Experimental Study on the Effect of Varying Operating Conditions on Performance of Compressive Cooling System

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Abstract—**Air conditioning and cooling systems could be negatively influenced by the external conditions, and it is quite possible that this harmful effect reduces the performance of these systems. This is because these unites requiring the outside temperatures to be lower than the heat being released from them. Unfortunately, this would not work in a favor of saving energy. To avoid low efficiency and to maintain high performance of the cooling system, those devices should be carefully selected based on experimental studies undergoing different local conditions. This humble article aims to experimentally investigate the effect of changing the external operating conditions on the performance of a compressive cooling system. The test facility was designed and arranged to simulate the external operating conditions. The outside conditions surrounding the condenser (such as speed of air movement, external air temperature) were varied, and accordingly the pressures and temperatures of specific points in the system were measured.**

This study has found that the speed of air movement and high temperature of air ambient negatively influenced the performance of the cooling system. The optimum value of the performance of the compressive cooling system obtained at the external air temperature range of (18 → 28 C°). Additionally, the research suggested that the relative humidity of the atmosphere should exceed 50% for this case of study. Therefore, selecting a suitable place for the compressive cooling system is crucial to attain a better performance with less consumption of electricity.

Index Terms: **Compressive Cooling Systems, Operating Conditions.**

I. INTRODUCTION

Cooling process is the removal of undesirable heat from a particular object, material, fluid, or space and its transfer to another object, material, fluid, or space. Subtraction of heat drops the temperature and may perhaps be accomplished by the use of mechanical refrigeration or the use of chilled water, snow, or ice.

In mechanical refrigeration, mechanical components are put together in a refrigeration system for the purpose of transferring heat. The idea of cooling is based on changing the pressure of the cooling medium between high pressure (H.P) and low pressure (L.P), so that the saturation temperature corresponding to the pressure (saturation pressure) is changed.

Refrigeration has become an essential part of our lives, so its usages are in so many fields, at our homes, in the world of manufacturing, at commercial or in-service sectors. However, utilization of such devices could lead to a significant rise of consumption of electricity. Many studies have shown that air conditioning consumes about 40% of the total power produced in the building sector [1]. For instance, the annual cost of electricity power used in air conditioning at the American residential buildings is estimated about $ 29 billion; accordingly, an amount of almost 117 million metric tons of carbon dioxide is released into the atmosphere each year [2]. Due to the massive shortage in production of electricity and the difficulties that Libya suffers in this particular field with no expectation of solving this crisis in the near future, it is vital to reduce the consumption of electricity used in all sectors. Air conditioning and cooling devices are excessively used in Libya especially in summer season.

The most essential element to reduce the electrical power consumption in air conditioning and cooling devices is improving the thermal insulation of the buildings.

A previous research in this area was carried out by (Elrafaei et al., 2015) [3]. They added nanomaterials such as silica and methacholine dust in concrete to improve thermal insulation of the constructions at high temperatures. They found that the ability of the concrete to heat insulation significantly increased while maintaining its proper mechanical properties in construction considerations. Another study by (Hamza, 2012) [4] concluded that the improvement of the thermal insulation of buildings could be achieved by adding ceramic fillings such as magnesium oxide of phenyl ester; adding of such material helps to advance the thermal insulation of resin.

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Many other researches have been focused on the usages of renewable energy, primarily solar energy, in cooling systems to reduce electricity consumption. (Bermejo et al., 2010) [5] Studied a cooling system that absorbs water in condensate and uses solar thermal energy. This system is a dual absorption cooler with a cooling capacity of 174 kW; and solar energy accounts for 75% of the total heat input of the generators and the absorption cooler operates with an average daily performance coefficient of 1.1-1.25. (Fayyad et al., 2009) [6] Conducted a detailed analytical study on the thermodynamics of a 10-kw solar cooling system using a combination of ammonia and water as an intermediary liquid. The computer simulation model was developed to proceed calculations and obtain the results of such study.

There are also other studies that used different types of cooling liquids to improve the performance of cooling systems and decrease consumption of electricity. (Miguel, 2010) [7] Studied the utilizing of R413a instead of the R12 on the performance factor of a domestic cooling system using energy analysis. The simulation of evaporative work was performed at different temperatures, and the researcher concluded that there is a possibility of reducing the consumption of electricity by using the new liquid. While the researcher (Khalifa, 2013) [8] found there is a possibility of increasing the coefficient of performance by using R-134a instead of R-12.

In addition to the above factors, most air conditioning and cooling devices are affected by external factors and conditions, especially air ambient temperatures. As it is observed there is a decrease in the performance of air conditioners as the air ambient temperatures rises; and the performance coefficient of the cooling and air conditioning equipment drops in the summer period, specifically for the devices designed to operate at the high temperatures. Therefore, (Muhammad and Jawad, 2009) [9] studied the effect of changing the fluid flow and other various external conditions based on the weather in Iraq on the thermal performance of evaporative air coolers; they examined fluid flow rates for all temperatures. In order to achieve an outstanding performance of air conditioning and refrigeration which are suitable for the climate of Libya, this study aims to maintain the effect of changing the external operating conditions on the performance of a system of compressive cooling. Speed of air movement, air ambient temperature, and relative humidity are the point of interest in this work.

This article is outlined into two main portions, the first part has been focused on a theoretical illustration that deals with the compressive cooling cycle and its components; the standards of evaluating the performance of the cooling compressive system are also presented. The second part introduces the experimental tests and its steps. Then, the calculations and the results obtained from the experiment are illustrated, and eventually the conclusions and recommendations are presented.

II. COMPRESSIVE COOLING CYCLE

The mechanical cooling cycle of the compressive cooling system consisted of four main parts:

1- Compressor: the compressor is the key part of the cooling cycle, and it is considered as the heart (pulse) of the cooling cycle. The refrigerant gas is compressed with the constant entropy in this part. There are several types of compressors used in refrigeration, the main ones are: rotary compressors, reciprocating compressors, centrifugal compressors, rotary screw compressors; and screw rotary compressors.

2- Condenser: A condenser in the cooling cycle is a surface-heat exchanger where heat is transferred from the vapor refrigerate of the hot cooling medium through the walls of the condenser tubes to the condenser cooling fluid. As a result of the exchange, the temperature of the refrigerant drops to saturation temperature and then condenses into a liquid. Three types of condensers are used in compressibility cooling cycles: air-cooled condenser, water-cooled condenser, and evaporative condenser.

3-Expansion valve: The purpose of the expansion valves (the means of expansion) in the simple cooling cycle is to reduce the pressure of the refrigerant that was raised in the compressor, as well as the role of the control in the rate of flow of the refrigerant, depending on the need of the cooling cycle.

4- Evaporator: It is a heat exchanger where the heat is transferred from the medium to the refrigerant. Evaporators are manufactured according to multi-type designs, shapes, sizes, and capacities. It can be classified according to their usages, their form, or the way they are fed by the cooling fluid, the air or liquid flow through the evaporators and the control of the refrigerant fluid. Figure. 1 shows a schematic diagram of the mechanical cooling cycle of the compressive cooling system.

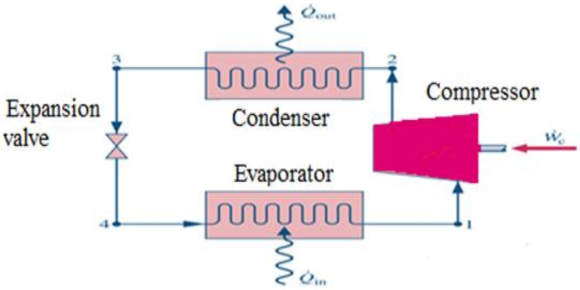

Figure 1. Mechanical Cycle Diagram of the Compressive Cooling System.

The cycle of vapor compressive cooling system is known as the Rankin cycle. The basic processes of the simple compression cycle are summarized in Table 1. While Figure. 2 shows the variation of pressure with Enthalpy in the Rankin cycle.

Table 1. Mechanical Cycle Components of the Cooling System.

No.	Element	Description
1 to 2	Compressor	Pressure rise of refrigerant with constant entropy.
2 to 3	Condenser	Loss of heat in the condenser (with constant pressure)
3 to 4	Expansion Valve	Throttle during the expansion valve (a constant enthalpy)
4 to 1	Evaporator	Heat absorption in evaporator (with constant pressure)

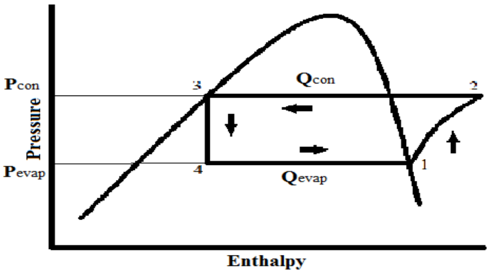

Figure 2. Pressure vs Enthalpy in the Rankin Cycle.

In addition to the basic elements of the cooling cycle, there are several accessories in such cycle. Figure. 3 shows a diagram of the main elements of cooling cycle with the accessories. The most important of these accessories are:

- Solenoid valve: It is used to automatically control the flow of the cooling medium; and is used extensively in cooling and air conditioning systems.
- Stop valves: These valves are used in cooling cycles to isolate a specific part of the cooling circuit during partial loading or maintenance and repair operations
- Dryer or filter: It works to remove the moisture entering the cooling cycle by reducing pressure in the cycle under atmospheric pressure; also, it is used to clean the pipes of the cooling cycles from dirt, crusts, and impurities.
- Flexible joints: They are used to reduce induced vibrations from moving equipment such as reciprocating compressors to the other stationary parts.
- Liquid Accumulator: the reservoir of liquid is a tank with a pipe; its job is to maintain the refrigerant fluid when it comes from the condenser. Existence of such accumulator in the cycle leads to an increase of the performance coefficient of the cooling cycle; because it lets the refrigerant fluid pass through the expansion valve when it is only in the liquid state, but not in the gaseous phase.
- Oil separator: To reduce the flow oil in the cooling cycle, the oil separator is placed on the line of the compressor, it is also used to refine the refrigerant of the oil and return the oil back to the compressor.
- Sight glass: the purpose of the sight glass is to indicate the amount of refrigerant in the cycle, and to place the liquid line after the condenser.
- Pressure regulators: control pressure during the cooling cycle.

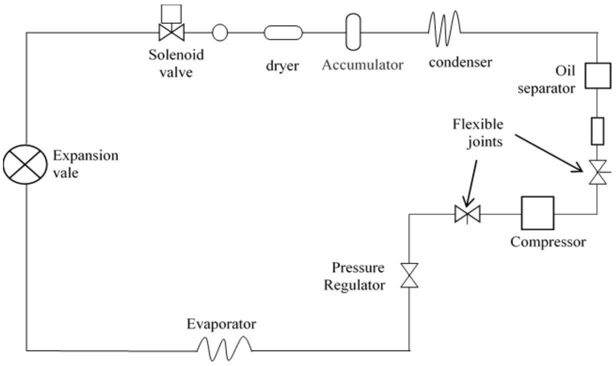

Figure 3. The Main Elements of the Cooling Cycle with the Accessories

To evaluate the performance of a simple compression cooling cycle, there are several standards should be considered; the most important of these standards are:

Refrigeration Effect (RE): it is defined by the amount of the heat absorbed by each kilogram of the refrigerant in the evaporator from the surrounding environment, and it is determined from Eq (1):

$$RE= [h_1-h_4] \tag{1}$$

Where (h) is the Enthalpy.

Compressor Work (Wc): The function of the compressor is to push the refrigerant into the cooling cycle as well as to increase the pressure of the cooling cycle from the suction pressure to the discharge pressure. It is calculated according to Eq (2):

$$Wc=\dot{m}\,[h_2-h_3] \tag{2}$$

Where $\dot{m}$ is the refrigerant flow rate.

Cooling Capacity (Qe): it is expressed as the rate of energy that the evaporator will remove from the cooled space or cooled product. It is evaluated as Eq (3):

$$Qe=\dot{m}\,[h_1-h_4] \tag{3}$$

Condensing Load (Qc): It is the heat expelled from the condenser and calculated from Eq (4):

$$Qc=\dot{m}\,[h_2-h_3] \tag{4}$$

Refrigerant Flow Rate ($\dot{m}$): The flow rate ($\dot{m}$) of the refrigerant in the cooling cycle is defined as Eq (5):

$$\dot{m}=Qe/RE \tag{5}$$

Compressor Displacement Size: From the previous equation, the volumetric flow rate of the refrigerant (V) drained from the compressor can be calculated based on the specific size of the refrigerant (ν) at the input of the compressor. The compressor displacement size is calculated from Eq (6):

$$V=\dot{m}\nu \tag{6}$$

Coefficient of Performance (COP): The cooling cycle performance coefficient is a measurement of efficiency of the cycle and is expressed as a proportion of the energy absorbed by the evaporator attributed to the energy needed for the compressor. The COP is expressed as Eq (7):

$$COP=Qe/Wc=RE/Wc= (h_1-h_4)/ (h_2-h_1) \qquad (7)$$

III. DESIGN OF THE TEST FACILITY

This section deals with the experimental procedures of this study. It investigates the effects of changing the external conditions on the performance of the cooling system. A cooling system equipped with pressure gauges and temperature gauges at the Mechanical Lab at Misurata University was used in this experiment. The tests were carried out under a wide range of conditions of speed of air movement, air ambient temperature and the humidity ratio of the air surrounding the condenser. The system was exposed to a range of temperature of (10-45) C°. The speed of air movement varied between (0 to 9 m/s) using an adjustable speed fan. The humidity ratio varied with a range of (15-92 %).

Figure. 4 displays a sketch of the simulation system, where Figure. 5 shows the mechanical electrical circuit of the household refrigerator that used in this experiment.

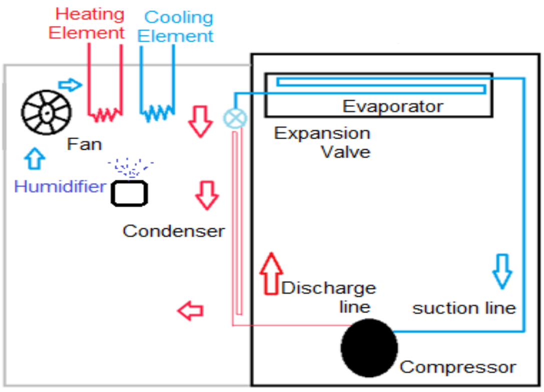

Figure 4. Simulation System

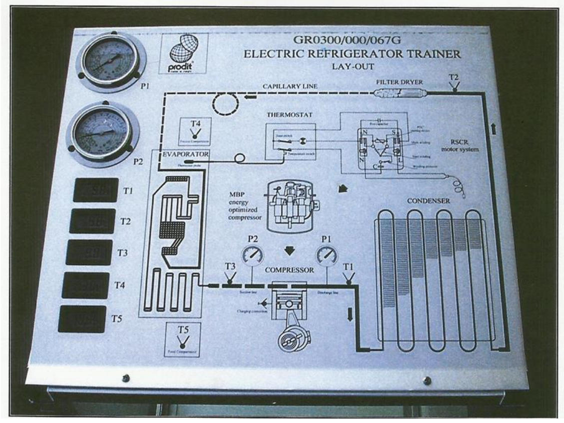

Figure 5. Mechanical and Electrical Circuit of the Refrigerator "Case Study"

IV. PROCEDURES

The following simplification assumptions are taken in consideration during the experimental tests:

1- Pressure and temperature of the refrigerant in the condenser do not change.

2- Pressure and temperature of the refrigerant in the evaporator do not change.

3- Neglecting the change of pressure in suction and discharge valves.

Before operating any tests on the system, the air ambient temperature and relative humidity were measured inside the laboratory. Then the refrigerator was operated and the following parameters were measured:

- Discharge pressure (P1), and suction pressure (P2)
-Temperature of the refrigerant at the outlet of the compressor (T1), the temperature of the refrigerant right after the condenser (T2), and the temperature of the refrigerant at the inlet of the compressor (T3).
- Current Amps (A) in the compressor.

The above steps are repeated at varied external conditions. Three experimental tests were undertaken in different external conditions as presented in the following cases:

Case 1: Varying the speed of air movement surrounding the condenser:

In this case, the air ambient temperature, and the relative humidity were fixed at 27 °C and 50% respectively. While the air movement around the condenser varied. This test was performed using an adjustable speed fan. The fan speed can be adjusted by a speed controller with a range of (0 to 9 m/s). The data collected from this experimental test is listed in Table 2.

Table 2. Test Runs of Case 1

	Air move (m/s)	**T2 (c°)**	**T1 (c°)**	**T3 (c°)**	**P1 (bar)**	**P2 (bar)**	**Current (A)**
1	0	47.8	62.4	-0.4	17.5	1.5	0.936
2	3	34	60.1	-0.7	15.5	1.4	0.922
3	6	32.9	60.1	-0.4	15.5	1.4	0.919
4	9	31.5	58.4	-0.4	15.2	1.5	0.904

Case 2: Varying the air ambient temperature surrounding the condenser:

In this case, the air speed set to be constant, and the relative humidity was fixed at 50%. While the ambient temperature varied at a range of (10-45) °C. The collected data of this experimental test is listed in Table 3.

Table 3. Test Runs of Case 2

No.	**Air Temp. (C°)**	**T2 (c°)**	**T1 (c°)**	**T3 (c°)**	**P1 (bar)**	**P2 (bar)**	**Comp. Current (A)**
1	10	22.7	66	-1.8	14	1.5	0.692
2	15	23	66	-1.5	14.5	1.5	0.828
3	20	24.5	67	-1.4	15	1.6	0.83
4	25	30.5	67.2	2	15.8	1.6	0.862
5	30	33.2	68.4	2.5	16.2	1.6	0.88
6	35	39.2	72	3	17.5	1.8	0.89
7	40	43.8	73.2	3	18.4	2	0.898
8	45	50.2	76.1	4.7	19.5	2.1	0.911

Case 3 - Varying the relative humidity surrounding the condenser:

In this case, the air speed set to be constant, and the air ambient temperature was fixed at 27 °C. While the relative humidity varied at a range of (15-92 %). The collected data of this experimental test is listed in Table 4.

Table 4. Test Runs of Case 3

No.	**(RH)%**	**T2 (c°)**	**T1 (c°)**	**T3 (c°)**	**P1 (bar)**	**P2 (bar)**	**Current (A)**
1	15	32.1	69.7	0.2	16	1.6	0.871
2	25	31.2	69.6	0.2	16	1.6	0.8
3	50	30	69.6	0.4	15.8	1.6	0.88
4	92	30.5	69.4	0.4	15.5	1.65	0.87

IV. ANALYSIS AND DISCUSSION OF THE RESULTS

After running the experimental tests of the three cases and collecting all applicable data, the standards of evaluating cooling system were calculated according to the set of equations (1-7) Then, the statistical curves were used to express the relations among the power consumption, the (C.O.P.) of the cooling system and the external conditions. The calculated results are to be stated as follows:

Effect of varying air movement: Figure. 6 shows the variation of air movement with the performance coefficient (C.O.P.) of the cooling system. The highest value of the performance coefficient is 5.22 at the highest speed of air.

Figure. 6 specifies that the performance coefficient gradually decreases with a drop of air movement. Fig. 7 displays the variation of power consumption with the air movement of the cooling system. Fig. 7 indicates that the lowest value of the power consumption is (199VA) at the high air speeds, and the power consumption gradually rises with a decrease of the air speed.

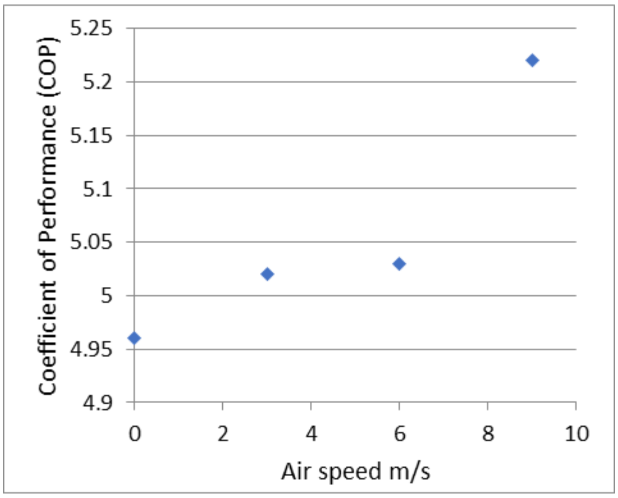

Figure 6. Variation of Air Movement with COP

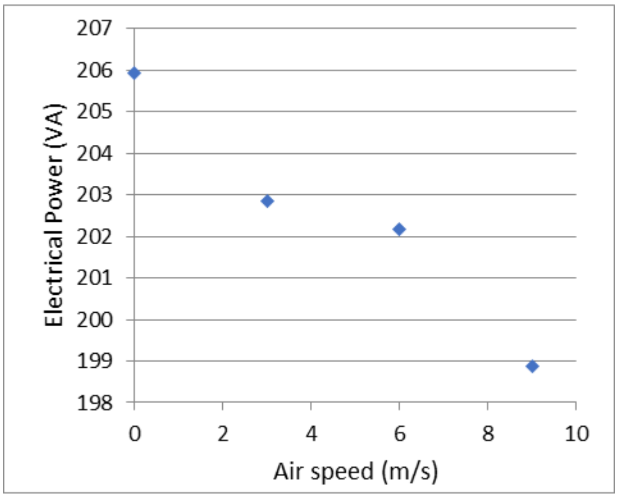

Figure 7. Variation of Air Movement with Power Consumption

The changings that happened to the other parameters due to the variation of air speed could be summarized as follows:

Suction pressure (LP) decreases at low and medium air speeds (1.4 bar), and increases at high air speeds (1.5bar). The discharge pressure (HP) has changed as well. The minimum pressure of the HP indicated at (15.2 bar) when the air speed reached (9m/s). It was noticeable that the HP progressively increases as the air movement rises at the range of (15.5 – 17.5) bar.

The refrigeration effect (RE) has clearly changed with the change of air movement of the system. The highest value of the refrigeration effect (RE) is equal to 157 KJ/Kg at air speed higher than 6 m/s. Then, the refrigeration effect (RE) steadily decreases as the air speed falls within a range of (134 – 154) kJ/kg. Table 5 states the calculated results of the variation of air movement surrounding the condenser.

Table 5. Calculated Results of the Variation of Air Movement Surrounding the Condenser

No	Air speed (m/s)	Pe	COP	Wc	E.R	h3=h4 kJ/kg	h2 kJ/kg	h1 kJ/kg
1	0	205.92	4.96	27	134	265.88	427	400
2	3	202.84	5.02	30.7	154	247	431.7	401
3	6	202.18	5.03	31.359	156	244.11	432.35	401
4	9	198.88	5.22	30.08	157	243.5	430.58	400.5

Effect of varying external air temperature surrounding the condenser: Figure. 8 shows the variation the air ambient temperature with the performance coefficient (COP) of the cooling system.

The figure explains that the highest value of the COP reaches (4.5) when the average air ambient temperature ranges from 18 to 28 °C. It revealed that the COP decreases either at low temperatures (less than 15°C) or at higher temperatures (more than 35°C). Figure. 9 demonstrates the effect of varying air ambient temperature on the power consumption of the system. Figure.9 shows that the lowest value of the power consumption (150 VA) happens at a value of ambient temperature of 10 C°. Then, as the air ambient temperature increases the power consumption rises.

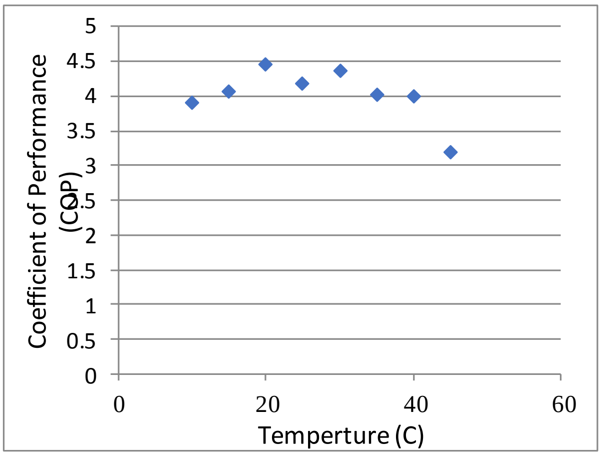

Figure 8. Variation of Ambient Temperature with COP

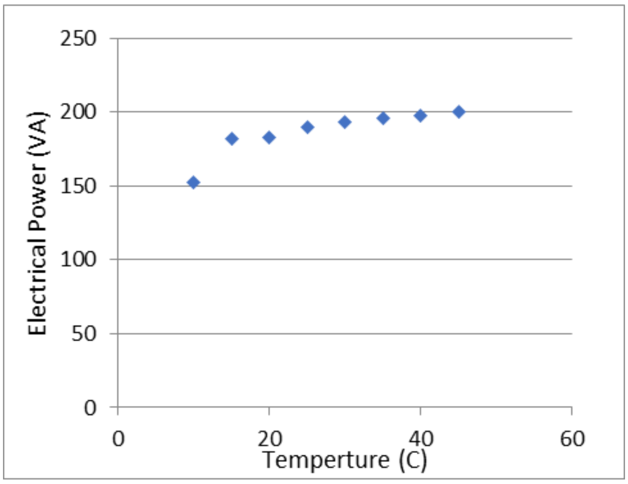

Figure 9. Variation of Ambient Temperature with Power Consumption

The changings that happened to the other parameters due to the variation of ambient temperature could be summarized as follows:

Table 6 displays the calculated results of the variation of air ambient temperature surrounding the condenser. The table shows that the suction and discharge pressures increase as the air ambient temperature rises. The minimum value of the suction pressure is 1.5 bar at a range of (10-15) °C, while the minimum discharge pressure is (14) bar at (10 °C) and the maximum discharge pressure is 19.6 bar at 45 °C. The effect of air ambient temperature on the refrigeration effect (R.E) is exactly the opposite. The compressor work and the R.E decrease with a rise of the air ambient temperature. The highest value of R.E is 172 KJ/Kg at 10 °C. It is observable that the R.E declines as the air ambient temperature escalates. At a range of (10 – 22) °C, it was achieved a better value of R.E than other ranges of temperatures.

Table 6. Calculated Results of the Variation of Air Ambient Temperature Surrounding the Condenser

No	°C	Pe	COP	Wc	R.E	h3=h4 kJ/kg	h2 kJ/kg	h1 kJ/kg
1	10	152.24	3.909	44	172	228	444	400
2	15	182.16	4.0546	41.617	168.74	231.76	442.117	400.5
3	20	182.6	4.4532	37.647	167.65	232.35	437.647	401
4	25	189.64	4.179	39	163	241	443	404
5	30	193.6	4.355	36.47	158.83	244.7	440	403.53
6	35	195.8	4.007	36.76	147.3	257.7	441.76	405
7	40	197.56	4	36	144	260	440	404
8	45	200.42	3.197	38.82	124.13	279.4	442.35	403.53

Effect of varying the relative humidity surrounding the condenser: Figure.10 shows the variation of the relative humidity with the performance coefficient (COP) of the cooling system. The lowest COP of the system is at 45%. Then, the COP starts to rise as the relative humidity varied from 50% to 30%. Figure. 11 demonstrates the effect of changing the relative humidity on the power consumption of the cooling system. Mostly, it is notable that there is stability in the power consumption at above 50% of relative humidity.

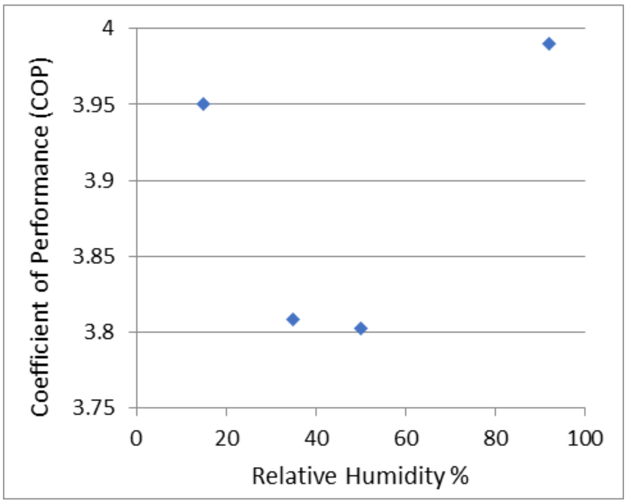

Figure 10. Variation of Relative Humidity with COP

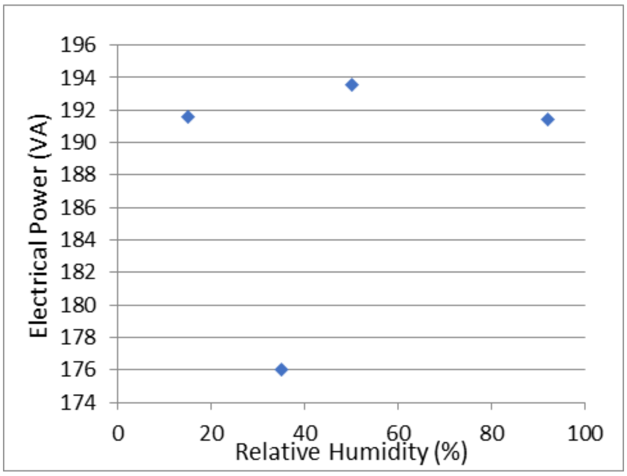

Figure 11. Variation of Relative Humidity with Power Consumption

The changings that happened to the other parameters due to the variation of relative humidity could be summarized as follows:

Table 7 displays the calculated results of the variation of relative humidity surrounding the condenser. The lowest value of the suction pressure is (1.6 bar). The suction pressure rises with an increase of the relative humidity. The discharge pressure drops with an increase of the relative humidity. The maximum discharge pressure reached 16 bar. The lowest value of refrigeration effect (R.E) is (157 kJ/kg). It summarized that R.E escalates with a rise of the relative humidity of the system.

Table 7. Calculated Results of the Variation of Relative Humidity Surrounding the Condenser

No.	**RH %**	**Pe**	**COP**	**Wc**	**RE**	**h3=h4 kJ/kg**	**h2 kJ/kg**	**h1 kJ/kg**
1	15	191.62	3.95	40	156.89	244.11	441	401
2	35	176	3.808	41.35	157.47	243.52	442.35	401
3	50	193.6	3.802	41.77	158.82	242.94	443.53	401.76
4	92	191.4	3.99	40.59	162.35	240	442.94	402.35

V. CONCLUTIONS AND RECOMANDATIONS

The main objective of this study was to determine the effects of varying the external operating conditions on the performance of a compressive cooling system. The three experimental tests were carried out under various conditions. The speed of air movement, air ambient temperature and relative humidity parameters varied and the effects on the other design standards of the cooling system investigated. From this work, the followings could be concluded:

- The COP of the cooling system increases with a decrease of the power consumption as the air movement surrounding the condenser rises.
- The RE of the system could be advanced at a value of the air movement around the condenser above 6 m/s.
- The RE of the system falls as the air ambient temperature rises.
- The superb value of COP of the system reached (4.4) at air ambient temperature (18 ° C); therefore, such a system is not suitable to be working under higher ambient temperatures.
- The electrical power consumption rises as the air ambient temperature climbs.
- The superb value of COP could be obtained at a relative humidity range of higher than 50%. At this range of relative humidity, there was an existence of stability in the power consumption and RE.
- Since, the data that collected from this work is valid only for the compressive cooling systems; the authors recommend that the same study on the other types of cooling systems should be carried.

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