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Design of Shell and Tube Heat Exchanger for Air Conditioning-Water Heating Hybrid System

Alaa H. Shneishil , Ahmed F. Atwan , Mohammed Jawad Yaseen

dralaa@uomustansiriyah.edu.iq Ahmed1973@uomustansiriyah.edu.iq m1964jy@uomustansiriyah.edu.iq

Department of Physics, College of Education, AL-Mustansiriyah University, Baghdad, Iraq.

Abstract

The use of air conditioning-water heating hybrid system for heating, cooling and hot water of buildings, has significantly importance for energy saving. It has been proposed a system to recover the waste heat of refrigerant after leaving the air conditioning system condenser in the heating mode and the waste heat of refrigerant after leaving the air conditioning system compressor in the cooling mode to heat water for domestics or other needs. Shell and tube heat exchanger has been designed as a refrigerant-to-water heat exchanger located between the condenser and the expansion valve in the heating mode and between the compressor and the condenser in the cooling mode. The simulation program of heat exchanger has been built by using (MATLAP) in order to determining the heat transfer parameters and the temperature difference between the inlet cold water and outlet hot water, the results show that the effectiveness decrease with increase of water mass flow rate, while increase with increase of tube length. As the tube length (15) m, the outlet hot water temperature from heat exchanger is (60.94) °C, for water mass flow rate (0.15) kg/s, and this value decrease exponentially and reach to about (7.528) °C, for water mass flow rate (2) kg/s, while for tube length (5) m, these values ranging between (43.92) °C, to (1.234) °C, respectively.

Keywords: Energy saving, Air conditioning-water heating hybrid system

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تصميم مبادل حراري صفيحة وأنبوب لنظام تكييف الهواء- تسخين الماءالهجين

م.د. علاء حسين شنيشل ، أ.د.احمد فرحان عطوان ، أ.محمد جواد ياسين
m1964jy@uomustansiriyah.edu.iq Ahmed1973@uomustansiriyah.edu.iq dralaa@uomustansiriyah.edu.iq
قسم الفيزياء- كلية التربية- الجامعة المستنصرية- بغداد- العراق

الخلاصة

استخدام نظام تكييف الهواء- تسخين الماء الهجين لاغراض التدفئة والتبريد وتوفير الماء الساخن للمباني، له أهمية كبيرة لتوفير الطاقة. في هذا البحث تم اقتراح نظام لاستثمار الحرارة المفقودة من مائع التبريد في نظام تكييف الهواء بعد خروجه من المكثف في نمط التدفئة والحرارة الناتجة من مائع التبريد بعد خروجه من الضاغط في نمط التبريد لتسخين الماء للاغراض المنزلية أو غيرها من الاستخدامات. تم تصميم مبادل حراري صفيحة وانبوب كمبادل ماء- مائع التبريد يوضع بين المكثف وصمام التمدد في نمط التدفئة وبين الضاغط والمكثف في نمط التبريد لنظام تكييف الهواء. وقد تم بناء برنامج محاكاة المبادلات الحرارية باستخدام (MATLAB) من أجل تحديد معاملات الانتقال الحراري والفرق في درجة الحرارة بين الماء الداخل البارد والماء الخارج الساخن. أظهرت النتائج ان قيمة الفعالية الحرارية تقل مع زيادة معدل سرعة تدفق الماء، بينما تزداد مع زيادة طول الأنبوب. عندما يكون طول أنبوب m (15) فان درجة حرارة الماء الساخن الخارج من المبادل الحراري (60.94) درجة مئوية لمعدل سرعة تدفق الماء (kg/s) 0.15 وهذه القيمة تنخفض اسيا وتصل إلى حوالي (7.528) درجة مئوية لمعدل سرعة تدفق الماء (kg/s)2 ، بينما لطول أنبوب m (5) هذه القيم تتراوح بين (43.92) درجة مئوية إلى (1.234) درجة مئوية، على التوالي.

الكلمات المفتاحية :توفير الطاقة، نظام تكييف الهواء- تسخين الماء الهجين

1. Introduction

The consumption energy in residential applications is almost one-third of the world's primary energy demand, while it is rapidly increasing due to improvement in human life standards and population growth. As a promising approach in energy conservation, air conditioning system can be combined with renewable energy sources to provide space cooling and heating system. Among the renewables, solar, wind and geothermal are more adoptable to sustainable buildings. Most of the research and developments in renewable energy based systems for residential application are conducted to provide heating, cooling, hot water and ventilation by air conditioning system or vapor-power cycles [1]. Iraqi's demand for energy and electricity is increasing rapidly. Iraq relies heavily on traditional energy resources of fossil fuels, which constitute a significant impact on the economy and environment. As would be expected, the rapid expansion of energy consumption and production has brought with it a wide range of environmental issues at the regional, local, and global levels. With respect to global environmental issues, Iraqi's carbon dioxide (CO_2) emissions have grown along with its energy consumption. States have played a leading role in protecting the environment by reducing the emissions of greenhouse gases. In this regard, renewable energy resources appear to be one of the most effective and efficient solutions for sustainable and clean energy development in Iraq. Iraqi's geographical location has several advantages for extensive use of most of these renewable energy resources.

The minimum temperature of domestic hot water (DHW) for residential and governmental applications is within (55–60) °C. On the other hand, heat distribution systems are designed to supply air with temperature range of (35–40) °C, in the heating mode and (10-15) °C, in the cooling mode. For this reason, electric backup heaters are used to obtain (DHW) at (60) °C, and the air conditioning system is often only used for space heating or cooling. This leads to decrease the energy performance because of coefficient of performance (COP) decreases rapidly for the energy consumed in the electric backup heaters and high pressure ratios in the air conditioning systems. Ghoubali et al. have found that (20%–25%) decrease in the seasonal energy performance of a low-energy house [2]. The sub-cooling and superheating heat exchanger is used to sub-cool and superheat the refrigerant in outlet of the condenser and evaporator of the vapor compression air conditioning system, respectively. These procedures are applied for improving the system efficiency. In the literature, available studies on sub-cooling and desuperheating effects of vapor compression refrigeration cycles are very limited [3]. A number of investigations have been conducted by some researchers in the design, modeling and testing of the Sub-cooling and desuperheating heat exchanger in the air conditioning system for domestic hot water Applications.

Selbas et al. obtained optimum areas of heat exchanger and optimum superheating and sub-cooling temperatures under various operating conditions of vapor compression refrigeration system. The application was consisted of determining the optimum areas of heat exchanger with the corresponding optimum superheating and sub-cooling temperatures [4]. Kongre et al. introduced basic design principles and the test analysis performed in the laboratory for air conditioning cum water dispenser system to get cold and hot water with cold and hot air. The results indicated that hot water temperature increased from (28) ^{o}C, to (58) ^{o}C, and Cold water temperature decreased from (30) ^{o}C, to (5) ^{o}C, respectively. The coefficient of performance (COP) of air was first increase up to (5) and further varying in the range (4) to (5). (COP) of water is firstly increase up to (3) and then steady [5]. Fei et al. introduced the working principles and the basic features of air conditioning water heating (ACWH) system. They concluded that it can offer about (400) L hot water each hour when the inflow water temperature is (15) ^{o}C, and ambient temperature is (20) ^{o}C, [6]. The compression air conditioning system using wastewater as a heat source system has studied by Baek et al., the yearly mean operating air conditioning system (COP) was (4.5-5.0) which has higher value than that of conventional air conditioning system using ambient air, heat source and air conditioning system could provide over (90%) of the instant hot water load and satisfy (100%) of the hot water load, except for on weekends in winter. Huang et al. developed an integral-type solar-assisted air conditioning system water heater in Taiwan, the average energy consumption of hot water at (57) ^{o}C, is (0.019) kWh/L, that is much less than backup electric energy consumption of the pure electric heater and the conventional solar water heater [7]. The aim of this study is to design and performance analysis of shell and tube heat exchanger air conditioning-water heating hybrid system to provide hot water for domestic and other applications.

2. Combined Air Conditioning-Water Heating hybrid system

In some buildings like hospitals or hotels, which equipped with consumed hot water and air-conditioning, there is a potential to carry out energy saving, the ratio of hot water heating load to that of compressor power in hotels normally between (15%) to (30%). Hence, it is possible to eliminate the energy consumption for water heating by recovers a portion of rejected heat from the air-conditioning system to heat water. This system offers a substantial saving for tropical countries since the air-conditioning is needed year around for space heating and cooling and hence, hot water can be produced for free [8]. Sub-cooling can be gained by adding a mechanical sub-cooling heat exchanger to a basic cycle. The mechanical sub-cooling cycles include a main cycle and a sub-cooler heat exchanger cycle which are coupled together. The dedicated mechanical sub-cooling cycle comprises of two condensers, one for the main cycle and one for the sub-cooler cycle, whereas the integrated mechanical sub-cooling cycle consists of only one condenser serving both the main cycle and the sub-cooler cycle. Couillion et al. in 1988 presented a detailed theoretical model to predict the overall performance of a dedicated mechanical sub-cooling cycle with several different refrigerant combinations. Thornton et al. in 1994, and Khan and Zubair in 2000, evaluated this type of cycle's overall performance by using thermodynamic models based on dependences of the temperature and refrigerant's property. They all showed an improvement of (170%) in the capacity and up to (80%) in the (COP) under certain operating conditions [9]. A desuperheater is an additional heat exchanger that is installed directly after the compressor and before the condenser of the air conditioning system. The desuperheater transfers the heat of the superheated refrigerant vapor to a thermal energy storage system, where the energy can be stored and then used for domestic hot water (directly or indirectly). The condensation of the de-superheated refrigerant takes place in the condenser of the air conditioning system, which usually transfers heat to the heating system or to a buffer storage tank. Hence air conditioning system operation with a desuperheater usually means a simultaneous preparation of heating water for space heating with a moderate temperature (30) °C, to (35) °C, in case of a floor heating system) and domestic hot water with a relatively high temperature of (50) °C, to (60) °C. The advantage of this simultaneous operation is that the air conditioning system operates at a lower high-side pressure compared to domestic hot water preparation only [10].

3. Design and Calculations

It promotes the thermal comfort of the citizen, through the space heating, cooling and water heating systems (air-conditioners in heating, cooling mode and water-heaters). It is necessary to find some innovating solutions in this field in order to saving energy and to reduce carbon emission. For this reason, it has been proposed a system to recover the waste heat of refrigerant after leaving the air conditioning system condenser in the heating mode and the waste heat of refrigerant after leaving the air conditioning system compressor in the cooling mode to heat water and to use in the domestics or other needs. Shell and tube heat exchanger has been designed as a refrigerant-to-water heat exchanger located between the condenser and the expansion valve in the heating mode and between the compressor and the condenser in the cooling mode. When the air conditioning system is activated, a circulation pump draws cold water from the home tank or other source, passes it through the heat exchanger and returns it to the hot water storage tank. When the air conditioning system is in cooling mode, the hot water heat exchanger reduces the load on the compressor which led to decrease the amount of consumed energy and increase the system coefficient of performance, and, consequently, decrease the amount of heat rejected to the air. In heating mode, the heat recovered in the hot water heat exchanger represent as sub-cooling heat exchanger that cool the refrigerant before entering the expansion device. Fig., (1) shows the proposed space heating/hot water combined system when hot water heat exchanger lies between condenser and thermal expansion valve, whereas fig., (2) shows the proposed space cooling/hot water combined system when hot water heat exchanger lies between the compressor and the condenser.

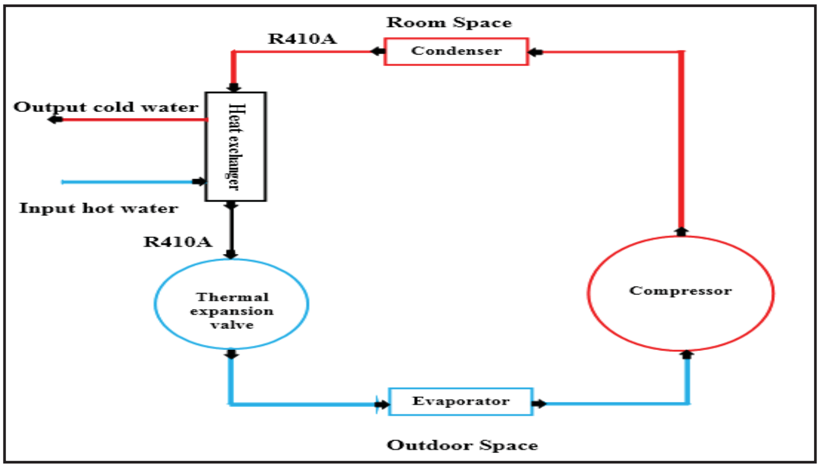

Fig. (1): The proposed space heating/hot water combined system.

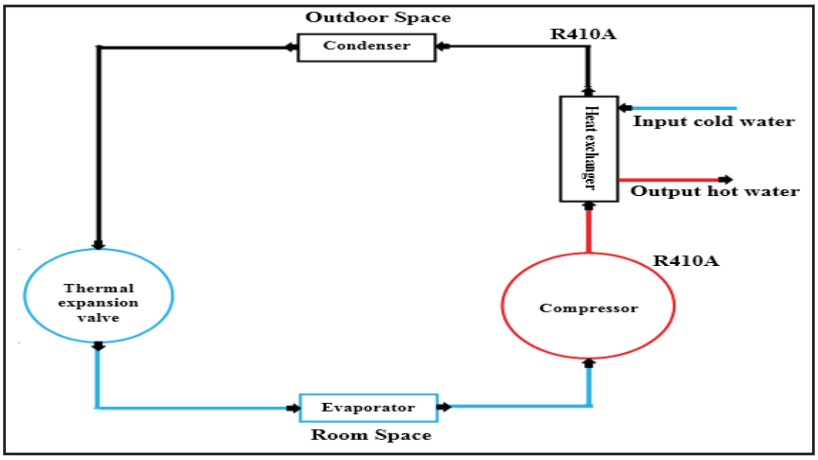

Fig. (2): The proposed space cooling/hot water combined system.

To simulate the heat exchanger for combined air conditioning-water heating system, the simulation program has been built by using, (MATLAB) in order to determining the heat transfer parameters by using the following equations. Prandtl (Pr) number can be calculated by using the following equation [11];

$$Pr = \frac{\mu c_p}{k} \tag{1}$$

Where (μ) kg/m.s, is the dynamic viscosity, (c_p) J/kg.K, and (k) W/m.K, are the specific heat capacity and the thermal conductivity of the fluid flowing in the tube respectively. Reynolds (Re) number is calculated by [11];

$$\mathrm{Re} = \frac{4\,\dot{m}}{\mu \pi D_o} \tag{2}$$

Where ($\dot{m}$) kg/s, is the mass flow rate of fluid and (D_o) m, represent the outer diameter of tube. Nusselt (Nu) number is given by [11];

$$\mathrm{Nu} = 0.3 + \frac{\left(0.62\,\mathrm{Re}^{1/2}\ \mathrm{Pr}^{1/3}\right)}{\left[1 + +(0.4/\mathrm{Pr})^{2/3}\right]^{1/4}}\left[1 + \left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right]^{4/5} \tag{3}$$

For $10^2 < \mathrm{Re} < 10^7$, the heat transfer coefficient outside the tube is given by [12];

$$h = \frac{\mathrm{Nu}\,k}{D_o} \tag{4}$$

The Rayleigh number defined in terms of Grashof number (Gr) and Prandtl number (Pr), (Ra=Pr Gr), If Ra > 10^6 the heat flow is turbulent, while if Ra < 10^6 the heat flow is laminar. The strength of the imposed temperature gradient is given by the presentation of the Grashof number (Gr) which is defined as [13];

$$\mathrm{Gr} = \frac{g\,\beta(T_{R410A} - T_{H_2O})D_i^3 \rho_{R410A}^2}{\mu_{R410A}^2} \tag{5}$$

Where (g) m/s^2, is acceleration of gravity, (β=1/ΔT), D_i (m) the inner diameter of tube, (ρ_{R410A}), the density of the refrigerant (R410A), (T_{H2O}), (T_{R410A}), are temperatures of water and refrigerant (R410A), respectively. A more complicated expression for use over a wider range of (Gr Pr) about $10^{-6} < \mathrm{Pr\ Gr} < 10^{12}$ is given by Churchill and Chu [14];

$$\mathrm{Nu} = \left\{0.6 + \frac{0.387\,\mathrm{Ra}^{1/6}}{\left[\left(1 + (0.559/\mathrm{Pr}\right)^{9/16}\right)\right]^{8/27}}\right\}^2 \tag{6}$$

Overall thermal resistance includes three types in series; the convective resistance on the inner surface, the wall conduction resistance and the convective resistance on the outside surface of the copper tube [12];

$$\frac{1}{U} = \frac{1}{2\pi(\ 0.5D_o)Lh_{H2O}} + \frac{1}{2\pi\,(\,5D_i)Lh_{R410A}} + \frac{\ln(0.5D_o/0.5D_i)}{2\pi\ Lk_{copper}} \tag{7}$$

Where (k_{copper}) W/m.K, and (L) m, are the thermal conductivity and the length of the copper tube respectively. The effectiveness of heat exchanger can be written as [15];

$$\varepsilon = \frac{1-\exp(-U/c_{min})(1+c_{min}/c_{max})}{(1+c_{min}/c_{max})} \tag{8}$$

Where (c_{max}=$(\dot{m}c_p)_{H2O}$) and (c_{min}=$(\dot{m}c_p)_{R410A}$). The amount of heat (Q) between hot refrigerant and cold water in heat exchanger is given by [11];

$$Q = \varepsilon(T_{R410A} - T_{H2O}) = c_{max}\Delta T_1 = c_{min}\Delta T_2 \tag{9}$$

Where (ΔT_{1w}=($T_{w,out}$-$T_{w,in}$) and (ΔT_{2R410A}=($T_{R410A,IN}$-$T_{R410A,out}$), therefore, from equation (9) (ΔT_1) K and (ΔT_2) K, can be calculated as in the following two equations;

$$\Delta T_1 = \frac{Q}{c_{max}} \tag{10}$$

$$\Delta T_2 = \frac{Q}{cmin} \tag{11}$$

The parameters that used in the preceding equations for the present work are listed in Table (1). Fig., (3) shows the flowchart of the programming which written by (MATLAB).

Table (1): Input parameters of (H_2O) and (R410A) that using in this research.

Fluid	Temperature (T) ^oC	(ρ) kg/m^3	(μ) kg/m.s	(C_p) J/kg.K	(K) W/m.K	(P_r) W/kg.m	($\dot{m}$) kg/s
H_2O	05	10^3	$152x^{-5}$	4202	0.571	11.2	2
R410A	71	637	$4.8x10^{-5}$	12750	0.074	8.27	0.05
Copper	L (15) m	Out Dimeter (0.006) m		Inner Dimeter (0.005) m		K (400) W/m.K	

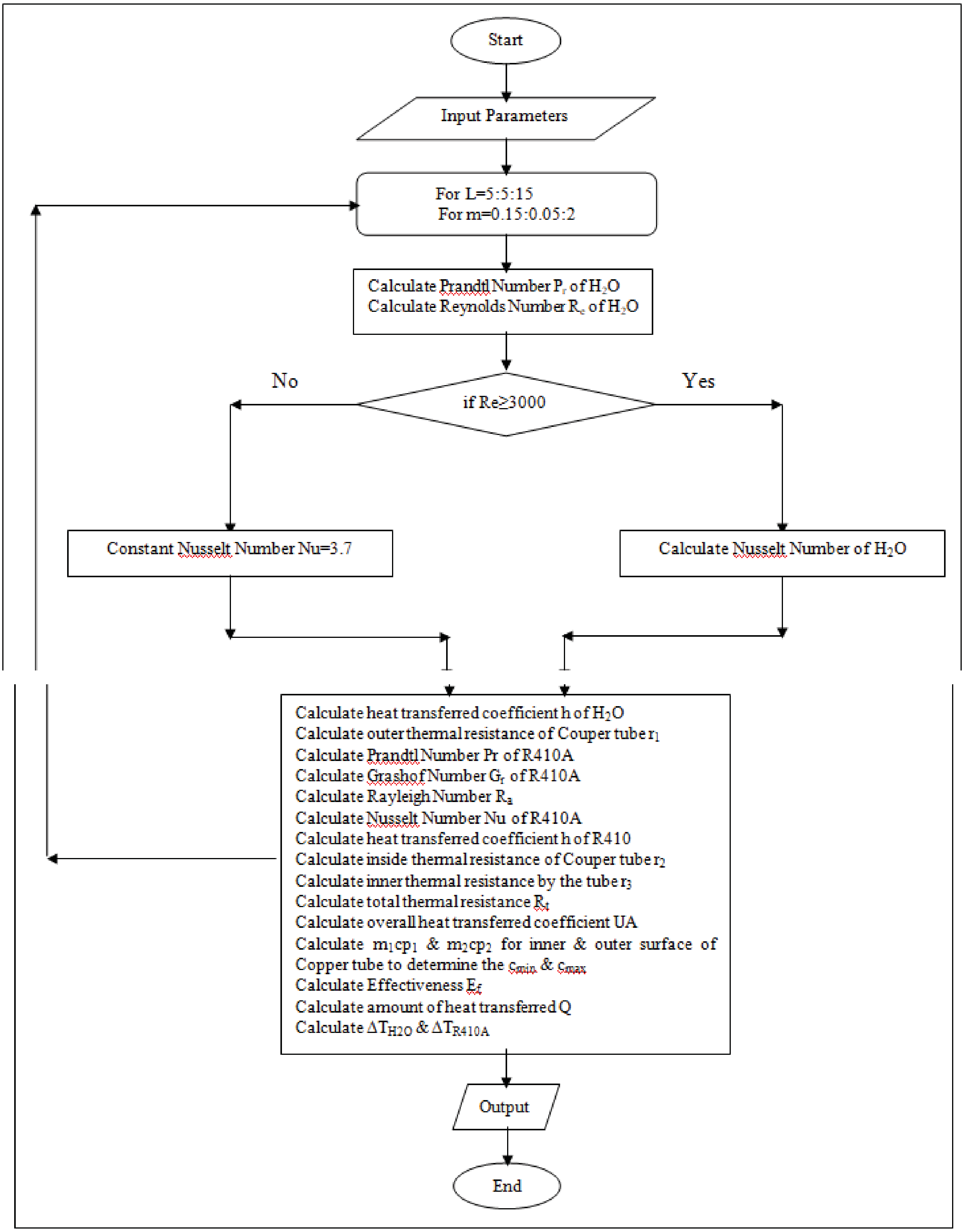

Fig. (3): Flowchart of programming that using in this research.

4. Results and Discussion

Shell and tube heat exchanger air conditioning-water heating hybrid system is important application for electrical energy saving, the effect of heat exchanger tube length and water mass flow rate on the heat transfer between the tap water and refrigerant (R410A) have been studied. Regarding the equation (4) one can plot heat transfer coefficient (h) against water mass flow rate ($\dot{m}$) as shown in fig., (4) where (h) and ($\dot{m}$) sketched for diverse values of the tube length. It is seen that heat transfer coefficient increases linearly with increases of water mass flow rate. It is worth to mention, the optimum value of heat transfer coefficient is equal (118100) W/m^2.K, for mass flow rate (2) kg/s. As well as the effect of mass flow rate on the thermal resistivity according to equation (7) this relationship has been clarified in fig., (5) for various values of the tube length. It is observed that the thermal resistivity decreases exponentially with increasing of water mass flow rate. However, the values of thermal resistivity are (0.002679, 0.004018, and 0.008036) for deferent values of the tube length at mass flow rate (2) kg/s. In order to focus attention about equation (8), the results of calculated effectiveness of heat exchanger variation of mass flow rate for different values of the tube length is plotted in fig., (6). It is important to mention that, the effectiveness decreases with increases of water mass flow rate, while increases with increasing of tube length. The values of effectiveness decreases when slowly from (0.6579) to (0.2466) at water mass flow rate (0.15) kg/s, and (2) kg/s, when the tube length equal (5) m, on the other hand, its values various from (0.838) to (0.505) for the tube length (15) m. The result of equation (10) plotted in fig., (7), during operation of heat exchanger with air conditioning system, as water mass flow rate decreases; it is easy to realize high outlet water temperature, i.e., the temperature difference between the outlet and inlet water increases with decreasing of water mass flow rate when the mass flow rate of refrigerant is constant. The inlet water temperature and refrigerant temperature are equal (5) °C, and (71) °C, respectively, as the tube length (15) m, the water temperature difference is approximately (55.94) °C, (the outlet water temperature from heat exchanger is (60.94) °C) for water mass flow rate (0.15) kg/s, and this value decreases exponentially and reach to about (2.528) °C, (the outlet water temperature is (7.528) °C) for water mass flow rate (2) kg/s, while for tube length (5) m these values ranging from (43.92) °C, to (1.234) °C. The result of equation (11), however, is sketched in fig., (8). It can be seen that the temperature difference from the outlet and inlet refrigerant (R410) decreases with increasing of water mass flow rate, thus its values ranging between (55.31) °C, to (33.33) °C, for tube length (15) m, and from (43.42) °C, to (16.27) °C, for tube length (5) m, respectively. By means of tube length effect figs., (9, 10, 11, and 12) represents the effect of tube length on the total thermal resistance, effectiveness, temperature difference between the outlet and inlet water and temperature difference between the outlet and inlet refrigerant (R410), for three values of water mass flow rate (0.15, 0.2, and 0.25) kg/s, respectively. The results indicated that total thermal resistance decreases with increasing of the tube length; on the other hand, the three curves that represent three values of water mass flow rate are comparable to each other this means that there is a convergent of values. Therefore, the water mass flow rate does not influence on thermal resistance, see fig., (9). However, there are increasing in the values of effectiveness, temperature difference between the outlet and inlet water and temperature difference between the outlet and inlet refrigerant (R410) for all values of mass flow rates, see figs., (10, 11, and 12) respectively.

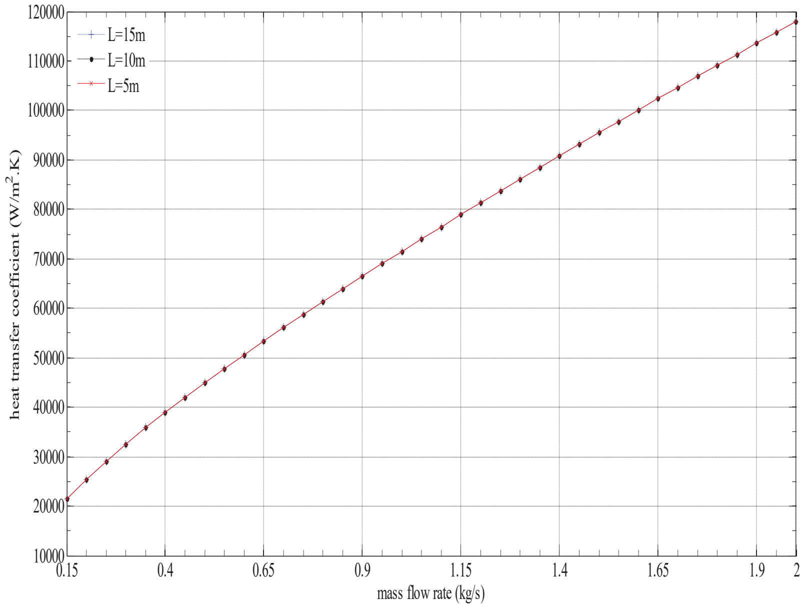

Fig. (4): Heat transfer coefficient h and mass flow rate ṁ for various values of L.

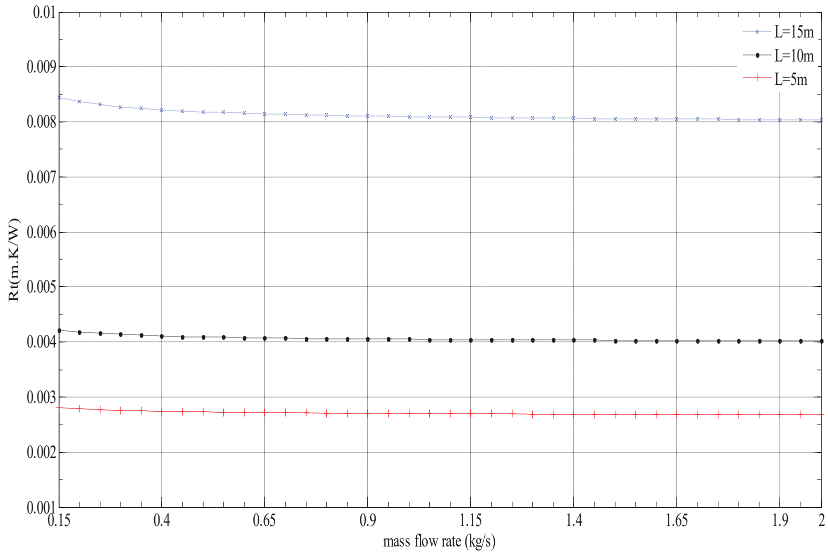

Fig. (5): Total thermal resistance R_t with mass flow rate ṁ at different values of L.

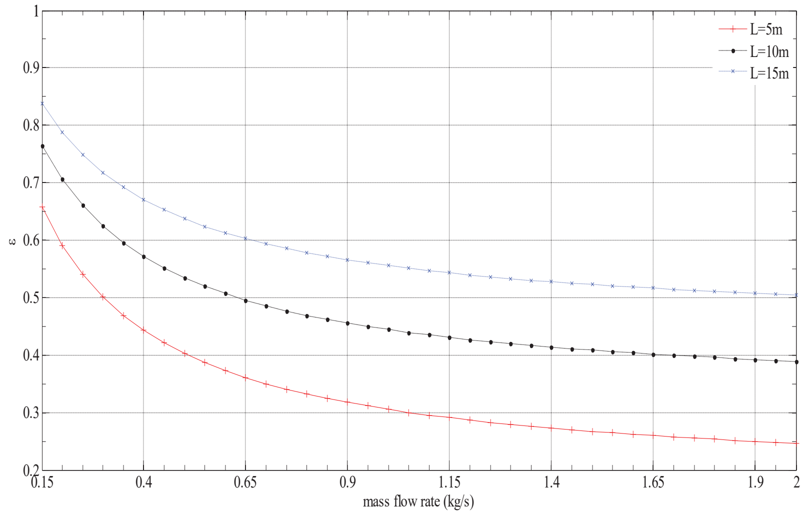

Fig. (6): Effectiveness ε versus mass flow rate ṁ for various values of L.

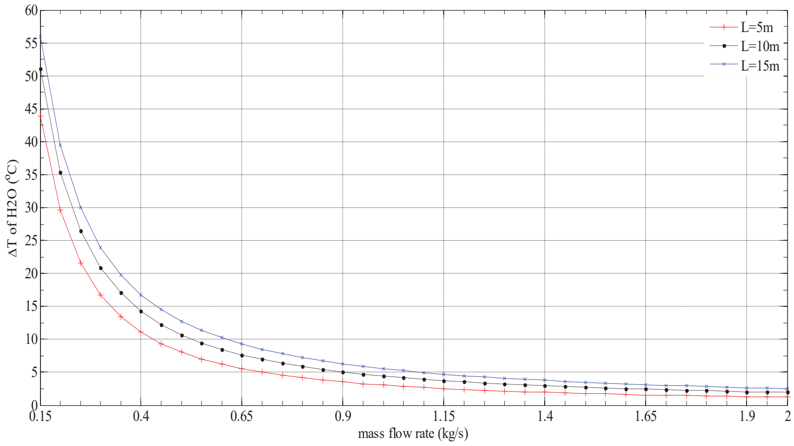

Fig. (7): Variation of ΔT of H_2O and mass flow rate ṁ at different values of L.

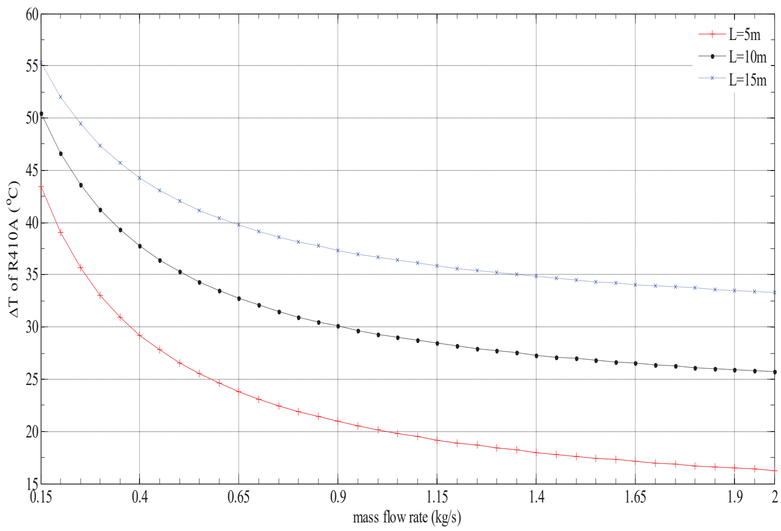

Fig. (8): Variation of ΔT of R410A and mass flow rate ṁ at different values of L.

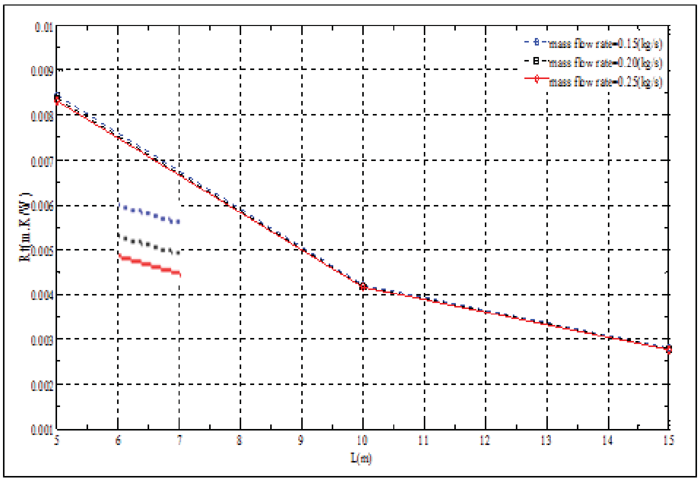

Fig. (9): Total thermal resistance R_t with L at different values of mass flow rate $\dot{m}$.

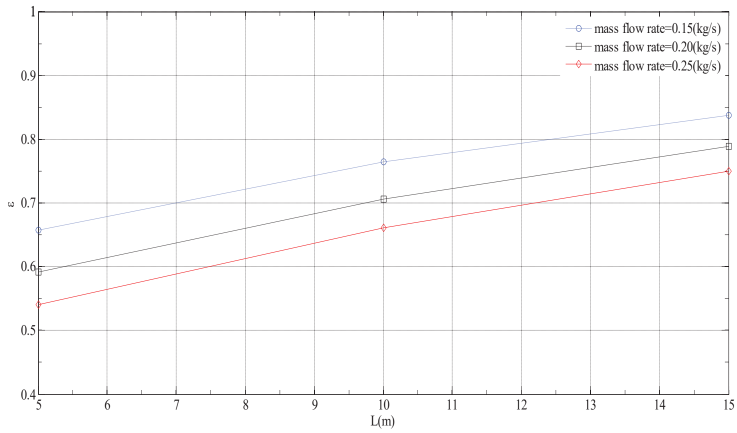

Fig. (10): Effectiveness ε of heat exchanger versus L for various values of mass flow rate $\dot{m}$.

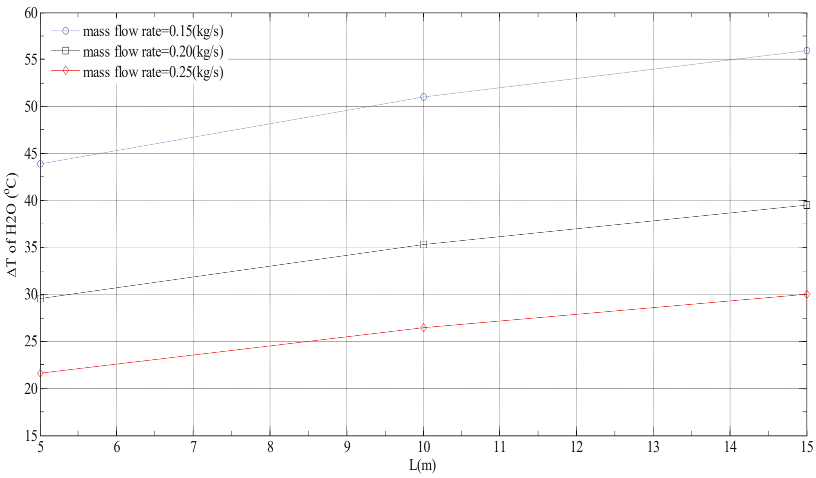

Fig. (11): Variation of ΔT of H_2O and L at different values of mass flow rate $\dot{m}$.

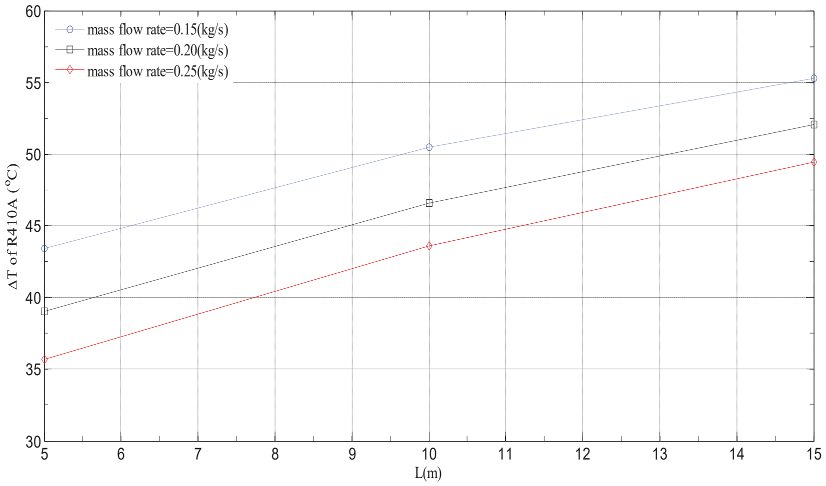

Fig. (12): Variation of ΔT of R410A and L at different values of mass flow rate ṁ.

5. Conclusions

The air conditioning-water heating hybrid system can operate with high efficiency and save energy over the year. This system can be designed and fabricated with low costs. In addition to save energy in providing hot water, there is save energy by decreasing the consumed power for air conditioning in cooling mode.

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