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Solar Hybrid Cooling System Using Variable Speed Compressor

Hasanen Mohammad Hussain†, Laith Jaafer Habeeb‡ and Orhan Jalal Abbas‡†

†Mechanical Engineering Department, University of Technology.
‡Training and Workshops Center, University of Technology.
‡†Ministry of Construction and Housing and Public Municipalities

*Corresponding Author Email: **20021@uotechnology.edu.iq**

ABSTRACT

The present work investigates experimentally the effect of varying the rotating speed of a compressor on the power consumption of an air conditioning system assisted by a solar collector. The outdoor temperature in Iraq exceeds 50 ºC in summer months. This weather effects on the power plants and also needs an air conditioner, which is the principal on high electrical demand. So, the need of power saving is available. This work aims to save power and increases the COP of the A/C units by using a variable speed compressor. The experiments were carried out by using a hybrid system that includes an evaporator indoor, condenser and compressor outdoor plus the vacuumed pipes solar collector to air condition a room of 3×4.5×3 m under 46 ºC ambient temperature and with three speeds (1400 rpm, 934 rpm, and 467 rpm). The system uses R22 as a refrigerant. The flow of the refrigerant is controlled by using solenoid valves to select the path after compressor either to the condenser or to the solar collector considering its temperature. The results manifested that the best COP obtained is with the lowest speed.

KEYWORDS

Experimentally, temperature, high electrical, solenoid

INTRODUCTION

The Heating, Ventilating, and Air Conditioning (HVAC) systems for commercial and residential buildings are consuming a large amount of electrical power by about 50% of the total energy consumed. In addition, these systems lead to the decrease of fossil fuel sources and effect on the ozone layer depletion [1]. The amount of energy consumed by these systems will grow by 34% in the next 20 years with a rate of 1.5%, so the performance enhancement of HVAC systems will affect on the amount of energy consumption and enhancement of human comfort in buildings. In addition, the use of renewable energy and its combination with the A/C systems for reducing the power consumption is a very important fact. In recent years, different modes of cooling systems via a combination of A/C systems with the solar thermal energy have been accomplished. The solar power has been appraised about 35% to 45% minimization in the overall system cost for solar cooling by 2030. The solar power integrates with the A/C systems, both solar collector or photovoltaic panels for driving the systems [2].

The solar energy is the electromagnetic radiation and belongs to the infrared and ultraviolet wavelength. The amount of solar radiation arrives to the Earth is about 1,000 watts per square meter depending upon location, weather conditions, and orientation. The solar collector usually refers to the hot panels treated with hot water or to the solar towers and solar parabolic troughs . The solar plants generally use a complex collector for generating the electrical power through evaporating the water for turbine driving via connecting it to the generator. The collectors are usually used in the residential and commercial buildings for heating purposes. The solar heat collector and radiator for building roofs were designed by William H. Goettl [3].

In Iraq, the outdoor temperature may reach higher than 50ºC during the summer months [4]. The air conditioning devices consume most of the electrical energy production. This is because there are few residential and commercial buildings in this country using central air conditioning, and the split type air conditioners are the most commonly used. The condenser unit of these A/C devices which is used for heat rejection process is mostly air-cooled condenser. Air-cooled condensers are economic if compared with other types, water-cooled and evaporative-cooled condensers. Rising the cooling capacity and heat rejection, decreasing the refrigerant pressure losses, reducing the gap in pressure between condenser and evaporator and decreasing the power consumption of the compressor can increase the performance of an A/C system.

So, the need to save the power is available. The world started searching about alternative sources of energy and using them as swapped source or assisting the original source as hybrid systems. One of these hybrid systems is the solar assisted air –conditioning, which is used in high outdoor temperature areas to reduce the power consumption of the compressor. This system is an air-conditioning device integrated with a solar collector to rise the temperature of the refrigerant flow from compressor to condenser. The main advantage of this system is using the solar energy, which is available to anyone on earth. By this fact, the operation power of the hybrid system is lower than, if compared, the conventional systems [5]. There is a new way to increase the performance and decrease the energy consumption by using solar energy in conjugate with A/C system in countries of high temperature ambient. With this new way, many experimental and theoretical investigations have been done to achieve the maximum power reduction in A/C and refrigeration systems. Comfortable environment in hot places like Iraq required systems like air conditioning. Experimental and numerical investigations was performed to study the efficiency of electrical and mechanical systems of air conditioners.

It was found that utilizing solar air conditioners decreases the COPU, COP, condenser capacity, and cooling capacity [6-12]. Zhai et al. 2005 [13] studied experimentally and theoretically a 500 mm width and 1500 mm channel length solar air collector. It was found that 45^o inclination angle was the optimum for the solar air collector. Li et al. 2007 [14] investigated a direct expansion solar assisted heat pump with aluminum plate collector and evaporator, compressor with constant speed and immersed condenser coil. The COP of DX-SAHPWH during daytime and rainy night is up to 6.61 and 3.11, respectively. The seasonal average value of the collector efficiency and COP is 1.08 and 5.25, respectively. Umberto et al. 2009 [15] described solar cooling limits, advantages, and operation. An absorption chiller was included in the investigations. The solar radiation from the summer which would help in the consumption of electric energy. Ha et al. 2012 [16] investigated a performance improvement for DX A/C systems via integrating them with a vacuum solar collector. The advantage of the proposed design was that the new proposed system runs with the high sub cool temperature, so the overall system coefficient of performance COP increased, as well as, the power consumption decreased.

The gained results showed that the proposed system has a higher efficiency than the conventional system, due to the increasing in the cooling capacity of DX evaporator. The importance of the proposed hybrid air conditioning system is that the compressor stills off in a longer period. The results obtained depicted that the average monthly energy saving is about (25-42) %. Vahid et al. 2013 [17] studied experimentally the essential characteristics of a proposed DX air conditioning system joined with a vacuum solar collector. The hybrid A/C was integrated with a number of instrumentation devices and sensors, for data collection. Mathematical models were firstly derived for the components of the system and after that, the experimental results were gained. The oscillation in the system energy consumption is processed via turning off the compressor, while the cooling process remains continued until the desired room temperature changes due to the refrigerant pressure change. The results revealed that the monthly average energy saving is (23-40) %. Elzahzby, et al. 2013 [18] provided a predicted mathematical model for the performance of solar energy assisted hybrid A/C system of Student Health and Counseling Services (SEAHACS). They used a two-stage regeneration process, and a two-stage pre-cooling process, two-stage dehumidification process with only one wheel.

The experimental data were used to validate the mathematical model. The range of inlet temperature, area ratio, inlet velocity and the rotational speed changed from (65 to 140)^{o}C, (1 to 3.57), (1.5 to 5.5) m/s and (6 to 20) rev/h, respectively. Based on the thermal coefficient of performance, the relative moisture removal capacity and optimization of these parameters were conducted. Rosiek et al. 2013 [19] investigated a cooling mode concentrated on the chilled water. The importance was that the solar-assisted A/C system must be run according to the actual load conditions not at maximum load that may lead to more energy consuming. The main purpose of performance enhancement of the system was to achieve the heating and cooling with the help of Solar Energy Research Centre (SERC). The authors demonstrated a new technique for improving the efficiency of solar-assisted A/C systems and reducing its power consumption. The results depicted that a 42% energy saving is gained of the total power consumed by the system. Baniyounes, et al. 2013 [20] clarified that the A/C systems in Australia are a very high demand, so the energy saving of these systems is very important. The improvement of these systems was achieved via using a solar fraction as solar assisted A/C, which has the significant amount of greenhouse gas emission and energy savings, also these systems are environmentally safe. Solar assisted A/C is a fast-growing technology and new if compared with the other solar energy submissions. The electrical COP of the system is 2.5, and the primary energy consumed is assumed 80%. The results obtained displayed that the proposed A/C system has 80% of the primary energy savings for 1.8 m^3 of hot water's storage tank and 50 m^2 of solar collectors.

Kadhum, 2015 [21] considered a thermal performance improvement of the indirect expansion solar assisted heat pump under Iraqi environment conditions. Experimental and theoretical investigations were achieved using an evacuated tube solar collector integrated with the Heat Pump of 1 hp. The theoretical analysis comprised a simulation for the system using TRNSYS software for analyzing the effect of condensing and evaporating temperatures, solar collector area, refrigerant type, and compressor speed on the performance of the system. It was found that the increasing of solar radiation and outdoor temperature increased the collector heat gain and, accordingly, increased the heat transfer rate of evaporator. The COP increased from 2.2 to 2.39 with the solar radiation, while the ambient temperature and heat flux increased from 9.9 ℃ and 268 W/m^2 to 14.9 ℃, and 689 W/m^2, respectively. The literature survey demonstrates number of studies depending on some techniques to improve the performance of air conditioning system using the solar energy to assist the cooling purpose. The present research, implements a hybrid air conditioning system of a vapor compression refrigeration type assisted with an evacuated tube solar collector in an attempt to improve the thermal performance of the air conditioning system and reduce the electricity consumption in Iraq. This work aim to improve the air conditioning system saving of energy and develop the performance. The investigations performed mathematically and experimentally.

THEORY

The Solar Cooling (SC) technology is used for a close conditioned space in the summer months based on the Vapor Compression Refrigeration (VCR). This technology consumes the solar energy to create a cold feeling via absorbing the solar energy and to obtain a significant energy savings for A/C systems if compared with the conventional A/C systems. The SC has several advantages compared to conventional A/C systems, like saving more energy, and low noise. The cooling demand for close spaces can be achieved at maximum solar radiation in the summer months. The solar energy gives heat to the thermodynamic systems for producing cold water at different ranges of temperatures. This energy is used for both air conditioning and industrial refrigeration processes at the considerable electricity. The schematic diagram for the solar cooling system is shown in Fig. 1. Commonly, the solar air conditioning systems are divided into two main kinds:

- Open systems or Desiccant Cooling systems (DEC), these systems are fit to large buildings, for cooling and dehumidification.
- Closed systems, which are commonly used in the air treatment unit for cooling and dehumidification [22].

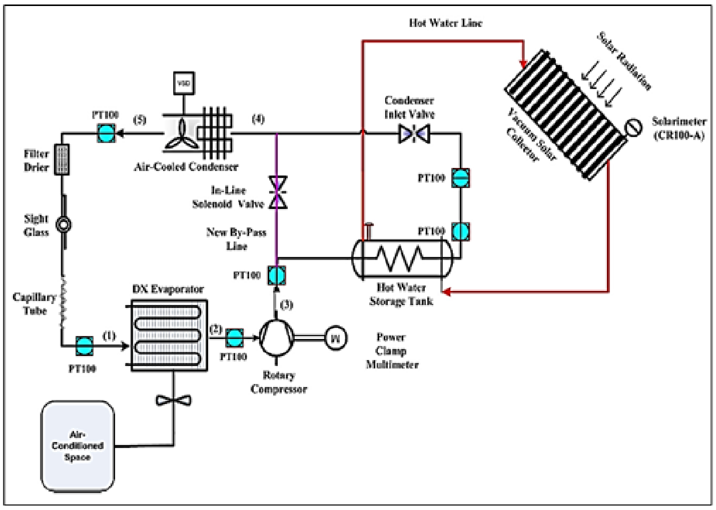

Figure 1. Vapor compression refrigeration cycle [15]

In the ideal vapor compression cycle, the vapor that comes from the evaporator as illustrated by point 1 shown in Fig.2 is compressed with a constant entropy line to the specified condensation pressure as depicted by point 2, this will represent the outlet of the compressor, while in the actual cycle, the pressure losses in the valves, pipe, etc. should be considered. After that, the condenser will serve a two-fold operation, the first high temperature vapor outlet from the compressor, point 2, must be de-superheated to the condensation saturation temperature, as illustrated by point 2'. At this point, the condensation of superheated vapor can begin with a continued reduction in the entropy and a constant temperature until the refrigerant has been completely condensed at the outlet of the condenser as revealed by point 3, while in the actual cycle, the sub-cool process may occur. After that, the irreversible expansion at the constant enthalpy of saturated liquid is illustrated by point 3 to the evaporator pressure, depicted by point 4, then the reversible addition of heat at a constant pressure causes evaporation to saturated vapor at point 1.

The essential differences between the actual and ideal compression cycle appear in the pressure drop in the evaporator and condenser, in the sub-cooling liquid outlet of the condenser and in the superheating of the vapor outlet of the evaporator. The sub-cool of the liquid in the condenser is a normal occurrence and it is needed to ensure that 100% liquid will enter the expansion device. The super-heating of the vapor usually occurs on the evaporator and is recommended as a precaution against the droplets of liquid being carried over into the compressor. The final difference in the ideal cycle is that the compression is no longer isentropic and there are inefficiencies due to friction and other losses. Assuming no heat exchanger pressure losses, the evaporator and condenser heat transfers are easily determined by applying the First Law of Thermodynamics [23]. The condenser-saturated temperature in the air-cooled condensers is mainly depending on the ambient temperature and will affected the compressor power consumption, cooling capacity, condenser capacity, and COP.

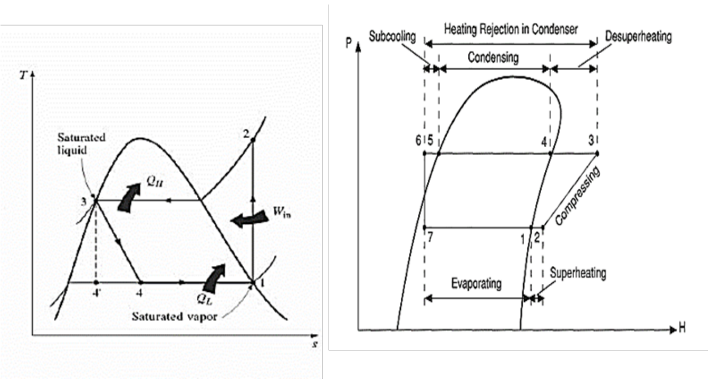

Figure 2. Vapor compression refrigration cycle [14]

To find out the performance of the hybrid air conditioning system, some equations may be taken into consideration. The evaporator coil is an essential component used in the refrigeration cycle and looks like an automobile radiator. It's usually found inside the conditioned space that needs to remove the heat. The cold feeling air that exits in the air conditioner has just transferred some heat energy to the flashing refrigerant as it passes through the evaporator coil. The energy observed from the conditioned space is shown in Fig.1, and the cooling capacity of the evaporator is given by [24]:

$$Q_{evap} = \dot{m}_r(h_1 - h_4) \tag{1}$$

The heart of the vapor compression cycle is the compressor and it is used to elevate the pressure of the refrigerant. Compressors can be classified into two categories; one of them is the positive displacement, which depends on reducing the volume to raise the pressure, and the other is the dynamic, which uses the angular momentum to raise the pressure and transforms it to the vapor, the input power to the compression is given by [24]:

$$W_{comp} = \dot{m}_r(h_2 - h_1) \tag{2}$$

The operation of air-cooled condensers is to reject the heat of the refrigerant to the air. Typically, the air cooled condensers are of the round tube and fin type. The condenser is a heat exchanger configuration, and the refrigerant flows through the tubes, and a fan forces the air between the fins and over the tubes. When the refrigerant exits the compressor, it enters the condenser as a superheated vapor and exits as a sub-cooled liquid. The condenser is separated into three stages, as shown in Fig.3, which are superheated (de-superheating zone), saturated (two-phase zone), and sub-cooled zone [25]. The total heat rejection by the condenser depicted in Fig.1 can be found as:

$$Q_{cond} = \dot{m}_r(h_2 - h_3) \tag{3}$$

The heat rejected in condenser depends on the heat absorbed by the evaporator (refrigerating capacity) and the temperature of evaporation and condensation. So, the heat rejected by condenser is the heat absorbed by the evaporator and the work applied by the compressor [26]:

$$Q_{cond} = W_{comp} + Q_{evap} \tag{4}$$

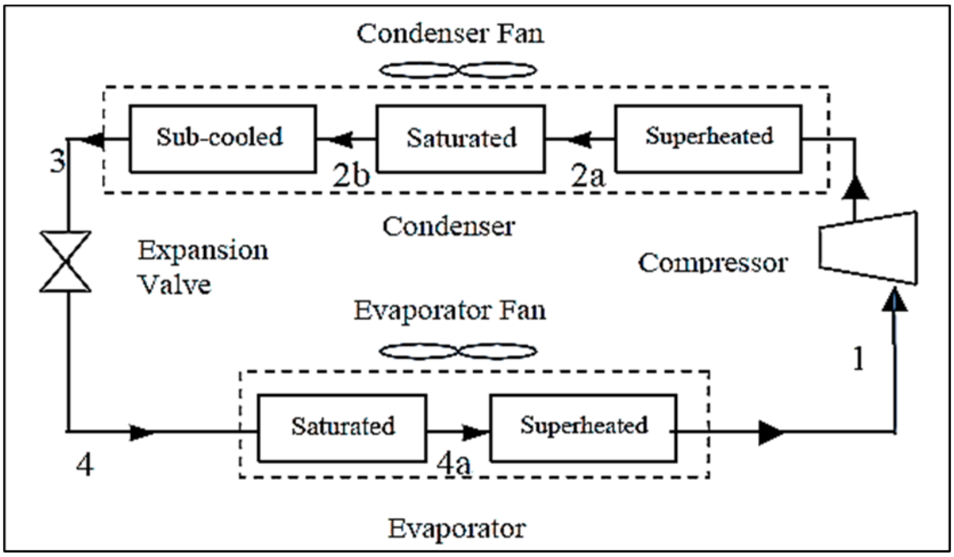

Figure 3. Components of vapor compression refrigeration cycle [17]

The primary function of the expansion device is to reduce the pressure from the high value prevailing in the condenser to the lower one in the evaporator. The secondary function is to meter the flow of the refrigerant, so that the mass flow pumped by the compressor equals that fed through the evaporator. The expansion valve is used to pass a liquid refrigerant, so it cannot operate if there is a vapor refrigerant remaining in the condenser. This leads to an increase in the condenser pressure because the vapor refrigerant backs to the condenser until it is condensed. This case makes the expansion valve maintain the saturated refrigerant liquid property at the end of condenser, whereas it should be maintaining the superheated properties of vapor refrigerant at the end of the evaporator. The expansion process across the expansion valve is constant enthalpy and is given by following equation:

$$h_3 = h_4 \tag{5}$$

The ratio of net heat energy removed at the evaporator to the compressor power supplied is called the Coefficient of Performance (COP) [25]:

$$COP = \frac{Q_{evap}}{W_{comp}} \tag{6}$$

But, the power consumed is not just in the compressor, also there is a power consumption in fans of condenser and evaporator, so the unit coefficient of performance which is defined as the ratio of refrigeration capacity in (kW) to the total power consumed by the system in (kW) including the power consumed by the condenser and evaporator fans [27] is the most accurate COP and is given by:

$$COP_U = \frac{Q_{evap}}{W_{comp}+W_{cf}+W_{ef}} \tag{7}$$

EXPERIMENTAL WORK

The experimental apparatus is composed of air-conditioning system assisted by evacuated tube solar system and several measuring devices. A split type air-conditioning system model [SK–1.5W] was used and delivered with a rotary compressor that was made in Mitsubishi company with a (600-860 W) rated input power, this was swapped with a variable speed double acting compressor that used for the automobile air conditioning, as shown in fig.4. The new system has motor, inventor, belt, solenoid valve, relay and thermostat in addition. The inventor was used to change the motor velocity. The relay controlled the three solenoid valves, one on the line between the compressor and condenser. The second one is between the compressor and collector. The last is one between the collector and condenser. When the outlet temperature from the compressor is low, the valve to condenser closes and the other two valves open forcing the refrigerant to flow through the collector. The thermostat gives the order to the relay to open and close the valves. The condenser characteristics are illustrated in table (1). The refrigeration cycle was run by valves. Storage tank and solar collector were used to develop the performance coefficient and reduce the consumption of power. round copper tubes with two rows of fins made from aluminum was used to design the condenser coil. The condenser and the solar collector assisted the A/C system are illustrated in fig. 5 and 6.

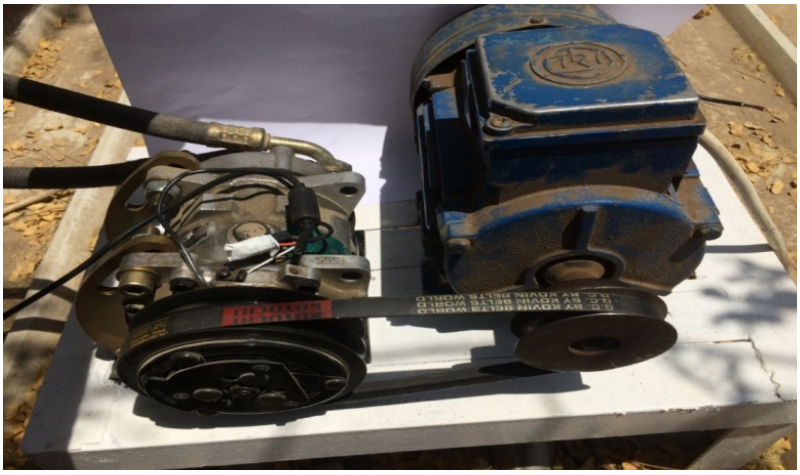

Figure 4. Variable speed compressor and motor system

Figure 5. Air cooled condenser with pressure gauges

Figure 6. Solar collector assisted air conditioner

Table 1. Specifications of storage tank, coil, collector, connection pipes and valves

Outside length	(cm)	80
Outside diameter	(cm)	20
The coil inside the tank		
Number of cycles	30 cycle	
Shape	Spiral	
cycle diameter	(cm)	10
Length	(cm)	50
Collector		
Number of tubes	40	
Length of tube exhibit to the sun	(cm)	43
Clearance between tubes	(mm)	5
Outside diameter	(cm)	4.7
Inside diameter	(cm)	3.7
Length of tube	(cm)	50
Connection tubes		
Location	Length (cm)	Diameter (in)
Pipe from evaporator to compressor	3.4	1/2
Pipe from capillary to evaporator	3.4	1/4

Pipe from tank to condenser	80	3/8
Pipe from compressor to tank	80	3/8
Valves		
Number of valves		3

The DX evaporator is made from copper tubes with aluminum fins. The interior wall around the evaporator is insulated with arm flex material. The test room (3×4.5×3) m^3 contains an indoor unit and the measuring devices, such as power meter, pressure gages, temperature sensors connected with data logger and computer device. The specifications of the evaporator and condenser are listed in table 2.

Table 2. Specifications of condenser and evaporator

Condenser		
Item	Scale	Amount
Materials	Copper tubes, aluminum flat fins	
Motor power	(W)	20
Length of tube	(cm)	75
Fan	Propeller	
No. of tubes	40	
Evaporator		
Materials	Copper tubes, aluminum flat fins	
Length of tubes	(cm)	65

The experimental tests were carried out using a variable speed compressor at three different speeds that are 1400, 934 and 467 rpm. The readings were taken at the ambient temperature 46ºC, while the water temperature was found to be 80ºC during July. As a control system to the flow of refrigerant, a relay and two solenoid valves were used in order to control the flow. The flow of refrigerant was run into two ways. If the refrigerant discharge temperature is less than the water temperature, the flow will travel through the solar storage tank and then to the condenser, while its flow is directly through the condenser if the discharge temperature is the largest.

RESULTS AND DISCUSSION

A variable speed compressor was used to improve the air cooling of the system under an ambient temperature of 46ºC. Three tests were conducted with three speeds of 1400, 934, and 467 rpm. The flow of refrigerant was run into two ways. If the refrigerant discharge temperature is less than the water temperature, the flow will travels through the solar storage tank and then to the condenser, while its flow is directly through the condenser if the discharge temperature is the largest. The results of these tests are shown in figs.7 to 11. Figure 7 elucidates the variation of work with the rpm of compressor. The curve evinces that the work increases as rpm increases. This is because the speed increased the compression effect on the gas molecules. Figure 8 illustrates the variation of power with the rpm. It is behaved in a similar manner to the work as the enthalpy differences across the compressor increased. The increase in the mass flow rate will also play a considerable role in this increase. The relation between the evaporator capacity and rpm is viewed in fig. 9. It can be seen that the increase of evaporator capacity is proportional to the rpm.

This is because the refrigerant pressure drops rapidly as it flows through the tube of the evaporator causing the cooler refrigerant in the evaporator tubes to absorb more heat from the warm room air. Figure10 demonstrates the variation of condenser capacity with the rpm. This figure reveals again that the condenser capacity increased as rpm increased because of increasing the difference between the enthalpy across the condenser and the expected sub-cooled of refrigerant. The required heat rejected by the condenser increases or decreases according to the refrigerating capacity and the temperature of evaporation and condensation. The condenser must release the heat absorbed by the evaporator plus the work done by the compressor. Figure11 clarifies the variation of COP with the rpm. It is clear that the COP is the maximum at the low speed 467 rpm. This is because the compressor work is small in this case and the refrigeration effect is large compared to that of 1400 rpm since part of it is due to the hot water in the solar collector tank. Therefore, the ratio between the evaporator capacity and the work of compressor is a maximum in this case which represents the COP for 467 rpm.

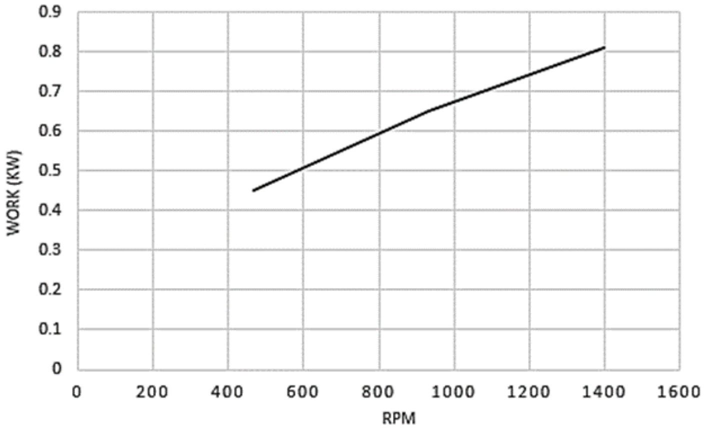

Figure 7. Variation of work with rpm

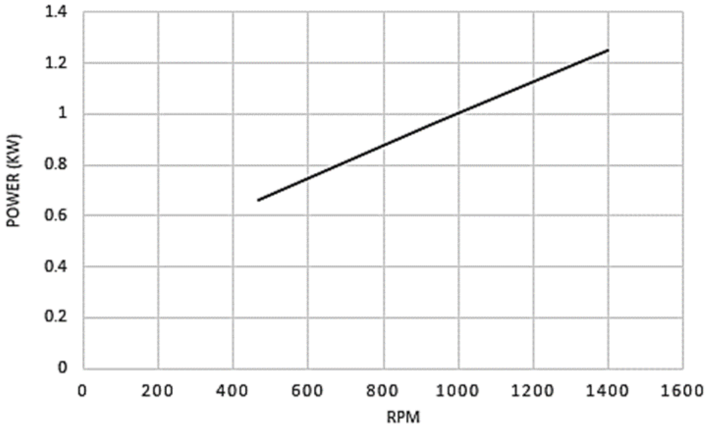

Figure 8. Variation of power with rpm

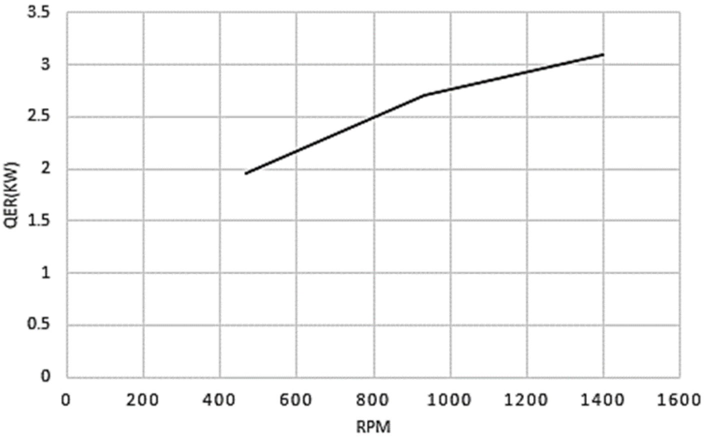

Figure 9. Variation of evaporator capacity with rpm

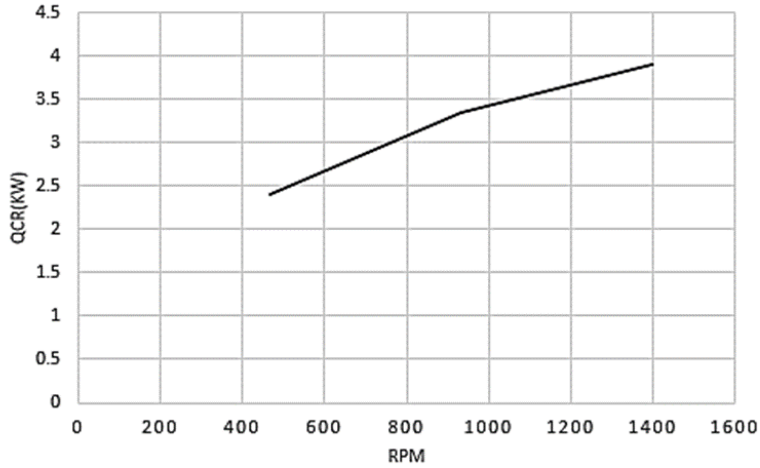

Figure 10. Variation of condenser capacity with rpm

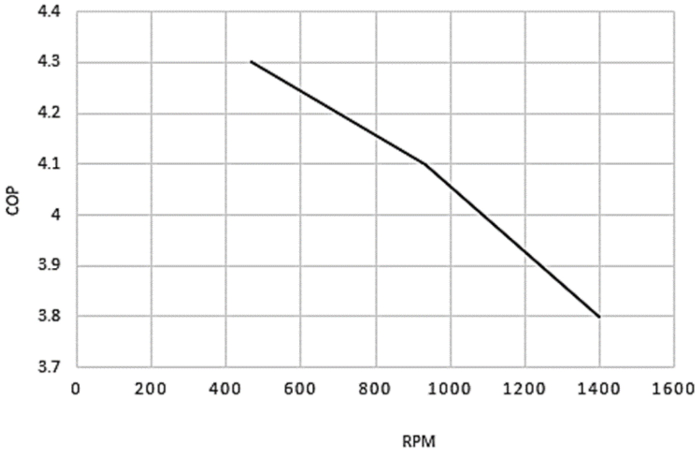

Figure 11. Variation of COP with rpm

CONCLUSIONS

1. The implementation of a variable speed compressor has increased the cooling efficiency, especially at a low speed value of 467 rpm.
2. Increasing the speed from 467 rpm to 1400 rpm leads to an increase in the work of the compressor and a decrease in the COP of the system.

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