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CHARACTERISTIC OF ORC FINNED - TUBE CONDENSER DESIGN USING AMMONIA-WATER MIXTURE

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ABSTRACT

Heat exchanger is a device that facilitates the exchange of heat with different temperature between two or more fluids with or without phase changes. Energy recovery by using ORC system is an effective method to recover low grade heat source because organic fluid employs low saturated temperatures in comparison to water. This paper presents the design of a cross flow Organic Rankine Cycle (ORC) condenser using numerical modeling. In this paper, the condenser is numerically design to obtain a designated model for a 3kW heat load with 1kW turbine power. This is achieved by obtaining a suitable mass flow rate using the ORC calculation with 70 % turbine efficiency. Apart from that, the design of the condenser also considers; (1) the size of an extruded finned tube, (2) types of working fluid and (3) fluid temperatures. The condenser design point was established for 75:25 of ammonia-water concentration mixture. Theoretical results show that the requirement number of tube, n is 36 tubes. At n=36, the characteristic of the condenser shows the heat transfer coefficient, UA, of the condenser is 88% higher compared to the base fluid. The internal heat convection occur at the condenser is 28% difference with the external heat convection. This is because of the enhancement by factor of thermal conductivity; k of the mixture is higher compare to the base fluid.

Keywords: organic working fluid, condenser, extruded finned tube, ammonia-water mixture.

INTRODUCTION

Systems such as power plants and heat recovery process in industry are using heat exchanger as a significant role in their operation. General application of heat exchanger involves in heating and coolin to recover or reject heat, distill, concentrate, control a process fluid, sterilize, fractionate, crystallize and pasteurize (Shah, R. K, 2006). A few examples of heat exchangers that commonly used by industries are shell and tube exchanger, condensers, evaporators, air preheaters, cooling towers and automobile radiators. A condenser is an important component in Organic Rankine Cycle (ORC) which is has significant effect on the overall system performance in heat transfer system (J. Wang, Wang, Li, Xia, and Dai, 2013). This cooling device eliminate heat from the gas or vapor; once the heat that removed is sufficient, liquefaction occur.

Nowadays, industries are searching for an effective and satisfy design of heat exchanger that follows the first law of thermodynamics which are; (1) maximum heat exchanger effectiveness, (2) minimum volume and heat transfer surface, and (3) maximum thermodynamic availability (Bracco *et al.*, 2013; Gawande *et al*, 2012; Sekulić and Herman, 1986; D. Wang, Lin *et al.*, 2013). There are many important methods to increase the performance and the energy efficiency of real components and systems. The ideal behavior is usually known from modeling by two of the more widely methods used to analyze heat transfer in heat exchanger which are the log-mean temperature difference method (LMTD) and effectiveness NTU (ε-NTU) (Fakheri, 2007).

Air cooled condenser is an economic condenser compared with water cooled condenser. Furthermore, air cooled finned tube are widely used in various application such as air-conditioning and in refrigeration. Several techniques can be made to improve the performance of air cooled finned tube operation such as (1) changing the tube geometry, (2) enhance the inner pipe surface and (3) apply external fins (Awad *et al.*, 2007).

This paper presents a characteristic of ORC finned-tube of a cross flow condenser. Concentration of 75:25 of ammonia-water mixture is used as working fluid to analyze the requirement number of tubes, n, in the condenser. A few parameters such as tubes diameter size and two phases of working fluid temperature were considered and calculated. The amount of the recovered heat will be analyzed depending on the number of tubes in the condenser to achieved 3 kW heat load.

ORC LAYOUT

The process of this recovery system consists of a few stages:

Stage (1-2): The working fluid is pumped from low pressure to high pressure.

Stage (2-3): The high pressure liquid enters a heat exchanger where it is heated at constant pressure by an external heat source (in this case; exhaust gas) to become a dry saturated vapor.

Stage (3-4): The superheated vapor expands through a turbine, generates mechanical power. This decreases the temperature and pressure of the vapor, and some condensation may occur.

Stage (4-1): The wet vapor then enters a condenser where it is condensed at a constant pressure to become a saturated liquid.

As refer to Figure 1, the evaporator changes the working fluid into the hot vapor and expands it into the turbine. In the turbine, the hot vapor will converts the thermal energy into the mechanical work and generate the power. Then, at the outlet of the turbine the hot vapor is condensed in the condenser and the fluid returns to the evaporator by a pump to close the cycle.

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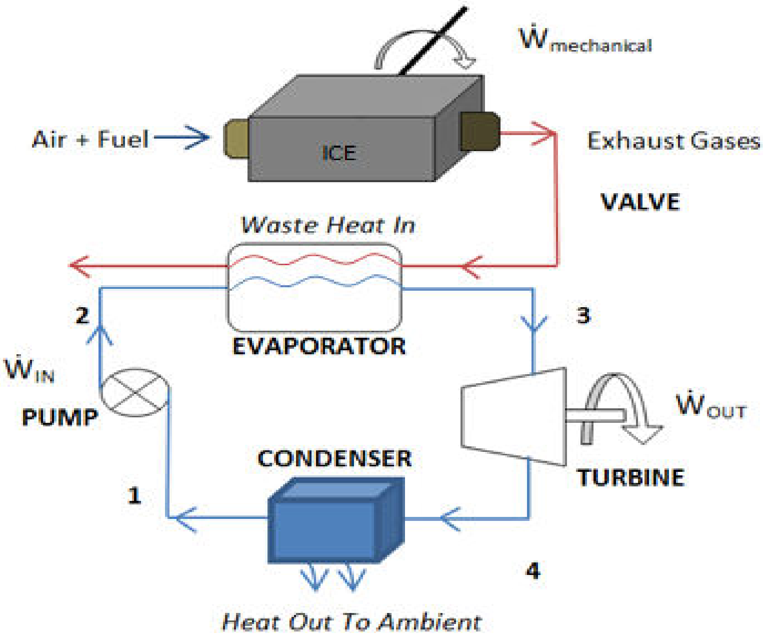

Figure-1. ORC schematic diagram.

HEAT TRANSFER ANALYSIS

Thermal modeling was developed by using a simple design of cross flow heat exchanger as a datum to determine the designated point of a condenser in order to achieve a 3 kW heat load of a condenser. Table-1 shows the parameters of the heat transfer.

Table-1. Heat transfer parameters.

PARAMETER	VALUE	UNIT
Inner diameter	**0.01**	**m**
Outer diameter	0.015	m
Mass flow rate of heat source Mass flow rate of cooling source	0.003 1.649	kg/s kg/s
Heat Transfer Rate (Condenser)	3	kW
Pressure	1	Bar
Cold Fluid Temp. (Air)	in- 26 out-30	°C
Hot Fluid Temp (NH_3: H_20 Mixture)	in -95 out -36.9	°C

Apart from that, ammonia-water mixture has potential to be used as working fluid for the ORC application (X. Zhang, M. He, and Y. Zhang, 2012). The use of ammonia will act as a catalyst to accelerate the boiling temperature of the mixture. The analysis of thermophysical properties of ammonia-water mixture can be used in the investigation of the heat transfer process in the compact heat exchanger.

Table-2 shows the comparison of the thermal conductivity, k of the ammonia-water mixture and the base fluid which is water. At vapor phase; inlet at 95 °C, and liquid phase; outlet at 36.9 °C, the thermal conductivity of ammonia-water mixture is greater than the base fluid with 12% of enhancement.

Table-2. Thermal conductivity of ammonia-water mixture and base fluid.

Temperature, T, (C)	**Thermal conductivity,k, (W/mK)**	
	Mixture	**Base fluid**
Inlet-95	0.02739	0.02455
Outlet-36.9	1.47727	0.67897

The Nusselt number, Nu for the heat transfer inside the tube pipe is calculating using equation is given as,

$$\mathrm{Nu} = 0.026\mathrm{Pr_f}^{1/3}\mathrm{Re_m}^{0.8} \quad (1)$$

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Where Rem is a Reynolds number of a mixture and it is given by Akers, Deans and Crosser (Holman, 2001) as,

$$Re_m = \frac{D_i}{\mu_f}\left[G_f + G_v\left(\frac{\rho_f}{\rho_v}\right)^{1/2}\right] \quad (2)$$

Where D_i = Inner diameter
μ_f = Dynamic viscosity of liquid
G_v = Velocity of mixture at vapor state
G_f = Velocity of mixture at liquid state
ρ_v = Density of mixture at vapour state
ρ_f = Density of mixture at liquid state

For the flow across the tube pipes, the Nusselt number, Nu is calculated using equation (3) which defined by Churchill and Bernstein (Holman, 2001)

$$Nu = 0.3 + \frac{0.62\,Re^{1/2}Pr^{1/3}}{\left[1+\left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{Re}{282{,}000}\right)^{5/8}\right]^{4/5} \quad (3)$$

Equation (3) is applicable for 102 < Re < 107 and Pr > 0.2.

The heat convection coefficient, hex can be determined once the Nu is calculated. The hex can be defined as

$$Nu = \frac{h_{ex}D}{k} \quad (4)$$

The overall heat transfer coefficient, U is the total thermal resistance which exists in the tube pipes. It is given by;

$$\frac{1}{UA_s} = \frac{1}{h_{conv}A_i} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi k_{pipe}l} + \frac{1}{h_{conv}A_o} \quad (5)$$

The equation for condenser power is expressed by,

$$Q = UA\Delta T \quad (6)$$

Where UA= UAn; n = a x b; n, a, b = number of tubes. Refer Figure-2.

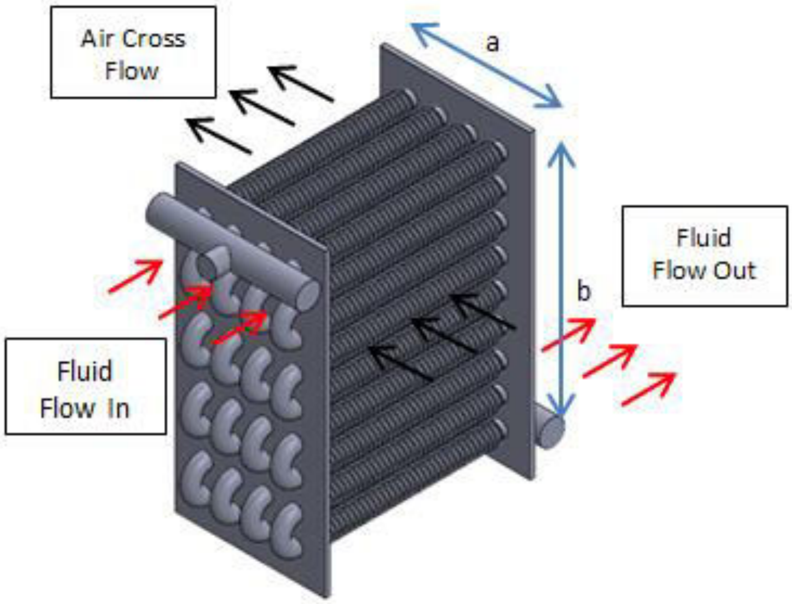

Figure-2. Schematic diagram of condenser.

Analysis of heat transfer for a cross flow heat exchanger consists of internal and external convection. As refer to Figure-2, fluid flow in and flow out is when the internal convection occur where; hot fluid flows inside the tubes from 95 °C to 36.9 °C. In order for external convection to occur the air across over the tubes ranging from 26 °C to 30 °C. Hence, condensation process follows from vapor to liquid.

Figure-3 shows an extruded finned tube that was installed to the condenser.

This tube was made of stainless steel and the root soldered fin were from aluminum which is increas the thermal transfer. The length of tube of every level is 1.7m with 0.15m diameters.

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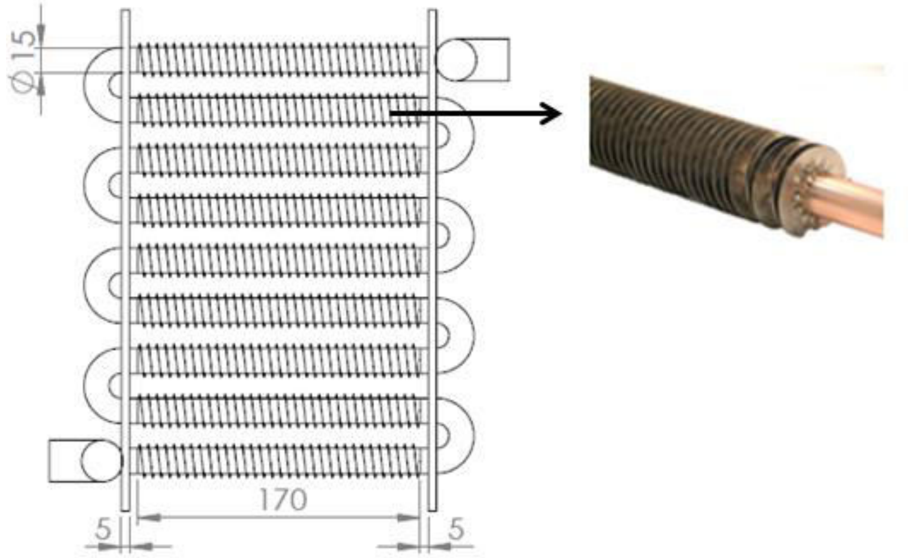

Figure-3. Extruded finned tube.

Fins are used to increase the surface area and total rate of heat transfer when the heat transfer coefficient is relatively low. Moreover, the total number of tubes and cost required can be reduced. Thus, will reduce the overall equipment size. Typically the radial of air cross flow finned tube exchanger can be circular or square.

RESULT AND DISCUSSIONS

Figure-4 shows the rate of heat transfer, *Q* of the condenser which is directly proportional to the number of pipe tubes, *n*. 3kW of heat load is achieved at *n*=36 for the mixture and *n*=1089 for base fluid. It is interesting to point out that the ammonia-water mixture has effective heat transfer compared to the base fluid which is water.

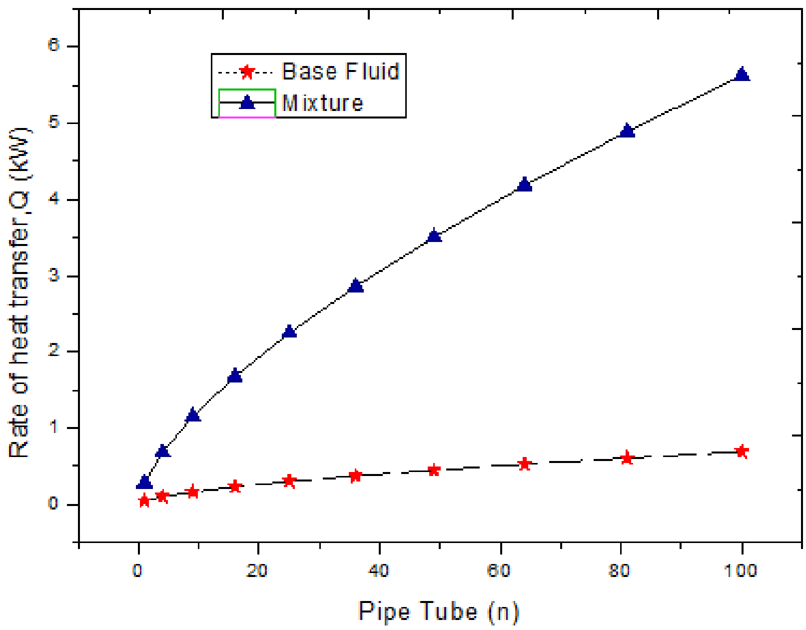

Figure-4. Rate of heat transfer, *Q* increase with number of tubes, *n*.

The heat transfer coefficient, *UA,* of the mixture, increases with the number of tubes increased. At *n*= 36, *UA*=41. While, the base fluid shows that, at *n*=36, *UA* is only 5 with deviation of 88% to the mixture. As a result, ammonia-water mixture is acceptable in achieveing 3kW of heat load and enhancing the heat transfer process in the condenser.

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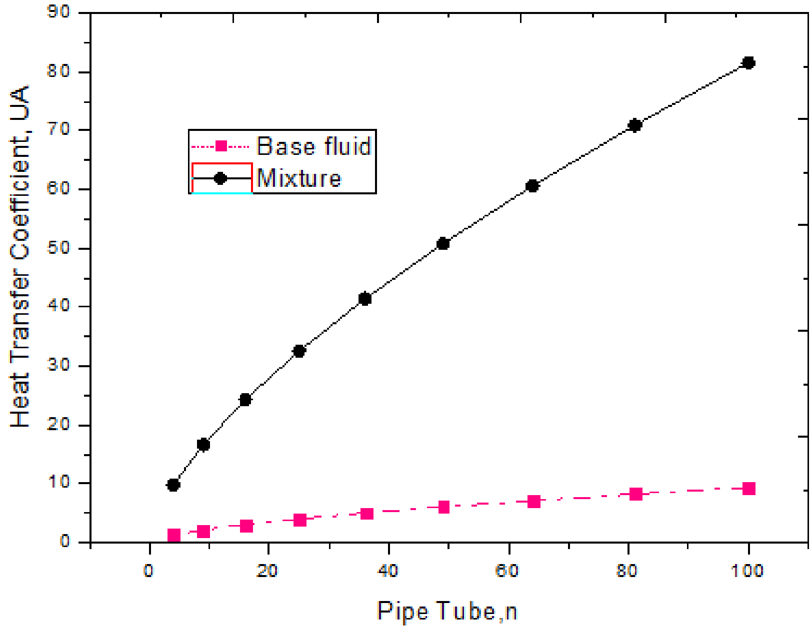

Figure-5. Heat transfer coefficient, *UA* of the mixture and base fluid.

Figure-6 shows the result of heat transfer coefficient on internal and external convection. The result shows that, at internal heat convection that involved with hot fluid enters the tubes has decreament in heat transfer coefficient. Therefore, at n = 36, h_i is 256 kW/m^2.K. Whilst, the heats transfer at outside the condenser with cold air across the tube of the condenser, h_o is 183 kW/m^2.K.

Heat transfer that's occurs inside the tubes is higher compared to outside of the tubes. This is because, ammonia water mixture is a working fluid that flow inside the tube has larger of thermal conductivity which is 0.02739 W/m.k at the fluid phase and 1.47727 W/m.k at the gas phase. Whilst, external convection is involved with ambient air at thermal conductivity is 0.026321 W/m.k.

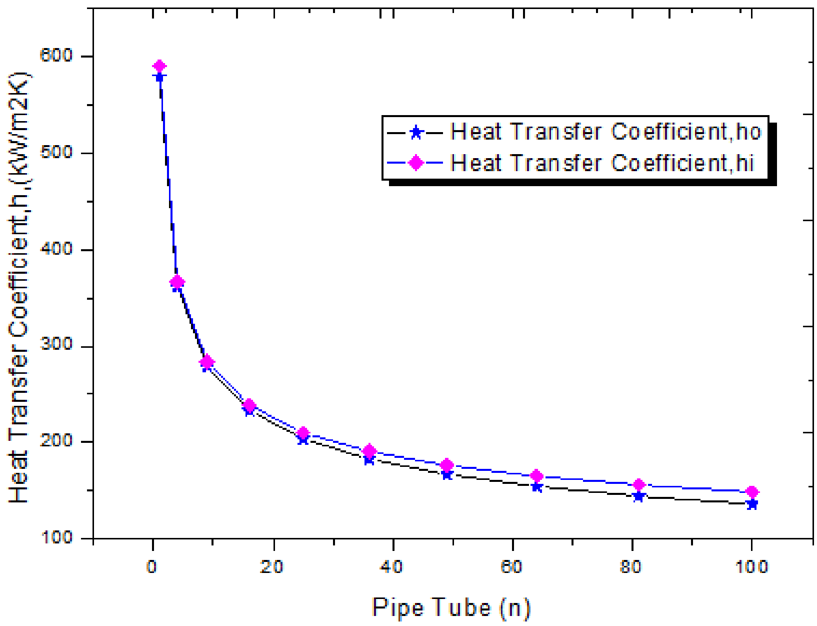

Figure-6. Number of tubes, n increase with inner heat transfer coefficient, h_i and outer heat transfer coefficient, h_o.

Figure-7 and Figure-8 show the flow that occurs inside and outside the condenser. As refer to equation (2), the Reynolds Number of a mixture, R_{em} is calculated by considering the state of the working fluid. This is because, phase changes from liquid to vapor is occurs at this stage. As refer to Figure-7, at n = 36, Nusselt Number, Nu is

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1.73 with Reynolds Number,Re is 579 which is flow can be regarded as a laminar flow. For external convection outside the condenser, at n = 36, Nu is 104 with Re is 26 222 which is consider as turbulent flow.

The both graphs show that as the numbers of the tube increases, the Nusselt number decreases. This is because in long tubes, most of the heat transfer occurs in thermally fully-developed region, which is Nusselt number nearly constant independent of any of the above parameters.

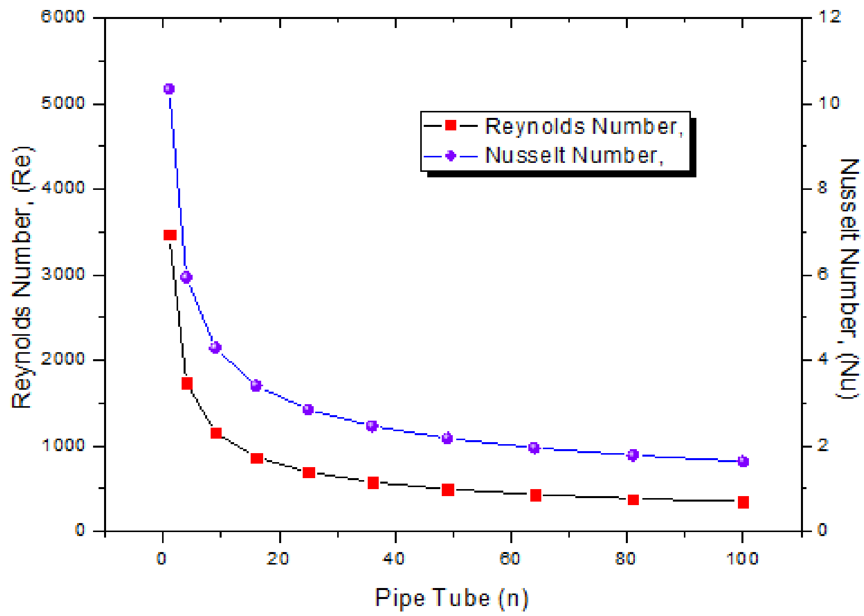

Figure-7. Flow at internal convection.

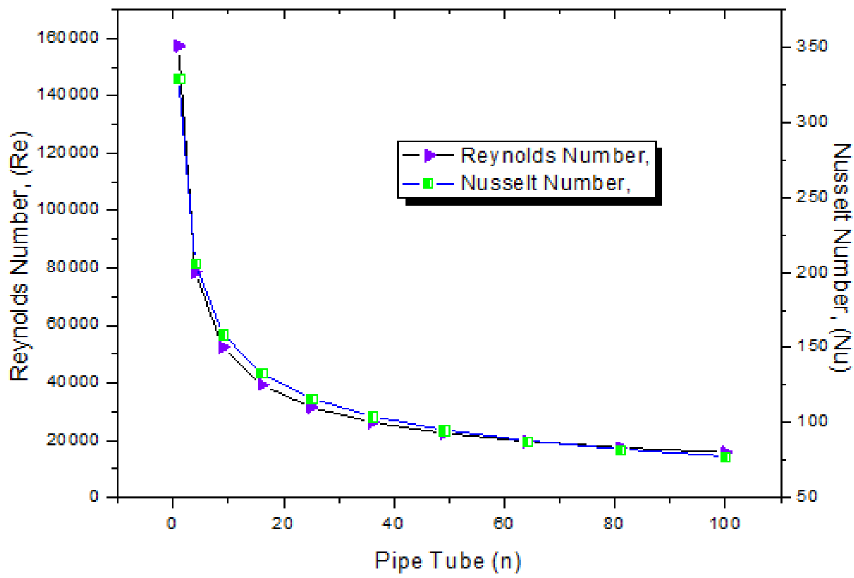

Figure-8. Flow at external convection.

CONCLUSIONS

In conclusion, the numbers of the tube in the condenser affected to the heat transfer process. 3 kW heat load of the condenser can be achieved with 36 extruded finned tubes installed in the condenser. Applying ammonia-water mixture as working fluid which have lower boiling temperature than water can help in speed up the heat transfer process combining with air cooled condenser design.

The analysis of parametric modeling of condenser can be researched further by investigating the heat transfer process using ammonia-water mixture with a several concentration levels. An experimental investigation also need to be conducted to investigate the condensation heat transfer coefficient in the presented paper.

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