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Experimental Investigation of Performance of Conventional Vapor Compression Refrigeration Cycle Using Geothermal Cooling in Extreme Hot Weather Conditions

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ABSTRACT

The well-known traditional vapor compression refrigeration cycle is considered to be the most effective technique used in the field of refrigeration and air-conditioning systems. It's used almost in every facility including industrials, homes and food storages. There are some environmental hazards concerning the use of vapor-compression cycles such as global warming and ozone layer depletion mainly due to refrigerant's leakages. However, it's still considered as a leading technology for its capability of producing high cooling and heating powers with great coefficient of performance. The present work represents an experimental investigation of the effect of the condenser's temperature on the thermal performance of a conventional vapor compression refrigeration cycle. The geothermal cooling technique was introduced and utilized for cooling the temperature of the condenser that operates in harsh climate conditions. The experiment was performed using two additional heat exchangers for enabling heat exchange with geothermal temperature. The first heat exchanger (primary HX_1) was connected directly to the condenser while the other one (secondary HX_2) was installed inside the geothermal hole intended for heat exchange with the geothermal temperature. These exchangers (HX_1 and HX_2) were thermally connected via two PVC tubes with straight water circulating inside them (using a DC water pump). The experimental results proved the success of the current utilized method in improving the thermal performance of the system. Cooling the condenser via geothermal cooling has led to a considerable reduction in the temperature of the refrigerant and improved the overall performance of the cycle. The experimental apparatus showed an increase in both cooling capacity and COP by 25% and 21.5%, respectively. In addition, a considerable enhancement in the temperature of the evaporator was accomplished to reach a minimum temperature of 14.5ºC.

1. INTRODUCTION

Ordinary vapor compression refrigeration systems are the most used devices in industrial and domestic applications (mainly for their advantages of high cooling power and efficiencies). The Summer season in Iraq is considered to be extremely hot and dry, especially during June and July. Hence, traditional vapor compression refrigerators (air-conditioning systems) face a remarkable reduction in their cooling power capacities and efficiencies when operating under such climate conditions. This is due to the significant increase in the temperature/pressure of their condensers as the ambient air often reaches 45ºC or higher (exceeds 55ºC on some days) during these two months. Some previous studies concerning lowering the temperature of the condenser and improving the Coefficient of Performance (COP) and cooling capacity (Q_c) were considered for the present investigation. Geothermal heating and cooling systems are valuable renewable energy sources that may be utilized for a variety of purposes, such as room heating and cooling, water heating and cooling, and so on. In the summer, the earth functions as a heat sink, and in the winter, it acts as a heat source to cool and warm buildings, with the temperature of the soil at a specific depth from the earth's surface remaining mostly constant throughout the year. Some prior studies on this subject are listed below:

Ghosal and Tiwari [1] presented an earth-air-heat exchanger (EAHE) experimental research study. For many typical sunny days throughout the year, an EAHE was buried at 1 m below the ground surface. The temperature of the room air was primarily measured and compared during operation with and without the EAHE. He discovered that the air temperature of the indoor room was decreased by 3 to 4°C during the summer season and increased by 6 to 7°C during the winter season. Al-Ajmi et al. [2] created an earth-air-heat exchanger (EAHE) analytical model to predict the air outlet temperature and cooling potential of these devices in a hot and arid climate. In their model, the disturbed soil thickness is assumed to be equal to the radius of the buried pipe, and the thermal resistance of the pipe material is ignored. Their model was integrated into the TRNSYS-II SIBAT environment to investigate the thermal performance of a typical dwelling coupled with an EAHE in the climatic conditions of Kuwait. They discovered that the EAHE can meet 30% of the cooling energy demand during the summer season. Lee and Strand [3] investigated the effect of pipe diameter, pipe length, buried pipe depth, and flow rate on the overall performance of the EAHE with a circular pipe. They came to the conclusion that by increasing pipe length while decreasing pipe diameter and air velocity, they might obtain good thermal performance.

In Iran, Abbaspour-Fard et al. [4] investigated the impact of numerous variables such as pipe length, buried depth, air velocity, and pipe material. After 72 studies, they discovered that all characteristics were directly related to performance, with the exception of pipe material. Misra et al. [5] evaluated the performance of a hybrid EAHE in the lab. They found that using the EAHE as an air conditioning system reduced energy consumption by 18% as compared to using ambient air for condenser cooling. Peretti et al. [6] studied how soil cover, climate, and soil composition affect the EAHE's performance. They came to the conclusion that the bare surface improves the EAHE's heating performance, whereas the wet surface is better for cooling. They also discovered that higher water content and tightly packed soil around the EAHE pipes improve the EAHE's performance. Li et al. [7] presented a series of studies on the EAHE system in conjunction with a building and solar chimney, in which continuous measurements of the soil temperature at various depths, external temperature, air temperature, and humidity in the EAHE were made for years. In terms of airflow rates and external circumstances, the cooling capacity of both active and passively driven models was investigated. They came to the conclusion that the improved EAHE system could keep the indoor temperature in a tolerable range without the use of a fan. However, in both modes, the EAHE system's performance was reduced due to soil saturation. The effect of thermal insulation on the EAHE's outflow portion was studied by Xamán et al. [8]. Based on the outcomes, they concluded that the performance of the EAHE improved with an insulation thickness of 0.05 m. Mathur et al. [9] showed that the soil temperature around the pipe depends on the thermal conductivity of the soil where the soil with a lower thermal conductivity will saturate a faster compared to the soil with higher thermal conductivity. Kaushal et al. [10] presented a 2D simulation model. They used computational fluid dynamics (CFD) Ansys Fluent to investigate the heat transfer. Their results showed that there was a difference in the air temperature reaching to 14.3K. Mathur et al. [11] presented a numerical simulation to study the problem of accumulation of heat around the pipe during the summer season with soil having high specific heat and low moisture content. Their results showed that the saturation of soil by heat restricts the performance of the EAHE system, and it can be improved by running the system on winter days. Khabbaz et al. [12] performed a numerical and experimental investigation of an EAHE connected to a Moroccan residential building. Even when the outside temperature reaches more than 40°C, the recorded blown air temperature in the building is quasi-constant at 25°C with an air humidity of roughly 40%, indicating that EAHX is a good semi-passive system for air refreshment. Furthermore, as pipe length increases, the reduction in daily and annual air temperature amplitudes is characterized by an exponential drop. Jakhar et al. [13] used TRNSYS 17 to create an experimental and simulation model to estimate the heating potential of an EAHE with and without a solar heat duct (SHD). Based on the experimental and simulation results, they discovered that using SHD improved the outlet air temperature and heating capacity of EAHE. They also concluded that during the winter season, the outlet air temperature increased with decreasing air velocity. Hasan and Noori et al. [14] presented a numerical study of the overall performance of the EAHE with five shapes of the EAHE channel using CFD (circular, elliptical, square, rectangle, and triangle). They concluded that increasing pipe length or decreasing air velocity caused the outlet air temperature to decrease and increase during the summer and winter seasons, respectively. They also concluded that there is no significant difference in thermal performance between the shapes, but there is a difference in overall performance, with the circular shape providing the best overall performance because it has the lowest pressure drop when compared to other shapes. Yu et al. [15] have stated that depending on the weather, evaporative coolers can improve the refrigeration effect and coefficient of performance to varying degrees. The refrigeration effect increased up to 17.5 percent with an evaporative air-cooled condenser, while the compressor power consumption decreased by less than 15.5 percent. The experiment results on the air-conditioner test rig increased the coefficient of performance for the system by spraying water on the condenser and decreasing the condenser temperature by the evaporative cooling effect by 39.04 percent. Eidan et al. [16] studied the use of evaporative cooling to improve the performance of the HVAC system. The design consists of a window-type air-conditioning system supported by an evaporative cooling system and both function as a single compact unit. The proposed design is able to simulate a wide range of weather conditions including hot weather temperature and relative humidity.

The presented above previous-studies show the potential of using geothermal energy to reduce a room temperature in the summer and rise it in the winter. It was reported that a reduction in the temperature of the air by 3 – 4ºC or an increase of 6 – 7ºC could be easily met by using EAHE at only 1m down the ground. In addition, it was stated that a reduction of 18% in power consumption of vapor-compression systems can be accomplished utilizing geothermal cooling.

To conclude, it can be clearly noted that all the reviewed studies in this paper showed a user manipulation of geothermal technologies (both cooling and heating applications). This has led to the motivation behind the present experimental investigation to utilize the cooling geothermal energy for the enhancement of the overall performance of an A/C system by the reduction of condenser temperature. The current research will investigate the possibility of using geothermal temperature as a cooling source (colder than the ambient air) to bring down the temperature of refrigerant within the condenser. This could lead to an improvement of the overall thermal performance (cooling power produced and coefficient of performance) of the vapor-compression refrigeration system. Two extra heat exchangers will be used to enable exchanging heat between the condenser and geothermal temperature. One of them shall be directly attached to the condenser while the other one is anchored inside a prepared hole to exchange heat with the geothermal temperature. The two heat exchangers should be thermally connected using PVC pipes with straight water being circulated inside them (using DC water pump).

2. METHODOLOGY AND EXPERIMENTAL SET-UP

Many refrigeration's, air conditioning, and other cooling applications operate based on the vapor-compression cycle. Moummi et al. [17] presented an analytical model of the earth cooling pipe, the results were compared with experimental data obtained in south Algeria (university of Biskra). Amara et al. [18] studied the ancient Fouggara system and investigated its possible use as a source for heating, cooling and ventilation of buildings. The Fouggara consists of: the source where the water seeps into the channel from a ground water source, an underground channel which brings the water to its intended destination, an over ground channel which leads to a network of channels feeding the water to particular areas or fields for irrigation. Gómez et al. [19] developed a ceramic evaporative cooling system, which works as a semi-indirect cooler, where the water to be cooled is passed into a cooling tower made ceramic tubes. This type of system allows the indoor air to be recalculated as a temperature drop ranging from 5-12°C was obtained. Jain [20] developed a two-stage evaporative cooling system to improve the efficiency of the evaporative cooling system at high humidity and reduce air temperature. The results showed an increase in cooling efficiency by (100 to 110)%. El-Dessouky et al. [21] improved performance of a two-stage evaporative cooling system Where the operating system was considered a function of the thickness of the package and the rate of water flow as a function of the direct and indirect evaporative cooling unit. Hammadi [22] designed and connected an evaporative cooling unit with the condenser of split-type air conditioner in order to reduce energy consumption and improve the performance of the cooling system. The evaporative cooling unit used was made of aluminium and covered with glass wool, a cellulose pad was used and placed in the face of the cooling unit evaporative, one of the most important results that have been reached is energy savings is 23%. The coefficient of performance increase with decreasing the ambient temperature and reducing the maximum load of the power network in the hot weather region. Xu and Peilin [23] analysed the heat transfer process in a direct evaporative cooling system, where they developed a simplified physical model of the process DEC in which air was forced to flow over a wet plate to coincide with the mass and heat transfer process. Qiang et al. [24] constructed a model to predict the performance of air treatment for a system in different working conditions. Direct evaporative cooling technology, which uses water evaporation in a wide range, was used for environmental control in agricultural buildings. For more information about the last different applications cooling electronic systems, minimizing energy leakage from energy conservation storage solar collectors, heat exchangers and double glass windows [25-31].

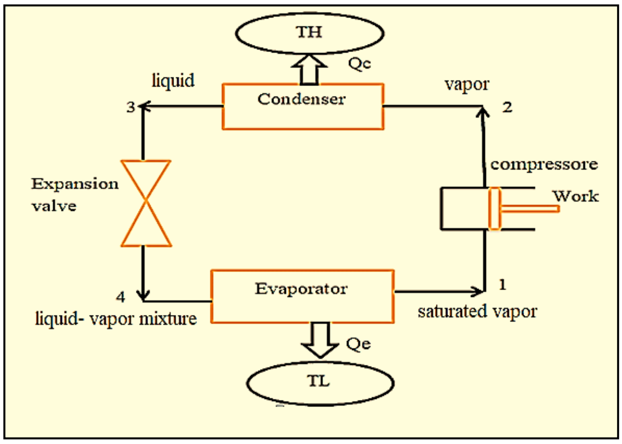


Figure 1. Schematic diagram of traditional vapor compression refrigeration cycle

The refrigerant enters the compressor as low pressure and low-temperature vapor at the start of the thermodynamic cycle (see Figure 1). The pressure is then increased, and the refrigerant exits as a superheated gas at a higher temperature and pressure. This hot pressurized gas then passes through the condenser, where it cools and condenses completely by releasing heat to the surroundings. This high-pressure liquid will pass through the expansion valve (throttle valve), which abruptly reduces the pressure, causing the temperature to fall dramatically. The cold low-pressure mixture of liquid and vapor will travel through the evaporator, where it completely vaporizes as it absorbs heat from its surroundings before returning to the compressor as low pressure and low-temperature gas to repeat the cycle.

In order to take advantage of geothermal cooling an explanation of how an ideal compression refrigeration system works, as well as its four main components shill be given. A liquid refrigerant is circulated through four stages of a closed system in the compression refrigeration cycle. The refrigerant is compressed and expanded alternately as it circulates through the system, changing its state from liquid to vapor. Heat is absorbed and expelled by the system as the refrigerant changes state, lowering the temperature of the conditioned space. A traditional vapor compression cycle shall have the main four components: compressor, condenser, expansion valve, and evaporator.

Compressor: - vapor refrigerant is compressed to a relatively high temperature and pressure and requiring work which can be calculated as follow:

$$\dot{W}_c = \dot{m}(h_2 - h_1) \tag{1}$$

where, $\dot{m}$ is the mass flow rate of the circulated refrigerant and h_2 and h_1 are the specific enthalpies (kJ/kg) at the exit and inlet of the compressor, respectively (see Figure 1).

Condenser: - vapor refrigerant condenses to liquid via the rejection of heat to the cooler surrounding (usually ambient air or water being used);

$$\dot{Q}_c = \dot{m}(h_3 - h_2) \tag{2}$$

where, h_3 and h_2 are the specific enthalpies (kJ/kg) at the exit and inlet of the condenser, respectively (see Figure 1). The condenser pressure P_c is the saturation pressure corresponding to evaporator temperature T_e,

$$p_c = p_{sat}(T_e) \tag{3}$$

Expansion/Throttle valve: - liquid refrigerant expands to the evaporator pressure (throttling process, $h_3 = h_4$)

Evaporator: - liquid-vapor mixture refrigerant absorbs heat from the refrigerated space as it flows through the evaporator.

$$\dot{Q}_e = \dot{m}\,(h_1 - h_4) \tag{4}$$

where, $\dot{Q}_e$ is the refrigeration capacity, $\dot{m}$ is the refrigerant mass flow rate in kg/s, h_1 and h_4 are the specific enthalpies (kJ/kg) at the exit and inlet of the evaporator, respectively. (h_1-h_4) is known as the specific refrigeration effect or simply refrigeration effect, which is equal to the heat transferred at the evaporator per kilogram of refrigerant. The evaporator pressure P_e is the saturation pressure corresponding to evaporator temperature:

$$p_e = p_{sat}(T_e) \tag{5}$$

The coefficient of performance (COP) of a refrigerator is given by: -

$$\mathrm{COP} = \left(\frac{\dot{Q}_e}{\dot{W}_C}\right) = \frac{(h_1 - h_4)}{(h_2 - h_1)} \tag{6}$$

At any point in the cycle, the mass flow rate of refrigerant can be written in terms of volumetric flow rate and specific volume at that point

$$\dot{m} = \dot{V}/v \tag{7}$$

where, $\dot{V}$ is the volumetric flow rate at the compressor inlet and v is the specific volume at the compressor inlet. At a given compressor speed, V_1 is an indication of the size of the compressor. It can also write the refrigeration capacity in terms of volumetric flow rate:

$$\dot{Q}_e = \dot{m}(h_1 - h_4) = \dot{V}_1\left(\frac{h_1 - h_4}{V_1}\right) \tag{8}$$

where, $\left(\frac{h_1-h_4}{V_1}\right)$ is called as volumetric refrigeration effect (kJ/m^3) of refrigerant.

In an extremely hot climate such as Iraq (especially in June and July), the efficiency of the vapor compression refrigerator would be noticeably decreased due to the considerable increase of the temperature/pressure of the condenser (directly affected by the temperature of the ambient). This would also increase the work consumption of the cooling system due to the increase in the pressure ratio (see Figure 2). Hence, the utilization of the ground temperature (geothermal cooling) can be a great solution for considerable reduction of both temperature and pressure of the condenser.

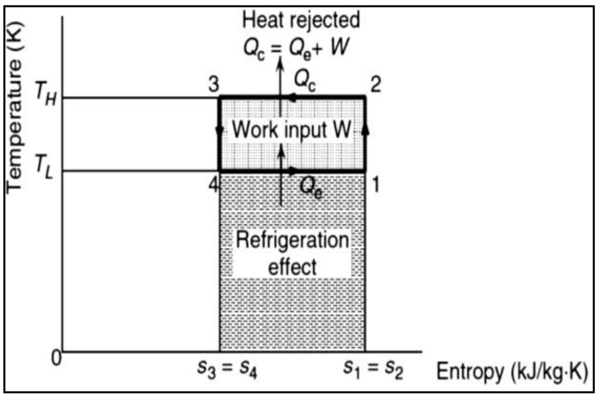


Figure 2. T−s diagram of the Carnot refrigeration cycle [32]

The geothermal temperature at a certain depth (3-4 m) from the ground surface is relatively stable, and is lower than the outside air temperature in summer and higher in winter. Hence, it can be utilized as a source of heat in the winter and a heat sink in the summer to heat and cool spaces in residential and commercial buildings. This heat exchange can be achieved by using coiled pipes or heat exchangers.

Figures 3 and 4 show both schematic diagram and actual photos, respectively, of the present experimental apparatus. It consists of the main four parts (compressor, condenser, evaporator and throttling valve). The present setup is taking advantage of the earth's temperature (geothermal cooling) by digging a hole on the surface of the earth (3 m depth, 2 m length and 2 m width). Two extra heat exchangers (HX_1 and HX_2, see Figures 3 and 4) were used to exchange heat between the condenser and geothermal temperature. The first heat exchanger (primary-HX_1) was directly attached to the condenser while the secondary (HX_2) was anchored inside the prepared hole to exchange heat with the geothermal temperature. The two heat exchangers (HX_1 and HX_2) were thermally connected via two PVC pipes with straight water being circulated inside them (using DC water pump). A perforated wooden board with circular holes of 5 mm of diameter was made to allow air circulation between the inside and outside of the prepared hole. The secondary heat exchanger was installed on the perforated piece of wood and placed inside the prepared hole. In addition, a DC fan was connected to the secondary heat exchanger (HX_2) with a control switch to manage forced convection heat transfer (to speed up heat transfer when needed).

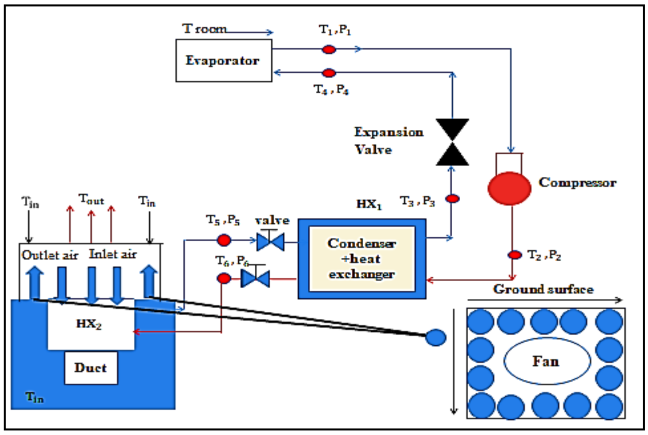
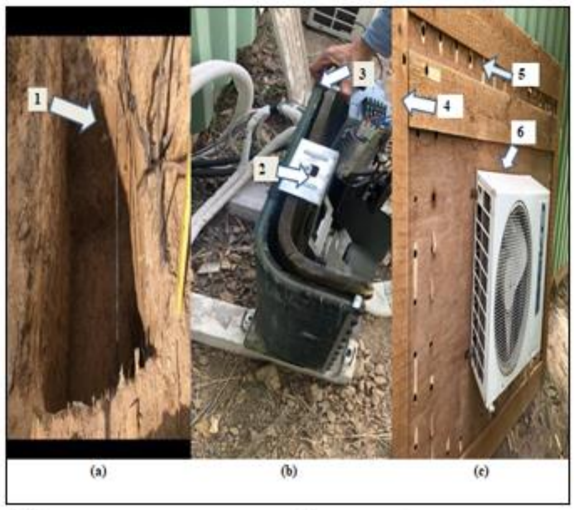


Figure 3. A schematic diagram of the experimental setup of the used vapor compression system



No.	Components
1	deep hole for geothermal cooling
2	Original condenser
3	Additional condenser (primary heat exchanger)
4	Perforated piece of wood
5	Circular holes
6	Secondary heat exchanger with the fan

Figure 4. (a) The deep hole (geothermal cooling), (b) the evaporator of the split ac unit, (c) the secondary heat exchanger inside the earth

The straight water flows through heat exchangers (HX_1 and HX_2) carrying heat away from the condenser to the buried heat exchanger (HX_2) that is anchored at geothermal temperature. This would lead to improving the overall performance of the vapor compression refrigeration system.

For the present paper, three different types of setups were used. In the first setup (stage one) the vapor compression refrigeration system was tested with no modifications being made. In the second setup (stage two) the condenser was further cooled down via the attached primary heat exchanger (HX_1) that connected to HX_2. For the second setup the attached fan to the secondary heat exchanger (HX_2) was kept off to perform a natural convection heat transfer between HX_2 and the geothermal temperature. For the third setup (stage three) the heat transfer between the secondary heat exchanger (HX_2) was speeded up by turning on its attached fan to perform a forced convection.

3. UNCERTAINTY ANALYSIS

Verification of the uncertainty in the experimental measurements is necessary to ensure the accuracy of the results. In the current experimental investigation, thermocouples were used to measure the temperatures of the refrigerant at the inlets and outlets of the compressor, condenser, evaporator and other locations. These thermocouples were originally calibrated by the manufacturer with uncertainty of 5-7%. In addition, pressure gauges with uncertainty measurement of 5 up to 10%, were used for the purpose of measuring the pressure of the refrigerant at desired position.

4. EXPERIMENTAL RESULTS

One of the major factors affecting the performance of the vapor compression refrigeration system is the ambient air temperature which is used for cooling the condenser. Accordingly, the primary heat exchanger (HX_1) was integrated with the condenser of the system to allow more heat being rejected to the surrounding. Figure 5 represents the change in the temperature of the condenser with the time after the utilization of the primary heat exchanger (HX_1- geothermal cooling). Looking at Figure 5, it can be clearly seen that there is a significant decrease in the average temperature of the condenser. This decrease indicates the effectiveness of the geothermal cooling in enhancing the heat transfer of the condenser after being linked to HX_1 which is connected to the geothermal temperature via the secondary heat exchanger HX_2 (see Figures 3 and 4). The reduction in the temperature of the condenser means more refrigerant to be converted from vapor (as leaving the compressor) into liquid (as leaving the condenser and entering the expansion valve). This would lead to improving the coefficient of performance (COP) and managing more cooling loads.

This decrease in the temperature of the condenser confirms the success of thermal cooling by using the temperature of the Earth's interior to improve the general performance of the vapor pressure cycle.

Figure 6 shows the variation of the average temperature of the evaporator over the time after the manipulation of geothermal temperature for cooling the condenser. Examining this figure shows that the temperature of the evaporator has remarkably decreased to reach a minimum value of 14.5ºC. This reduction in the temperature of the evaporator would also enable more heat being injected into the refrigeration system (more cooling capacity). This drop of evaporator's temperature confirms the success of the geothermal cooling for the enhancement of the overall performance of the vapor compression cycle.

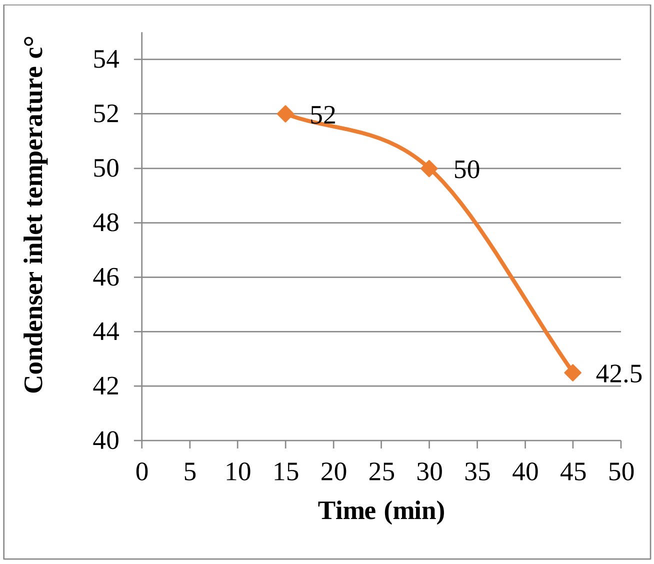


Figure 5. The drop of condenser's inlet temperature with the time after the manipulation of geothermal cooling

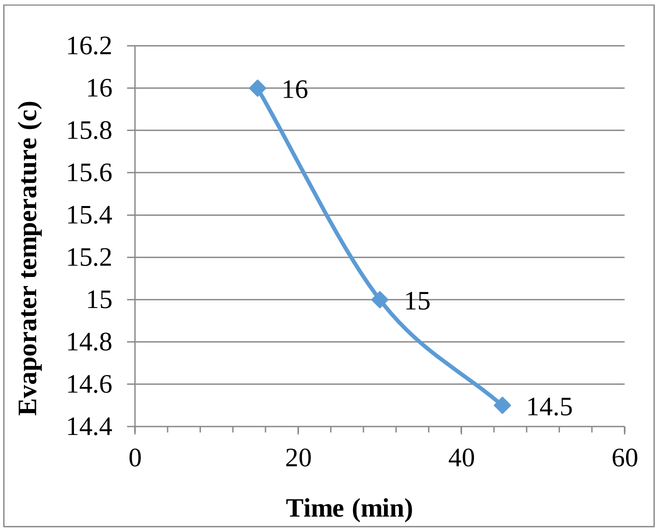
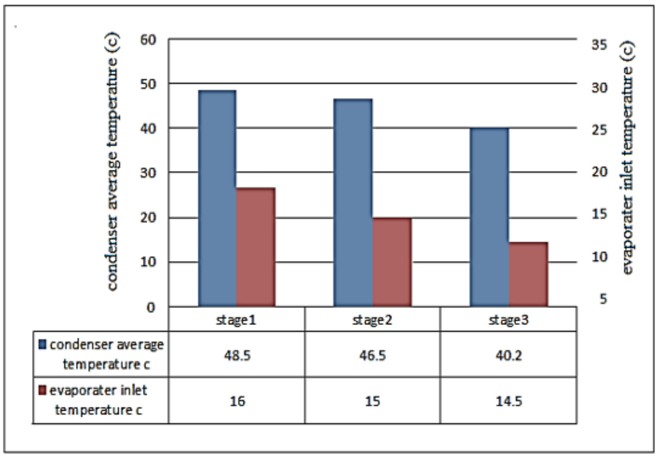


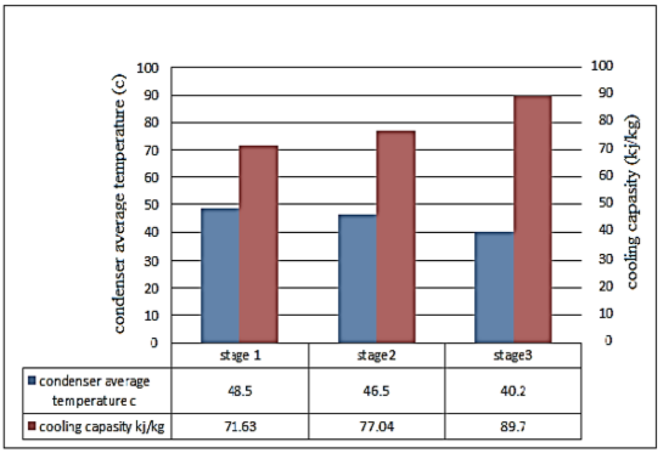
Figure 6. The drop in evaporator's temperature with the time after the manipulation of geothermal cooling

As mentioned earlier that three different experimental setups were considered. In the first experiment/setup (stage one) the vapor compression refrigeration system was tested with no modifications being made. In the second experiment/setup (stage two) the condenser was further cooled down via the attached primary heat exchanger (HX_1) that connected to HX_2. For the second setup, the attached fan to the secondary heat exchanger (HX_2) was kept off to perform a natural convection heat transfer between HX_2 and the geothermal temperature. For the third experiment/setup (stage three) the heat transfer between the secondary heat exchanger (HX_2) was speeded up by turning on its attached fan to perform forced convection.

Looking at Figure 7a, it is obvious that the condensing temperature (both refrigerant inlet and average temperatures) decreased during the second and third setups (stage 2 and 3) when compared to the first setup (stage 1). The decrease in the condensation temperature is due to the use of the additional heat exchanger (HX_1), which, in turn, exchanges heat with the ground (geothermal temperature). It can be noted that the evaporator's temperature was reduced during the second and third setups (stage 2 and 3) after the temperature of the condenser was decreased. In addition, the utilization of the geothermal cooling has led to an appreciable increase of the cooling capacity by 25% (see Figure 7b). This improvement of the cooling capacity is due to the change in the values of enthalpies of the leaving and entering refrigerant of the evaporator (see Eq. (3)).



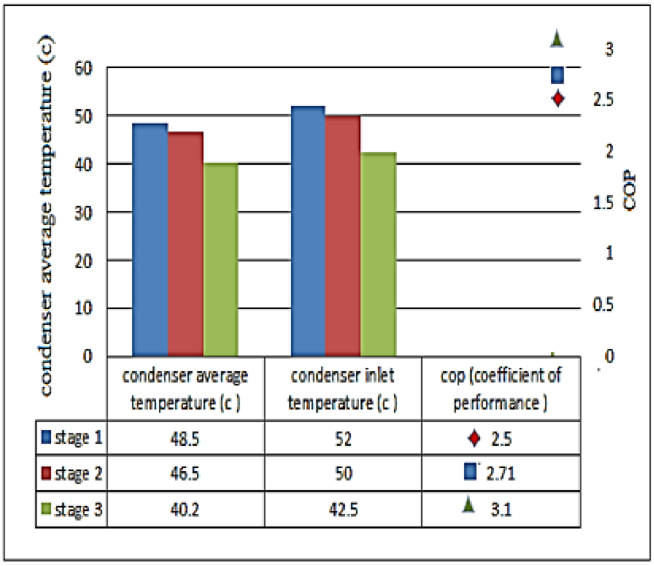
(a)



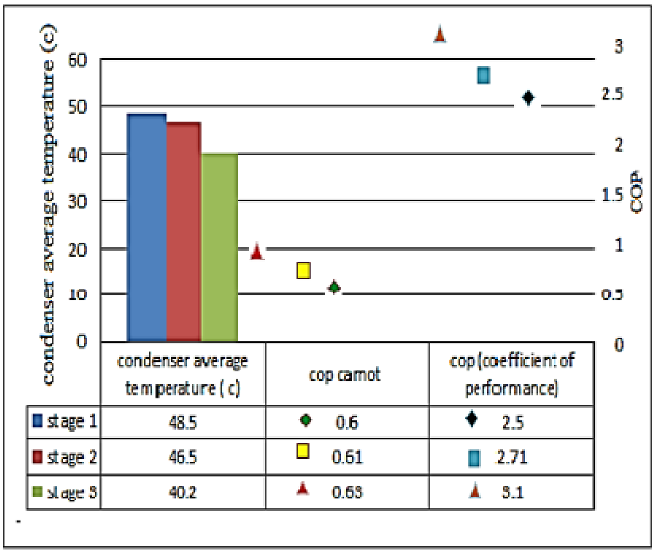
(b)

Figure 7. The effect of condenser average temperature on the evaporator temperature (a), the effect of condenser average temperature on the cooling capacity (b)

After examining Figure 8, it can be noticed that the manipulation of the geothermal temperature for the purpose of reducing the temperature of the condenser has led to huge improvements of the overall performance of the experimental apparatus. These improvements include the reduction in the temperature of the evaporator and the increase of the cooling capacity and coefficient of performance as shown in the Figure 8 (see equations 2, 4, 6 and 8). It can be also observed that the third setup (stage 3) has always shown the highest performance/improvements as the heat transfer rate being speeded up by the forced convection between the secondary heat exchanger (HX_2) and the prepared whole for geothermal cooling.



(a)



(b)

Figure 8. Comparison of the COP for the refrigeration system under different condenser temperature (a), the effect of variation of inlet temperature of condenser on COP and COP of Carnot cycle (b)

5. CONCLUSION

In the present study, a standardized vapor compression refrigeration system (split air conditioning unit) was experimentally tested in the laboratory of the university of Diyala in Iraq during the two hottest months of the year (June and July). The results of the first setup (stage 1, standardized system) were then compared with the results of the other two setups (stage 2 and 3) after modifications were made to advantage of the geothermal cooling. Accordingly, it was observed that a considerable decrease in the temperature of the condenser was achieved after the introduction of the extra heat exchanger (HX_1). The utilization of geothermal cooling/temperature has led to great improvements of the overall efficiency of the apparatus to increase its cooling capacity and COP by 25% and 21.5%, respectively. In addition, a considerable enhancement in the temperature of the evaporator was accomplished to reach a minimum temperature of 14.5ºC. After comparing the results with the revised studies in this paper, it seems that the hottest the weather conditions can result in achieving higher improvements of the thermal performance of traditional-vapor refrigeration system. However, the current study was limited by the depth of prepared geothermal whole and it could be further investigated by reaching deeper depths as suggested by some previous researchers. It was suggested that future studies should focus on the effect of soil characteristics such as moisture content, density and type of soil on the thermal performance of the geothermal cooling. In addition, using buried pipes inside the geothermal whole may show different (better) results.

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