due to secondary flow motion caused by helical effects and centrifugal forces [23]. Due to the helical effect, the fluid flow on the outside of the pipe moves faster than the flow on the inside of the pipe. Dean's number is used to characterize the flow in a helical pipe. However, in this study, the flow pattern that occurs in the helical coil pipe occurs naturally due to the clove handle steaming process so it does not discuss Dean's number.

2.2 Experimental set-up and equipment

This research has made a helical coil pipe condenser as a clove essential oil distillation condenser by considering the simulation results. Figure 2 presents the fabrication steps of the helical coil pipe condenser.

The components of the clove essential oil distillation consisted of a boiler, and the condenser (coil and shell helical pipe) was made of G.304 stainless steel. After fabrication, the condenser is perfectly insulated to prevent heat loss from the outer surface of the condenser to the environment. Insulation uses polyurethane foam (PUF) as the first layer and asbestos tape as the second layer.

The condenser is positioned vertically during the experiment, where the flow arrangement is counter flow. Natural convection is considered a boundary condition for the inner and outer surfaces of the coil helical pipe, whereas forced convection is considered a boundary condition for the shell side.

Figure 2. Fabrication steps of helically coiled pipe and shell condenser; (a) helically coiled pipe, (b) placement of the helical coil pipe, (c) final assembly of distillation components (boiler, helical coil pipe, condenser)

2.3 Experimental procedure

The schematic diagram of the experimental set-up is shown in Figure 3. In this study, the hot fluid cycle and the cold fluid cycle occur simultaneously. The hot fluid is steam from the steaming process and the cold fluid is water.

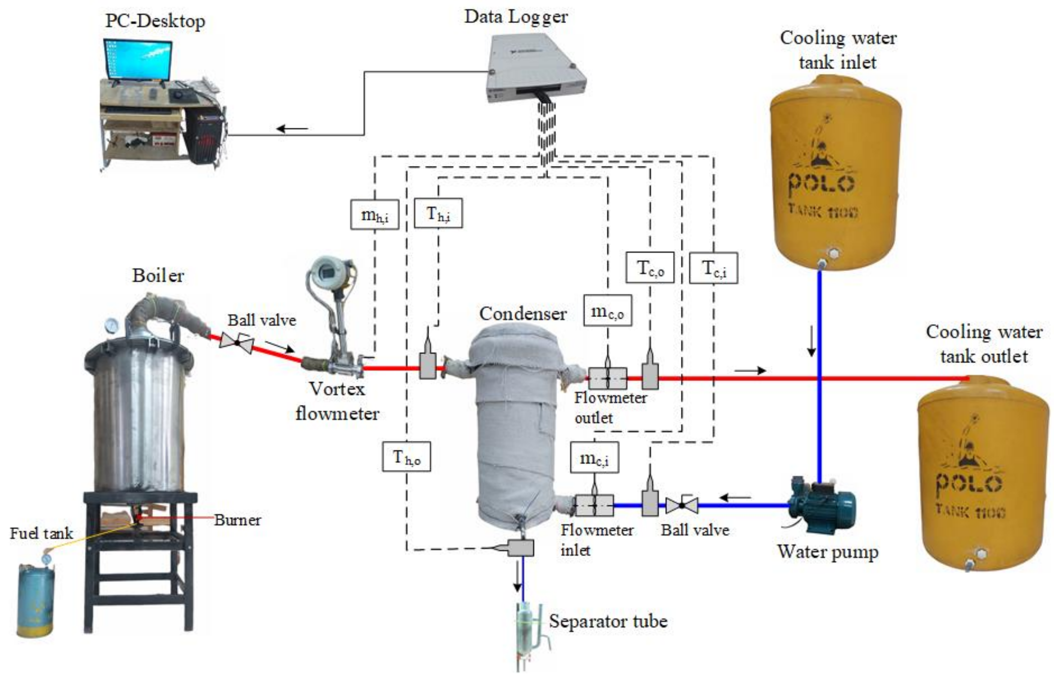


Figure 3. Experimental scheme set-up.

The hot fluid circulation begins by entering 20 litters of water and 5 kg of clove handles into the kettle, where the results of the steaming process take place after the boiler contents pressure of 1 bar and the steam temperature are reached ± 95-100 °C, then the steam from the steam is circulated after opening the ball valve, the steam will go through the vortex flowmeter to detect the mass flow rate of the hot fluid and enter the test section (condenser) on the side of the helical coil pipe.

Simultaneously the cold fluid circulation process also takes place from the inlet cooling water tank which is driven by a Shimizu DB 125 water pump through a ball valve to regulate the mass flow rate of the cold fluid. Furthermore, the cold fluid flows to the test section (condenser) on the shell side after passing through the water flow meter and temperature sensor and then to the outlet water tank. The test section (condenser) was designed and fabricated to carry out several experiments to investigate the effectiveness parameters within the range of operational parameters presented in Table 2.

Table 2. Ranges of operational parameters

Parameters	Range
Pitch (p), m	0.04, 0.05, 0.06, 0.07, 0.08
Number of turns (n)	6.2, 7.4, 8.5, 10.0, 12.2
The pipe length (L), m	4.75, 5.58, 6.40, 7.53, 9.19
Pitch ratio ($p/d_{t,o}$)	2.10, 2.62, 3.15, 3.67, 4.20
Long ratio ($L/d_{t,o}$)	482.62, 395.59, 336.25, 292.74, 249,22

Figure 3 schematic diagram of the experimental set-up with the layout of the LM35 temperature sensor and YF-S201 mass flow rate sensor as follows;

1) Shell inlet and outlet (that is $T_{c,i}$ and $T_{c,o}$)
2) Inlet and outlet of helical coil pipe (that is $T_{h,i}$ and $T_{h,o}$).
3) Measurement of the mass flow rate of cold fluid (water) using the YF-S201 flowmeter sensor with an accuracy of 1%, flowmeter sensor mounted on the inlet and outlet of the shell (that is $m_{c,i}$ and $m_{c,o}$),
4) While measuring the mass flow rate of hot fluid (steam) using a HUANDIAN China brand vortex flowmeter, with an accuracy of 1% is installed between the boiler and the condenser, namely the condenser inlet (that is $m_{h,i}$).

The results of recording temperature and mass flow rate by a data logger are then stored on a PC computer.

2.4 Data reduction

2.4.1 Coil helical pipe side calculation

The working fluid on the side of the helical coil pipe is naturally flowing steam, then the Rayleigh number on the side of the helical coil pipe is calculated by equation (1) which is obtained from [15]:

$$Ra = GrPr = \frac{g\beta(T_s - T_\infty)d^3}{\nu^2} \tag{1}$$

where Gr is Grashof number, Pr is Prandtl number, g is acceleration due to gravity (m/s^2), β is volumetric coefficient of thermal expansion (K^{-1}), ν is fluid kinematic viscosity (m^2/s), T_s is surface temperature (K), T_∞ is ambient temperature (K).

The focus of convection heat transfer is to find the Nusselt number which is the ratio of convection and fluid conduction. Calculation of the Nusselt number on the helical coil pipe, calculated by equation (2) obtained from [22]:

$$Nu_h = 0.0779(Ra)^{0.275}(D/d)^{0.184}(p/d)^{0.212}(L/d)^{0.108} \tag{2}$$

where (D/d) is ratio of coil diameter to pipe diameter, (p/d) is pitch ratio to pipe diameter, (L/d) is ratio of pipe length to pipe diameter.

To calculate the convection coefficient of the coiled helical pipe side (h_i) calculated by equation (2) obtained from [15]:

$$h_i = \frac{Nu_h \cdot k_h}{L} \tag{3}$$

where Nu_h is Nusselt number on the side of the coil helical pipe, k_h is thermal conductivity of the fluid on the pipe side of the helical coil ($W/m \cdot K$), L is helical pipe characteristic length (m).

2.4.2 Shell side calculation

The Reynolds number on the shell side can be calculated by equation (4) which is obtained from [24]:

$$Re = \frac{\rho \cdot u \cdot D_{h,shell}}{\mu_c} \quad (4)$$

where ρ is density of the fluid on the shell side (kg/m^3), u is fluid flow velocity on the shell side (m/s), $D_{h,shell}$ is hydraulic diameter, μ_c is dynamic viscosity ($N.s/m^2$).

Nusselt number on the shell side is calculated by equation (5) which is obtained from [24]:

$$Nu_c = 0.6(Re)^{0.5} Pr_c^{0.31} \quad (5)$$

where Pr_c is Prandtl number on shell side.

The convection heat transfer coefficient on the shell side is calculated by equation (2) which is obtained from [15]:

$$h_i = \frac{Nu_c \cdot k_c}{L} \quad (6)$$

where Nu_c is Nusselt number on shell side, k_c is thermal conduction of the fluid on the shell side ($W/m \cdot K$).

2.4.3 Overall heat transfer coefficient (U)

The overall heat transfer coefficient (U) of the coil side helical pipe and the shell side can be calculated by equation (7) which is obtained from [20]:

$$\frac{1}{U_o} = \frac{1}{A_{ii} h_i} + \frac{ln(d_{t,o}/d_{t,i})}{2\pi k_w L} + \frac{1}{h_o A_{io}} \quad (7)$$

where A_{ii} and A_{io} is the inner and outer surface area of the coil helical pipe respectively (m^2), d_i and d_o is inner and outer diameter of coil helical pipe respectively (m), k_w is heat conductivity of stainless steel coil helical pipe wall ($W/m.K$).

2.4.4 Logarithmic mean temperature difference (LMTD)

The magnitude of the logarithmic mean temperature difference (LMTD) for counter-flow using equation (8) obtained from [25]:

$$LMTD = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{ln\left(\frac{T_{h,o} - T_{c,i}}{T_{h,i} - T_{c,o}}\right)} \quad (8)$$

2.4.5 Effectiveness

Performance calculations are one of the special problems in heat exchanger analysis. The ratio of the actual heat transfer to the maximum possible heat transfer is defined as the effectiveness of the heat exchanger (ε) and is generally used as an approach to analysing performance, calculated by equation (9) obtained from [26]:

$$\varepsilon = \frac{Q_{actuall}}{Q_{max}} \quad (9)$$

If Q_{actuall} can be calculated as using equation (10) obtained from [27]:

$$Q_{actuall} = U \cdot A \cdot \Delta T_{\mathrm{lm}} \quad (10)$$

and Q_{max} can be calculated as using equation (11) obtained from [28]:

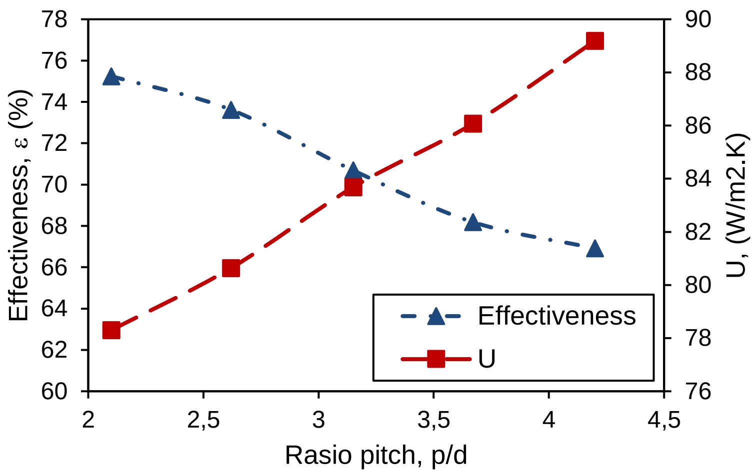
$$Q_{\mathrm{max}} = C_{min}\left(T_{h,i} - T_{h,o}\right) \quad (11)$$

where C_{min} can be calculated as using equation (12) obtained from [27]:

$$C_{min} = \min\left(\dot{m}_h \times c_{p,h}\right) \quad (12)$$

3. Result and Discussion

In this section the curve behaviour of the overall heat transfer coefficient and effectiveness are depicted for the five varied range pitch ratio study provided in Table 2. It is noted that, the cold-water flow rate was kept constant in 0,375 LPM. The curve behaviour of the overall heat transfer coefficient and effectiveness are illustrated in Figure graphic 1.



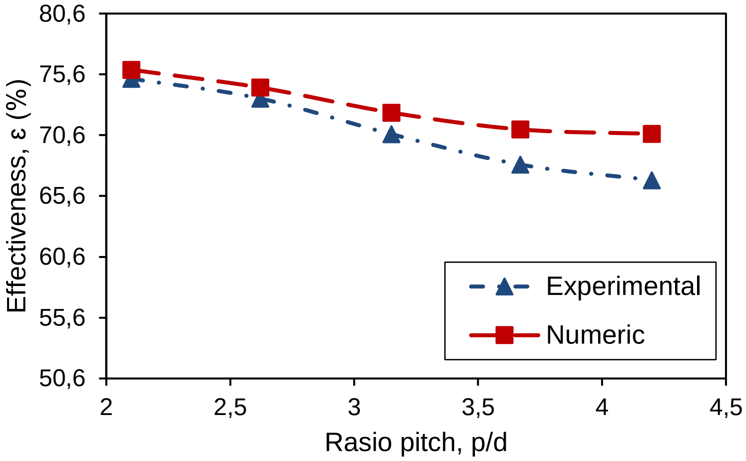
Graphic 1. Curve behaviour of overall heat transfer coefficient and effectiveness against ratio pitch

As can be seen in Figure 4, as the pitch ratio increases, the overall heat transfer coefficient also increases, and the effectiveness decreases. The maximum overall heat transfer coefficient at a pitch ratio of 2.10 is 61.58 W/m^2.K and the minimum at a pitch ratio of 4.20 is 35.78 W/m^2.K. The increase in the overall displacement coefficient is due to an increase in the convection coefficient on the coil side of the helical tube and on the shell side. The increase in the convection coefficient on the side of the helical coil pipe is influenced by the increase in Rayleigh number because the temperature gradient between the surface of the helical coil pipe and the surrounding temperature increases as the pitch ratio increases. Likewise, the increase in the shell side convection coefficient is affected by the increase in Reynolds number, because the hydraulic diameter increases with increasing pitch ratio. This is due to the smaller the heat transfer contact area due to the larger pitch ratio. At a pitch ratio of 2.10, the condensate temperature measured was 37.29 °C and the distillation time was only 2 hours.

The greater the pitch ratio, the lower the effectiveness of the essential oil condenser. The maximum effectiveness at pitch ratio 2.1 is 75.24%, while the minimum at pitch ratio 4.2 is 66.91% (see Figure 4 The decrease in the effectiveness of the condenser is caused by a decrease in the actual and maximum heat transfer. The decrease in actual heat transfer is because the heat transfer contact area decreases with increasing pitch ratio, while the overall heat transfer coefficient and the log average temperature gradient increase. The decrease in actual heat transfer is due to the fact that the heat transfer contact area decreases with increasing pitch ratio, while the overall heat transfer coefficient and the log average temperature gradient increase. The rate of increase in the overall heat transfer coefficient and the log mean temperature gradient is not significant when compared to the rate of decrease in the heat transfer contact area. It can be said that the rate of decrease in the effectiveness of the essential oil condenser is dominated by a decrease in the heat transfer contact area.

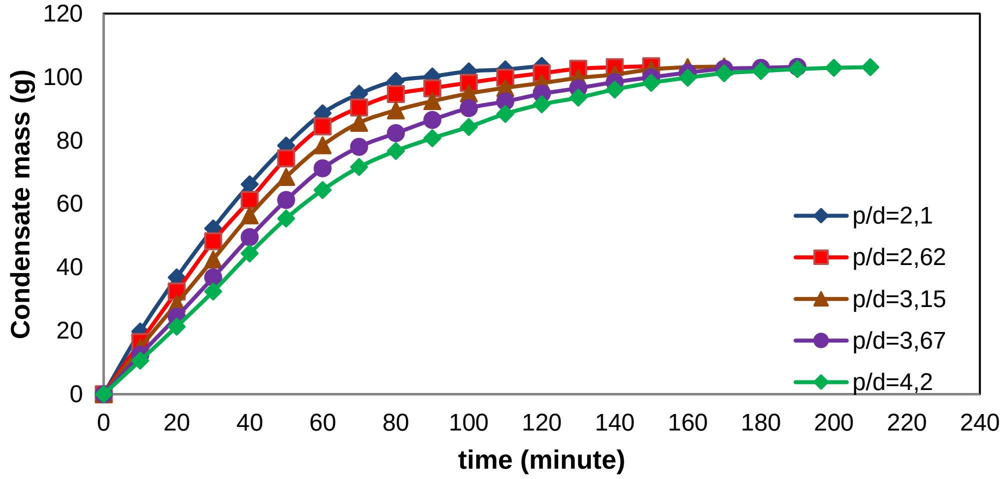
As can see in graphic 2, comparison of the effectiveness of the essential oil condenser experimental and numerical results. It appears that the numerical effectiveness is greater for certain pitch ratios. The effect of the helical coil pipe pitch ratio obtained from the experimental results with a mean deviation value of 2.81% compared to the numerical study. It appears that the numerical effectiveness is greater for the pitch ratio at some point. The maximum effectiveness is at a pitch ratio of 2.1 and the minimum is at a pitch ratio of

4.20. This means that the pitch ratio greater than 2.10 does not affect the effectiveness of the essential oil condenser.



Graphic 2. Comparison of the effectiveness of experimental and numerical results.

The experimental results show that the greater the pitch ratio (p/d), the longer the distillation time, is presented in Figure 6. The minimum distillation time is found at a pitch ratio of 2.10 of 120 minutes while the maximum distillation time of a pitch ratio of 4.20 is 210 minutes.



Graphic 3. Distillation time for various pitch ratios

4. Conclusion

The results of the experimental analysis of the effect of pitch ratio on a constant cold fluid mass flow rate obtained the following results:

1. The greater the pitch ratio, the more accelerated the overall heat transfer coefficient due to the accelerated convection heat transfer coefficient on the helical coil pipe side and the shell side which are affected by the influence of Rayleigh and Reynolds numbers on both sides, respectively.
2. The effectiveness of the condenser is decelerating due to the actual heat transfer decreasing as it is dominated by a decrease in the heat transfer contact area. The maximum effectiveness at 2.10 pitch ratio is 75.24% and the minimum at 4.20 is 66.91%.
3. Comparison of the effectiveness of the condenser between experimental and numerical with an average deviation value of 2.81%.

4. The minimum distillation time is found at a pitch ratio of 2.10 of 120 minutes while the maximum distillation time of a pitch ratio of 4.20 is 210 minutes.

Declaration of Competing Interest
The authors hereby declare there is no conflict of interest in terms of finding/methods or other means that will affect the quality of this research work.

Contribution statement
Nicolas Titahelu: Conceptualization, methodology, original drafting, validation, checking.
Jonny Latuny: Software, data accuracy, investigation, assessment, examination.
Cendy S E Tupamahu: Data accuracy, write-review and editing.
Sefnath Sarwuna: Data accuracy, formal analysis, administration.

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