Modeling Efficient Hybrid Air Conditioning System

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Abstract. The main objective of the present study is to investigate the thermal performance of the air chiller using the heat exchanger using the chilled water tank by Freon R-134a. The air chiller model was designed and fabricated with all measuring devices in the AL-Muthanna city environment. The practical tests were carried out with a change in the factors governing air coolant performance to investigate their effects on the properties of the system. The study covered the values of the cooling water flow rate at (2l/min) and the evaporator water temperature (2.5 to 5.69 °C) and the return water temperature in the reservoir ranged from 11.6 to 19.2 °C). The greatest coefficient of thermal performance in the system was (5) while the lowest coefficient of thermal performance was (3.6) and that agreement to the experimental studies of this type of system. The results showed that the average guidance in the consumption of air-chilled energy by using the water tank and Freon R-134a was about 13% to 32% compared to the conventional air conditioner. All through the results indicated that the addition of a cooling stage to the conventional cooler inside the testing room results in lowering the temperature (dry temperature) by (27%) and reduced the relative humidity by (36%).

Keywords. Air-cooled chillers, Air-conditioning, Coefficient of performance, Water, Humidity reduction.

1. Introduction

The use of water chilled for air-conditioning in sunny and hot weather is a new device that has been used in small spaces. The important utilization for the system of the air conditioning is that water chiller air conditioning uses for cooling and improving loads which happen at the seasonal level and at the same time. A Chiller is an apparatus that rejects heat from a liquid by the absorption or vapor-compression cycle [1]. Chan and Yu,(2002) [2] studied the energy performance modeling of an air-cooled reciprocating multiple-chiller plant, by using R-22 as a refrigerant with a 199 tons rated capacity of refrigeration (700 kW) and the test was in a subtropical climate. The result showed that the consumption of chiller would be maintained below 2 kW/refrigeration ton at (Tev=5.3-5.8℃), (Tcond=20-50℃) with (COP=2.7) of the multiple-chiller plant. They found that potential energy savings with the condensing-temperature control application into two chiller buildings were 18.2 and 29% in the yearly chiller consumption. Yu and Chan, 2005[3] investigated in what way the condensing temperature assists to precisely control the air-cooled chillers coefficient of performance (COP) or energy efficiency. The experimental operation included an air-cooled reciprocating chiller and an environmental space, where three manufacturers (A, B, and C) were given the performance data. The nominal cooling capacity of 120 kW used the refrigerant R22 in a chiller. The design was (3 °C) for evaporating temperature (Tev) of the shell-and-tube liquid evaporator. The results showed that the COP of the chiller varies at (maximum COP) A=4.3, COP B=4.5 and COP C=5.9), since the minimum COP) A=2.7, COP B=2.9 and COP C=2.7. Yu and Chan, 2006 [4] (for air-cooled chillers) improved condenser-fan operation and condenser design by using R134a, as a refrigerant with a nominal cooling capacity of 1000 kW. They showed that the chillers (COP) can be increased by regulating the set point founded on a wet-bulb temperature of the outdoor air and any given chiller load. Finally, they proved
that the chiller (COP) increase by (1.16) in dependence on the chiller loads at (Tev=3℃, Tcond=50℃).

The result also showed that a reduction in the electricity consumption of chillers offers important precognition for efficient air- chillers in the development of more energy. Yu and Chan, (2008) [5] presented the improvement of energy performance with variable chilled water flow in the air-cooled centrifugal chillers. The model is established with an centrifugal air-cooled chiller that having a nominal capacity of 1226 kW. Also, they used R134a as working fluid refrigerant at (Tev=5-6.2℃), (Tcond=50℃) and has one refrigeration circuit. They conclude that enabling the COP to increase by 0.8–191.7% by varying the chilled water flow rate of the evaporator and enhancing the control of condensing temperature depending on ambient conditions and the load. Chowdhury, (2009) [6] studied the modeling and analysis of an air-cooled chiller system in an office building. The cooling was provided by a two equally sized reciprocating central chilled water system. They found that the (COP) coefficient of performance of the air-cooled chiller was improving by 2.9.

The present study aims to investigate the chilled water system experimentally which studied the effect of air conditioning chiller at the operating conditions such as the rate of electricity, the amount of moisture, calculation of the amount of cooling, coefficient of performance and energy consumption. This system is designed in a laboratory in Al- Muthanna in the southern regions of Iraq is characterized by a high temperature that makes the traditional cooler work with less efficient.

1.1 Description of the chiller air conditioning:

An air conditioning chiller model having: two circuits, one for refrigerant R134a and the other for water. The refrigerant circuit consists of the usual parts are the compressor, condenser in addition to the heat exchanger coil as shown in Fig. 1. The chiller has a hermetic series compressor was used in this system and used the refrigerant R134a (tetrafluoro ethane) with a nominal cooling capacity of (0.24 kW). The liquid evaporating temperature of the evaporator is designed to be 2.2℃ at full load. The evaporator works at a constant flow rate (2L/min) of chiller water which supplies temperature of (2.8 to 11.10℃). The temperature of return chilled water has been varying between (15 and 21.5) ℃ and a COP of 2.8 at full load submitted with the performance data in the chillers according to the ARI Standard 550/590 for the specific load condition [7].

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1.2. Description of the chiller air conditioning:

The air-cooled chiller has a dual refrigeration circuit: the first one is Freon gas (R-134a) which used for cooling the water inside the tank. Then the gas would flow through the pipes that are coiled inside the tank, later the gas temperature starts to decrease gradually, leading to reduce water temperature inside the tank causing water cooling. While the second circuit includes the water unit that consists of the common parts: pump, plastic pipes, storage tank, and evaporator liquid. The purpose of using the pump was to circulate the cold water through the pipes, then transfer it into the evaporator fins. As a result of cooling water, the fan impulses the cold air into conditioning space.

![Diagram of the chiller air conditioning cycle](image)

**Figure 1.** air conditioning cycle of the model chiller

2. Mathematical formulation:

2.1 Modeling of hermetic series Compressors:

The following assumptions for the hermetic compressor are made:
1. The compressor works at steady-state conditions.
2. The compression process is assumed as polytrophic.
3. Kinetic and potential energies changes are negligible.
4. The compressor has a homogeneous flow and one dimensional.
5. Heat gain or loss from the surroundings is ignored.
6. The compression input work \( W_{in} \) is an isentropic [8].

In an actual compression process, the entropy increases as the irreversibility of the process increase. Hence, the compressor has a compression process that is normally polytropic.

- The power of the compressor is considered according to the following equation, hermetic series Compressors [2]:

\[
W_{in} = \frac{m_r \cdot P_{ev} \cdot v_r}{\eta_m} \left( \frac{n}{n - 1} \right) \left[ (c_r)^{\frac{n-1}{n}} - 1 \right] \quad (1)
\]

\[
c_r = \frac{p_{cd}}{p_{ev}} \quad (2)
\]

- The refrigerant mass flow rate is given by:
\[
 m_r = \frac{\eta_v \cdot \dot{m}_d}{v_r} \tag{3}
\]

- \( v_r \): Specific volume of refrigerant is calculated from the evaporating pressure is given by:

\[
 v_r = \frac{R \cdot T_{ev}}{P_{ev}} \tag{4}
\]

- The compressor volumetric efficiency is given by:

\[
 \eta_v = 1 + C - C \left( \frac{P_{cal}}{P_{ev}} \right)^{\frac{1}{n}} \tag{5}
\]

The volumetric efficiency of the compressor is given with approximated added by 10% to the power loss as a result of the compressor mechanical friction.

\[
 \eta_c = 1.1 \eta_v \tag{6}
\]

Where:
- \( C \): is a value of clearance volume ratio (C=5%), in Eq. (5) and obtainable from the manufacturer’s data [9].
- Mechanical efficiency of the compressor is given in [10] as \( \eta_m = 92.5\% \).

### 2.2 Modeling of Air-cooled condenser:
An air-cooled condenser is installed in this system with coil wire mesh type joined with sub-cooling coils, in which the heat removal is done by air. The refrigerant enters the condenser as a superheated vapor and exit as a sub-cooled liquid [2].

- The total heat rejection in the condenser by the refrigerant is given as:

\[
 Q_{cond} = m_r (h_1 - h_o) \tag{7}
\]

### 2.3 Modeling of Evaporator Chiller
The chiller modeled contains a cooling coil evaporator and the water heat flow at the evaporator can be represented, as:

\[
 Q_e = m_w \cdot c_{pw} (T_{chw} - T_{chws}) \\
 Q_e = m_w \cdot c_{pw} (T_{chw} - T_{ev}) \tag{9}
\]

Where \( T_{chws} \) and \( T_{chw} \) correspond to return chilled water temperature and the supply chilled water temperature in the evaporator. To reach a temperature higher than the temperature between the sides of the heat exchanger, the greatest heat transfer must be determined due to its dependency on the higher temperature difference [11].

### 2.4 Shell and Coil Water Tank
A water chilling system uses a refrigerated pipe that is a coiled directly inside the tank of water to be chilled. When the water reaches the desired temperature, it can be pumped into the rest of all pipes system. In addition, a water chilling system must be insulated regularly to avoid any leakage from the cooling medium [12]. In the evaporator, the heat transferred was calculated by computing the energy lost by the water and the enthalpy increase of the refrigerant [13] as shown below:

\[
 Q_{evap} = \dot{m}_r (h_{r,o} - h_{r,i}) \tag{10}
\]

### 2.5 Coefficient of performance (COP)
Define as the ratio of useful output or work to the amount of energy input or work. Thus, the COP is a measurement of efficiency of the system as given by:

\[
 cop = \frac{Q}{w} \tag{11}
\]

3. Experimental work
The model of the chiller system consists of two different processes of fluid loops; air-conditioning loop, and cooling water loop. Fig. 2 presents the diagram of the complete model, including all equipment installed in the system, in which all two loops are considered.

The loop of air-conditioning was joined in series between the cooling water loop and loop charge and using the working fluid R-134a. The apparatuses of the air-conditioning loop were hermetrical reciprocating compressor, a heat exchanger (water tank), condenser, capillary tube, and filter driers. A hermetic series type reciprocating compressor made by DONGER company was used in the present study, the compressor was (1/5 HP, LBP) capacity. The compressor motor type is QD70N single phase 220V, (50-60) Hz. The condensing tube in the form of the coil is wire mesh type. The condenser wire mesh tube has (5.52m) length, (1/4in) outer diameter. The tube is made of Iron and the refrigerant passes inside the tube. The capillary tubes of length (2.5 m) and diameter (2.5mm) each are used to reduce the pressure of the refrigerant after each heat exchanger. The filter drier is used to remove any particle such as dirt or metal from entering the refrigerant flow control.

In water chiller loop the system is characterized as a closed system where water is pumped by the water pump and circulated in a closed-loop and thus not affected by the atmosphere. The cylindrical reservoir in which water-cooled through Freon gas passing through the tubes that coiled inside the tank. The chilled-water is circulated by using a pump, which transfers the cooled water to the evaporator by high-pressure plastic pipes with (3/8 in) diameter. The evaporator has an aluminium tube with aluminium fins around it with (40cm width, 41.5cm height and 7cm in thickness) with a capacity of (17 litres). The heat exchanger shell and coil evaporator consist of a coil with 15 turns fabricated from a copper tube of (15.24 m) length and (5 mm) diameter coiled inside the tank of water of (30 cm diameter, and 35 cm height).

The instruments essential for experimental are divided into refrigerant and watersides. Refrigerant side measurements include the (TPM-type) digital thermometer with an accuracy of (±1°C), Range (-20 °C to +70 °C). The type of humidity device was Hygrometer (HTC-2). The humidity range (10% RH to 99%RH) and accuracy (±5%) of reading. Whereas, waterside measurements include water flow meter (rotameter), with a range of (0 to7) l/min was used to measure the cooling water flow rate.
4. Results and discussion

4.1 Model validation

According to ARI Standard 550/590 AG for the specific weather-load condition required. The validation of model can be done by the model equations calibrating depended on the making specify the chiller performance in units of COP or Energy Efficiency Ratio (EER).

4.1.1 Conventional Air-conditioning System Comparison

Fig. 3 clears that there is a convergence between the efficiency of the chiller air-conditioning system and the conventional air-conditioning system in the power consumption of the compressor. The results show that the effect of the chiller air-conditioning system on decreasing the water temperature is more significant than that on cooling load. thus the power consumption was decreased in the chiller air-conditioning while increasing in the conventional air-conditioning system.

Fig. 4 shows decreasing the compressor input power as compare to the conventional working systems also the power electricity was 14.7 amperes in air conditioners while the chiller air-conditioning was up to 1.07 amperes. thus, with a lower storage tank water temperature range can be expected more electricity savings.
Figure 3. Comparison of system energy consumption with the conventional air-conditioning.

Figure 4. Comparison of electricity consumption with conventional air-conditioning.

Figure 5. Comparison of the Coefficient of Performance (COP) with conventional air-conditioning.
In Fig. 5 the COP of chiller air-conditioning system is reached to 3.6 while it is increased by 4.2 in comparison with the conventional system.

4.1.2 **Comparison of the present study with other studies**

Fig. 6 shows a comparison of the present study with other studies. The present experimental results some of them are compared in this section with different past test works. It very well may be realized that the power consumption of new chiller air-conditioning is considerably less than the conventional system power usage. This conduct of energy consumption average was also indicated by Chan and Yu 2005, Yu and Chan 2006 and present work was the equivalent all through in. additionally, show the energy-saving and average COP that is compared between the new chiller system and the conventional device of the comparative limit by utilizing both experimental and model data. It can be noted that the average COP for the suggested system.

![Figure 6. Comparison of the Coefficient performance (COP) in the present study with others study.](image)

4.1.3 **COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL STUDY**

![Figure 7. The power consumption by comparing the theoretical and experimental effect of evaporator water temperature.](image)

4.1.4 **Comparison between Theoretical and Experimental study**
Fig. 7 shows the comparison of the evaporator water temperature which has been affecting the power consumption (\(w_{in}\)) of the system. Where the deviation between theoretical and the experimental power consumption of the system is about 0.08. Such as, it is clarified from this figure the predicted and measured values are in an acceptable agreement.

![Graph showing the comparison of theoretical and experimental power consumption.](image)

**Figure 8.** The power consumption effect by comparing between the experimental and theoretical effect on condensing temperature.

Figs 8 and 9 illustrate the measured COP and power consumption of the system where the variation of condensing temperature in comparison with the predicted results. The difference between the theoretical and experimental power consumption with the COP of the system is approximately (0.083 and 0.073 kW).

![Graph showing the comparison of COP and condensing temperature.](image)

**Figure 9.** Comparison between the experimental and theoretical effect of condensing temperature on COP.

### 4.2 Meteorological Condition of AL-Muthanna

Figs 10 and 11 clarify the ambient room temperature and relative humidity with and without a chiller respectively. Since, the reduction in relative humidity was from (45% to 23%) without chiller at 15 (May, Jun, July and Aug) to (32% to 17%) with a chiller. The inside room temperatures of the whole day show a reduction from 25.6 without chiller to 22.3 with a chiller.

### 4.3 Coefficient of Performance C.O.P

An investigation series were made to determine the performance of the system under different conditions. Two types of experiments were run: constant flow rate of water in the cooling tank, and constant mass refrigerant. The two types were run with different condenser temperatures, evaporator temperatures and storage tank temperatures. Fig. 12 shows the effect of evaporator cooling capacity as results in the evaporator water temperature effect. It is clear from this figure that the higher cooling
capacity is reached to 5.69°C. As the evaporating temperature increases are increased the load temperature. Accordingly, the cooling capacity is increased as averaged from 1.25 kW to 1.89 kW. This is due to the higher values of both enthalpy differences.

Fig. 13 predicts that the condenser heat transfer rate of the chiller air-conditioning system was increased with an evaporating temperature increase due to an increase in cooling capacity (evaporator heat transfer rate). Where increasing temperature refrigerant in the condenser, certainly causes the condenser heat transfer rate. The condenser heat transfer is increased as averaged from (0.019kW to 0.051 kW), as the evaporation temperature increased from 2.5 to 5.69°C. Fig. 14 it exposes that when the load temperature increases from 2.5 °C to 5.69 °C the power consumption increases from 0.34 kW to 0.4 kW.

**Figure 10.** Values for relative humidity with and without chiller in15 (May, Jun, July, and Aug, 2018)

**Figure 11.** Values for ambient room temperature with and without chiller in 15 (May, Jun, July and Aug. 2018)
Figure 12. Variation of evaporator heat transfer rates with evaporator tank water Temperature at $\dot{m}_w = (2L/min)$.

Figure 13. Variation of condenser heat transfer rates with Evaporator tank water Temperature at $\dot{m}_r = (0.014 \text{ kg/s})$.

Figure 14. Variation of evaporator tank water temperature with compressor power at $\dot{m}_r = (0.014 \text{ kg/s})$.

5 Conclusions

5.1 Theoretical part
These conclusions can be summarized as follows:
A. The important operating parameter is evaporating temperature that affects the system performance. Where the evaporating temperature is increased and its effects at the COP of the system was positive. The refrigeration capacity has been increased as the evaporating temperature increased. It is found
that the consumption of power is increased as the evaporating temperature increased in case of finding the evaporating temperature effect on the power consumption of compressor, of the system was increased from (3.37 to 4.5).

B. Also, the important operating parameter is condensing temperature that has been affected the system performance. As results of those effects, the power consumption is increased as the condensing temperature increased; consequently, the coefficient of performance of the system was decreased from (3.37 to 4.5).

5.2 Experimental part

A. The COP of the chiller air-conditioning system is increased with increasing the evaporator water temperature. Thus, the COP was increased responding to the increasing in evaporator water flow rate, the compressor power consumption is increase as a result of an increase in the evaporator temperature from (2.5 to 5.69).

B. The return chilled-water temperature has a great effect on the thermal performance of the system. Since the higher load temperature was caused in the increasing of the cooling capacity. Also, the compressor power consumption is increased. Consequently, as a result of these reasons the COP of the system is increased from (3.6 to 5℃).

5.3 Nomenclature:

| Symbol | Description |
|--------|-------------|
| CR     | Compression ratio |
| C      | Clearance volumetric ratio |
| $C_{PW}$ | The water-specific heat (kJ/kg, °C) |
| $M_R$  | The mass flow rate of refrigerant per compressor (kg/s) |
| $M_W$  | The mass flow rate of chilled water (l/min) |
| N      | Index of the reversible polytropic expansion process |
| $P_{EV}$ | Evaporator pressure of refrigeration circuit (kPa) |
| $P_{CD}$ | Condenser pressure of refrigeration circuit (kPa) |
| $T_{EV}$ | Saturated temperature of refrigeration (°C) |
| $T_{CHWR}$ | Return chilled water temperature (°C) |
| $T_{CHWS}$ | Supply chilled water temperature (°C) |
| $V_s$  | Specific volume of the refrigerant at compressor suction pressure (kg/m³) |
| $V_D$  | Volumetric displacement per cylinder (m³/s) |
| $W_{IN}$ | Work input (isentropic) at the compressor (kJ/kg) |
| $Q_{EV}$ | Required chiller cooling output of evaporated (kW) |
| $Q_{COD}$ | heat rejection of condenser |

Greek Symbols

| Symbol | Description |
|--------|-------------|
| $\nu$  | Specific volume m³/kg |
| $\eta_M$ | Mechanical efficiency |
| $\eta_V$ | Volumetric efficiency of a reciprocating compressor |
| $\eta_C$ | Compressor efficiency |

Sub-Script

| Symbol | Description |
|--------|-------------|
| CD     | Condenser |
| EV     | Evaporator |
| R      | Refrigerant |
| CH     | Chiller |
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