Study the flow direction and number of tubes in cross-flow heat exchanger to improve the heat transfer coefficient.

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Abstract. This study deals with the effects the number of tube and flow direction on the heat transfer coefficient. This investigation complete by study different lengths of smooth copper tubes (50, 100, 150, 200 and 250) mm with different passes (2, 4, 6, 8 and 10) for cross flow heat exchanger to attain the best length to heat transfer numerically, by Solid work 2017 and ANSYS 16.1 program. The diameters of outer and inner tubes are (24 and 19 mm), air velocity (3 m/s), volumetric flow rate (5 L/min) and the inlet temperature of cold and hot fluid (25 °C and 80° C) respectively. Also been studying the effect of a smooth and triangle finned tube (4 passes) to enhance the heat transfer. Moreover, studying the effect of up and horizontal direction of the flow on heat transfer, by designing smooth tube 8 passes heat exchanger with the same dimension, air velocity inlet (1 m/s), volumetric flow rate (6 L/min), the temperature of the cold fluid inlet (22 °C) and the temperature of the hot fluid (50 °C). It can be noted that whenever the number of passes of tubes increases, the amount of heat transfer increase at the expense of the increase in pressure drop. The finned tube gives better heat improvement than a smooth tube and the direction of flow does not effect on the heat transfer.

Keywords: Cross-flow heat exchanger, flow-direction, length of tube, heat transfer coefficient.

1. Introduction
The subject of heat transfer enhancement in the cross-flow heat exchanger is a very important at the design of effective, economical heat exchanger, lower cost compared with other forms; that give less amount of pressure drop and the tubes can be clean easily. Many researchers have studied a lot of methods to improve the rate of the heat transfer. Rahmah [1] studying experimentally (four and eight passes) for cross flow heat exchanger, with the two types of tubes from aluminum. Smooth tube with inner and outer diameters are (17 and 19 mm) and circular finned tube with inner, outer and root diameters are (17, 22 and 19 mm) the fin height, thickness and pitch (1.5, 1, 1 mm). The results showed that coefficient of the heat transfer of the low integral finned tube is better than smooth tube and the heat exchanger (4 passes is better than 8 passes because the heat transfer coefficient of the four passes is higher than the eight passes and the pressure drop of the four passes is less than the eight passes Abdullah [2] investigated experimentally the performance of cross flow heat exchanger arrangements in staggered tube. The test cross section consists of a draw-through wind tunnel (15×15 cm) set horizontally. The long of the copper tube is 15 cm carried between fabric-based plastic rods, the surface of tubes grooved with depth of (1 mm). The numbers of groves are (14, 29 and 59). It is found that when the Reynolds
number increases the heat transfer increase and the pressure drop decrease. On the other hand, the heat transfers in (14 and 29) groves is higher than the smooth tube in low Reynolds number but in high Reynolds number approximately had the same HT in 59 groves the heat transfer is high for high and low Reynolds number. Because the applications requiring high effectiveness use multi passes heat exchanges, Kadhim et. al. [3] presented experimentally study to the enhancement of heat transfer characteristics for cross flow heat exchanger by using low integral finned tube. The tubes manufacture from copper eight passes (smooth and low integral finned tube). The inner and outer diameters of smooth tube are (19, 24 mm) and the same for finned tube (19, 24 mm) with root diameter (21 mm). The thickness, pitch and height of the fin are (1, 2 and 1.5 mm). Water was used inside the tubes as a hot fluid and air outside the tubes as a cold fluid in the test section. The results showed that the coefficient of heat transfer and the rate of heat transfer of the low integral finned tube are higher than smooth tube. The maximum enhancement percentage of the rate of heat transfer for finned tube was 72.05% higher than the rate of heat transfers for smooth tube. Also, Nusselt’s number for air side finned tube was higher than the smooth tube. Applications requiring high effectiveness use multi passes heat exchanges. Dev and Ardhapurkar [4] carried out numerically the simulation of the cross, counter flow of heat exchanger. The results found that the using of the counter -cross flow arrangement better than using the counter alone or the cross alone in multi passes heat exchanger. Also, suggest for cross-counter direction, best proportion of the cold fluid to give maximum heat transfer performance. Oudah [5] Study the plain tube and three different fins spacing of finned tube heat exchanger models were invent numerically and used to verify the heat transfer coefficient enhancement. The experimental study focused on the effect of fin spacing (longitudinal and angular) on the rate of heat transfer and pressure drop across the heat exchanger. In numerical study used ANSYS design modular and Fluent 18.0 with a (SST) turbulence model to calculate the pressure drop (ΔP), heat transfer rate (Q) and heat transfer coefficient (h). Moreover, four different perforated pin finned tube models were evaluated numerically to show the effect of perforation position on heat transfer and ΔP. The experimental results showed an increase in the ΔP of the three finned tube models as compared with smooth tube. For solid pin finned tube model with circumferential angle between fins of (22.5°) and longitudinal fin spacing (6 mm) the average Nusselt number about 70% higher than that of the smooth tube and the ΔP is 63% higher than smooth tube and when the circumferential angle between fins of (45°) and longitudinal fin spacing (12 mm) it is about 29% higher than smooth tube and the ΔP is about 17% higher than smooth tube. The numerical results showed the average Nusselt number of hole pin finned tube with angle between fins (45°) and longitudinal fin spacing (12 mm) is about 30% higher than the same spacing model with solid fin with increasing of ΔP of approximately 28%. Ravikumar et. al. [6] 3D numerical simulation in ANSYS program smooth and finned tube cross flow heat exchanger has been studied. Calculated by different fin thickness the performance of the single row circular finned tube in cross flow heat exchanger. It’s found that the heat transfer decreases with the fin thickness increase. Krishnan and Gowtham [7] studied the heat transfer rate and pressure drop between classic staggered and double cross flow HE for laminar and turbulent flow, near rows of tubes in the classic staggered arrangement are normal to the fluid flow in the shell but in double cross flow arrangement, the rows of tubes normal to both fluid flow directions in the shell and to each other. The result showed, in the double cross flow the rate of the heat transfer per unit ΔP is higher in 2.5 per cent to 27.1 per cent than staggered heat exchanger. Thirumarimurugan [8] studied experimentally the plate fin cross flow HE with different Gas Liquid systems, using steam with water, Steam with 10% acetic acid and different volumetric flow rate. The results found that the temperature of the cold fluid decreases, the overall heat transfer coefficient increases when the flow rate of cold fluid increase. And the same behavior when increase in composition of the heat capacity of the fluid. The effectiveness decreases when the temperature increases and composition of high heat capacity of the fluid increase. Taher and Kadhim [9] conducted experimental study the effect of fins on transferred heat by eight passes cross flow heat exchanger, manufacture smooth and high integral finned tube. working fluids were air outer the tubes and water in the tubes under the working condition were the velocity of air inlet (1.17 and 2.3 m/s), volumetric flow rate (2.3,4.5 and 6 L/min), the inlet temperature of the air (22 °C) and water (50,60 and 70 °C). The results showed the high integral finned
tube is better than the smooth tube in transferred heat about 391% enhancement ratio and 291% enhancement factor. Jignesh et al. (2014) [10] presents a combined analytical, experimental and numerical investigation of the overall heat transfer coefficient of coolant as water by use of circular finned tube and smooth tube heat exchanger with force convection. The experimental system is quite similar to cars' cooling system. The overall heat transfer coefficient is studied for both heat exchangers with air velocity (3, 4, 5 and 6) m/s and coolant flow (180, 260, 340, 420 and 500) L/hr. The heat transfers and pressure drop results for the circular fin heat exchanger were compared with the results for a smooth tube heat exchanger. The experiment results for overall heat transfer coefficient with the finned tube 14.07W/m2K respect to smooth tube. Also, the increases in air velocity leads to increase in rate of the heat transfers of finned tube due to increasing in Reynolds number and Nusselt number is also increase. The summary of the researchers is finned tube is better than the smooth tube in rate heat transfer and coefficient of heat transfer and when the number of tubes increase rate of the heat transfer increase.

The goal of this study is enhancing the heat transfer by using different number of tubes and the effect of heat exchanger direction. also, to find out the effect of tringle fins on the rate of the heat transfer.

2. Numerical model

2.1 Number of tubes

In this work has study numerically different tubes length (50, 100, 150, 200 and 250 mm), the space between center of tube to the others center tube is 55 mm, the boundary condition of the velocity of the air, volumetric flow rate, inlet temperature of the air and water are (3 m/s, 5 L/min, 25°C and 80 °C). The fluids using inside and outside the tubes are water and air, to attain the better tube which transferred heat. Table 1 shown the dimension of the numerical model, Figure 1 showed the geometry of the different length of tubes.

| Sequence | Lengths | Dimensions (width, length, height) |
|----------|---------|-----------------------------------|
| A        | 2       | 250,400, 165 mm                   |
| B        | 4       | 250,400, 275 mm                   |
| C        | 6       | 250,500, 385 mm                   |
| D        | 8       | 250,600, 495 mm                   |
| E        | 10      | 250,800, 605 mm                   |

Table 1. The dimension of the different tube length.
Figure 1. The geometry of the heat exchanger for different lengths.
2.2 The flow direction

To find if the direction effects on the flow, analysis the test of a smooth tube (8 passes) heat exchanger in ANSYS 16.1 program and designed the geometry in Solid work 2017. The boundary condition of the velocity of the air, volumetric flow rate, inlet temperature of the air and water are (1 m/s, 6 L/min, 22°C and 50°C). Also, the fluids using inside and outside the tubes are water and air. Figure 2 shown the geometry of the horizontal and vertical heat exchangers.

Figure 2. The geometry of (a) the horizontal heat exchanger. (b) the vertical heat exchanger

2.3 Type of the tube (smooth and triangle finned tube)

In solid work 2017 and ANSYS16.1 program designed and analysis the smooth and finned tube. The outer and the inner diameters are (21 and 19 mm) of the smooth tube, (19, 21 and 24 mm) inner, root and outer diameters of the finned tubes. The working fluids are air as cold fluid in the test section (outer the tube) and water as hot fluid inside the tube. By using Naivers stroke (continuity, momentum and energy equations) and k-epsilon model and the inlet boundary condition of air and water temperatures are (25 °C) (50, 60, 70 and 80 °C), volumetric flow rate are (2,3,4 and 5 L/min) and air velocities are (1,2 and 3 m/s). Figure 3 shows the geometry of smooth and finned tube with dimension.
2.3.1 Mesh generation
In this work has used tetrahedral and wedge, these are good for complex shapes. Unstructured mesh has used to allowing the program to select the suitable shape of the mesh in complex places. When increase the number of divisions the element size decrease and the result will be more accurate, also increase the layers of water and air especial near the wall because there is a little movement near the wall. Another important thing term is aspect ratio must be less than 35 for complex shapes [11]. Table 2 includes the numbers of element, node and maximum aspect ratio. Figure 4 shows the mesh of smooth and finned tube.

| Types of tubes   | No. of element | No. of nodes | Max. aspect ratio |
|------------------|----------------|--------------|-------------------|
| Smooth tube      | 4377937        | 798622       | 11.22             |
| Formed tube      | 4458311        | 809438       | 12.888            |

Figure 3. The geometry with dimension of the (A) smooth tube. (B) Finned tube.

Figure 4. The mesh of (a) smooth tube. (b) Finned tube.
2.3.2 Grid independence
Must do test to the mesh to be sure that the results are accurate, and the solution is true, by change in some parameters and repeat the simulation in ANSYS. The method is to increase the number of elements by increasing the element size of the tube and repeat the simulation. The result variations are not significant after the marked cell size as show in Figure 5. This can be considered as the better mesh for the calculation. This mesh size will give better result with less time as compared to more fine mesh.

![Figure 5](image)

**Figure 5.** The test of grid independence between number of element and outlet water temperature.

2.4. Assumptions
To solve the flow and heat transfer equations (continuity, momentum and energy equations) some assumptions must be made to fit the case under consideration.

1- Three-dimensional analysis.
2- Incompressible fluid.
3- Steady state
4- Turbulent flow
5- Physical properties of fluids are constant with temperature.
6- Adiabatic walls of tubes.
7- Negligible heat generation.
8- Negligible Heat radiation and heat dissipation.

3. Basic equations
The rate of heat transfer for cold and hot fluid are: [12]

\[ Q = m_h \cdot C_{p_h} \cdot \Delta t \quad \& \quad Q = m_c \cdot C_{p_c} \cdot \Delta t \]  \hspace{1cm} (1)

The correction factor \((F_c \leq 1)\) equal [13]:

\[ F_c = \frac{\sqrt{(R^2 + 1)} \ln \left[ \frac{(1 - S)}{(1 - RS)} \right]}{(R - 1) \ln \left[ \frac{2 - S \{R + 1 - \sqrt{(R^2 + 1)}\}}{2 - S \{R + 1 + \sqrt{(R^2 + 1)}\}} \right]} \]  \hspace{1cm} (2)
To find the overall heat transfer coefficient (for smooth tube and finned tube) [14, 15]

\[
U_o = \frac{1}{\frac{d_{of} - d_{of}\ln \frac{d_f}{d_i}}{h_i d_i} + \frac{1}{h_0}}
\]  

(3)

\(U_o \neq U_i\) unless \(A_{0s} = A_{is}\) (for smooth and cleaning surfaces tubes)

\[A_{of} = A_{0s} = \pi d_{of} L\]

The Nusselt number in turbulent flow is [16]

\[\text{Nu} = 0.023 Re^{0.8} Pr^n\]  

(4)

The Prandtl number index \((n) = (0.3)\) for cooling process.

The air heat transfer coefficient for smooth tube [12] and for finned tube [15]

\[
h_o = \frac{1}{1 - \frac{d_{of}\ln \left(\frac{d_f}{d_i}\right)}{2K_t} - \frac{d_0}{h_i d_i}} \quad \& \quad h_o = \frac{1}{\frac{d_{of}\ln \left(\frac{d_f}{d_i}\right)}{2K_t} - \frac{d_0}{h_i d_i}}
\]  

(5)

The fluids mixed another unmixed, the effectiveness \((\varepsilon)\) is related to the number of transfer unit (NTU) with these equations [15]:

\[\varepsilon = \frac{C_{max}}{C_{min}} \text{mixed, } C_{min} \text{unmixed and for } C_{max} \text{unmixed, } C_{min} \text{mixed},\]

\[\varepsilon = \frac{1}{C_r} \left(1 - \exp\left[-C_r (1 - e^{-NTU})\right]\right) \quad \& \quad \varepsilon = \left(1 - \exp\left[-\frac{1}{C_r} C_r (1 - e^{-NTU})\right]\right)\]  

(6)

The heat capacity ratio is, \(C_r = \frac{C_{min}}{C_{max}}\)

(7)

The enhancement ratio (ER)

\[ER = \frac{h_{of} - h_{0s}}{h_{0s}} \times 100\]  

(8)

4. Code validation

In order to sure the accuracy of the result and the program used. It has been verified this work and compare the results with [9], by using the boundary condition of the best case of the previous research. The temperature of water 50 °C, air temperature 22 °C and volumetric flow rate 6 l/min. the comparison between rate of the heat transfer with air velocities (1, 1.7 and 2.3 m/s) was made between this study and [9]. The results showed a good match with the source. The results are almost identical to the previous study. The error in the rate of heat transfer is 0.0771%. Figure 6 shows the comparison between this study and [9]. In Figure 4.a due to the low error rate, the two lines are identical in the drawing however, it is illustrated in Figure 4.b.
5. Result and discussion

5.1 Effect of number of tubes

Table 3 shows the different number of tubes with the rates of the heat transfer and the pressure drop, the best length is (10 tubes) because transferred heat more than others but also the pressure drop increase. That’s mean the increasing in the length of the pipes leads to an increase in the rate of the heat transfer on account of the increase in pressure drop, when the number of pipes increases, the surface area increases, so the air is distributed over a larger area and the rate of heat transfer increases. Figure 7 shows when the number of tubes increase the Q increase and the ΔP is increase to. in order to know which length transmits more heat with less pressure. The choice is 4 pipes, because the heat transfer coefficient of the four passes is higher than the eight passes and the pressure drop of the four passes is less than the eight passes depending on previous survey [1].

Table 3. The number of tubes with the rate of heat transfer and pressure drop.

| number of tubes | Q (W)      | Pressure drop of water (pa) |
|----------------|------------|----------------------------|
| 2              | 130.3366   | 124.332893                 |
| 4              | 264.32949  | 259.052294                 |
| 6              | 400.229    | 391.250834                 |
| 8              | 536.08688  | 525.537742                 |
| 10             | 654.58901  | 651.215712                 |

Figure 6. The comparison between the comparative research and the present work, (a) the rate of heat transfer and air velocity. (b) 3-D area chart.
Figure 7. The number of tubes with the rate of heat transfer and pressure drop.

5.2 Effect of flow direction
The results showed that the vertical and the horizontal direction haven’t affect on the rate of the heat transfer and the pressure drop. the values of the vertical are the same to the horizontal values with a very slight difference. This is because the Earth’s gravity is little, and it does not affect the direction of flow. Table 4 showed the values of the inlet and outlet of the water and air (temperature, pressure), the rate of the heat transfers and the pressure drop of the water and air. Figure 8 by values, shows the behavior of the horizontal and vertical heat exchanger.

Table 4. The values of the inlet and outlet parameters of horizontal and vertical heat exchanger.

| Parameters                           | 8 tubes horizontal heat exchanger | 8 tubes vertical heat exchanger |
|--------------------------------------|----------------------------------|--------------------------------|
| Outlet Hot temperature(°C)           | 49.6149                          | 49.638                         |
| Outlet cold temperature(°C)          | 23.03479                         | 23.03326                       |
| Inlet pressure of water (pa)         | 771.55324                        | 770.591                        |
| Outlet pressure of water (pa)        | 66.323583                        | 66.374844                      |
| Pressure drop of water               | 705.229657                       | 704.216156                     |
| Inlet pressure of air(pa)            | 1.09064                          | 1.088031                       |
| Outlet pressure of air(pa)           | 0.624606                         | 0.623995                       |
| pressure Drop of air                 | 0.466034                         | 0.464036                       |
| Rate of the heat transfer(w)         | 157.66841                        | 158.36054                      |
| inlet Hot temperature(°C)            | 50                               | 50                             |
| inlet cold temperature(°C)           | 22                               | 22                             |
| Inlet volumetric flow rate           | 6                                | 6                              |
| Inlet air velocity                   | 1                                | 1                              |
Figure 8. The behavior of the direction of the tubes (vertical and horizontal).

5.3 Effect of finned tube
The results show that the finned tube is better than the smooth tube in heat transfer as Figures below: - Figure 9 shows the coefficient heat transfer of the finned tube is higher than the coefficient heat transfers of the smooth tube at air velocity (1, 2 and 3 m/s). Figure 10 shows that the water temperatures increase and the rate of heat transfer increase when the velocities of air increase. The increase in heat transfer rate due to increase the surface area for fin tube than smooth tube and the turbulence growth between the fins with increasing the air velocity. In Figure 11 shows the pressure drop increases when the volumetric flow rate increase.

Figure 9. The air velocity with the external heat transfer coefficient.
Figure 10. Air velocity with the rate of heat transfer and inlet water temperature.
Figure 11. The volumetric flow rate with the water pressure drop.
6. Conclusions

Conclusions reached from the current study, as listed below:

1. The rate of the heat transfer increase with increasing the length tube.
2. Increasing in the length of tubes leads to increase in the pressure drop.
3. The increasing in water temperature leads to increase in the rate of heat transfer and heat transfer coefficient for water.
4. The rate of heat transfer and the coefficient heat transfer of the finned tube is higher than the smooth tube.
5. When the velocity of air increases the external heat transfer coefficient increase.
6. Increasing in volumetric flow rate leads to increasing in pressure drop.
7. The direction of the flow in the tubes (vertical and horizontal) doesn’t effect on the rate of heat transfer.
8. The enhancement ratio of the rate of heat transfer for the finned tube to the smooth tube is equal to 21.44%.

**Symbols**

| Symbol | Title                  |
|--------|------------------------|
| ΔP     | Pressure drop          |
| h      | Heat transfer coefficient |
| NTU    | Number of transfer unit |
| Q      | The rate of the heat transfer |
| Vi     | Inlet velocity of air  |
| Thi    | Inlet hot temperature  |
| Tho    | Outlet hot temperature |
| Tci    | Inlet cold temperature |
| Tco    | Outlet cold temperature |
| Mw     | Volumetric flow rate   |
| Pi     | Inlet pressure         |
| Po     | Outlet pressure        |

**Abbreviations**

| Symbol | Title                  |
|--------|------------------------|
| HE     | Heat exchanger         |
| CFD    | Computational fluid dynamics |
| HT     | Heat transfer          |
| SST    | Shear stress transport |

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