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Development of an Experimental Apparatus for Demonstrating Vapour Compression Refrigeration System

B.O. Bolaji [a,]*, T.O. Falade [b]

[a] *Department of Mechanical Engineering, University of Agriculture, P.M.B. 2240, Abeokuta, Nigeria*
[b] *Department of Mechanical Engineering, Federal Polytechnic, P.M.B. 5351, Ado-Ekiti, Nigeria*

Abstract

This paper presents the design, construction and performance testing of a refrigeration system for use as experimental apparatus for demonstrating vapour compression refrigeration cycle and basic concepts of thermodynamic principles. The apparatus shows the visual observation of all-important processes. The experimental data were analysed using the first and second laws of thermodynamics to determine the refrigerating effect, the net heat rejected from the system, the compressor work input and coefficient of performance (COP). During the test, the COPs of the system and Carnot cycle were found to be 3.87 and 6.96, respectively. Also, the steady state discharge pressure and the average refrigeration capacity obtained were 830 kPa and 915.8 W, respectively, while the relative and isentropic efficiencies obtained from the system were 55.6 and 86.7%, respectively.

Keywords: *apparatus, experimental, refrigeration system, thermodynamics, refrigerant.*

1. Introduction

Many Engineering systems involve the transfer and conversion of energy, and the sciences that deal with these subjects are broadly studied under thermodynamics. Engineers use thermodynamics principles in their study and design of a wide variety of energy systems. Thermal equipment such as heat exchangers, boilers, condensers, heaters, furnaces, refrigerators, air-conditioners and solar collectors are designed primarily on the basis of thermodynamics principles. One of the important areas of application of thermodynamics principles is refrigeration.

The physical process whereby heat is removed from substance resulting in decrease in the temperature or keeping it constant is known as cooling. The process can be performed in two ways: naturally by utilising medium of a temperature lower than temperature of substance to be cooled and artificially by utilising thermodynamics process of working medium producing low temperature, mainly in a closed cycle. The branch of technology dealing with cooling being performed by means of a thermodynamic cycle, where heat is transferred from the cooled substance, is termed refrigeration [1].

For almost a century after the fundamental studies of Carnot refrigeration cycle, the pace of developments in refrigeration was largely governed by improvements in refrigerating machines that evolved from steam engine technology and Carre's invention of the absorption machine. Beginning in the 1930s, new innovations altering the course of artificial refrigeration include the hermetic compressor, the discovery of halocarbon refrigerants by Midgley, Pennhington's regenerative dehumidifier cycle and the commercial reversible air-to-air heat pump. More recent developments in refrigeration have been evolutionary in nature, directed at meeting worldwide needs for food, comfort and health [2-4].

Refrigeration making or keeping things cold is a process with very wide range applications in the modern world. Cooling is used for household and industrial purposes. Refrigeration allows us to preserve perishable food and distribute it over large distances. It is essential in many manufacturing processes including the automobiles and other transport system [5, 6].

Heat flows naturally from a hot to a colder body, but in refrigeration system, the opposite must occur i.e. heat flows from a cold to a hotter body. This is achieved by using a substance called a refrigerant, which absorbs heat and hence boils or evaporates at a low pressure to form a gas. This gas is then compressed to higher pressure, such that it transfers the

[*] Corresponding author. Tel.: +2348035785662
E-mail: bobbolaji2007@yahoo.com

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heat it has gained to ambient air or water and turns back (condenses) into liquid. In this way heat is absorbed or removed, from a low temperature source and transferred to a higher temperature source [7].

According to the second law of thermodynamics, to achieve heat transfer from a low temperature reservoir to a high temperature reservoir a cycle device which needs work input from an external source will be required [1]. External work is used in vapour compression refrigeration systems, whereas external heat energy is utilized in the absorption refrigeration systems and other less common types of refrigeration systems.

An experimental apparatus that will enhance the teaching and learning of thermodynamics is needed in various institution of higher learning. Through practical demonstration of refrigeration system, students would be able to apply thermodynamics principles, such as the first and second laws, learned in the classroom lectures, to real-life problems. This work therefore, presents the design, construction and performance test of an apparatus for use in the thermodynamics laboratory to demonstrate vapour compression refrigeration system and to carry out students' practical tests in relation to thermodynamics principles.

2. Materials and Methods

2.1. Basic Theory

Most refrigeration systems are based on the vapour compression process using a refrigerant allowing a change from the liquid to the gas phase. The main components of a refrigeration system are compressor, condenser, expansion device and evaporator.

***Compressor*:**
It is the heart of refrigeration system. It sucks the refrigerant gas from the evaporator through refrigerant piping and compresses it to a higher pressure. Compression also results in a higher temperature of the refrigerant.

***Condenser*:**
It is essentially heat exchanger device, where heat absorbed from the evaporator is transferred from the refrigerant to the ambient air. High-pressure refrigerant gas from this compressor is condensed into the liquid phase as it is cooled inside the condenser at about constant pressure. A high-pressure, medium-temperature liquid refrigerant is then leaving the condenser.

***Expansion device*:**
It releases the high-pressure liquid from the condenser in a controlled fashion and the pressure is thereby reduced to the same level as the evaporating pressure. When the refrigerant is depressurized, the boiling point of the refrigerant is reduced.

***Evaporator*:**
It is a heat exchanger in which the liquid refrigerant evaporates due to heat extracted from cooled medium at a very low temperature, producing a low-temperature, low-pressure refrigerant vapour.

2.2. The Design Process

The design process as outlined by some earlier researchers [8-10] was followed. The first essential and basic feature of this process is the formulation of the problem statement. This involves determining the requirements of the system, the given parameters, the design variables, any limitations or constraints, and any additional considerations arising from safety, financial, environmental, or other concerns. The following is a summary of the guidelines for the apparatus:

i. The system must be based on the vapour compression refrigeration cycle.
ii. All components of the system must be visible, and the different state points in the cycle must be instrumented to measure the temperature and pressure at these points.
iii. The system should keep the evaporator between temperatures of 5 and 7^{o}C (or 6 ± 1^{o}C).
iv. The working fluid for the system (refrigerant) must be environmentally friendly.
v. The system should operate on regular 220 V, single phase, grounded, 60 Hz a.c. power from a standard outlet.
vi. The system should be rigid and stable (not likely to tip over accidentally).

After the problem statement was formulated several conceptual designs were considered and evaluated. Each design concept was evaluated by the following criteria: effectiveness as an instructional laboratory apparatus, cost, safety, simplicity and size.

The design chosen was a hermetically sealed compressor, single stage vapour compression refrigeration cycle. The refrigerant selected was R134a. It is an environmental-friendly refrigerant. It has ozone depletion potential of zero. In small refrigeration and air conditioning systems, one of the commonly used expansion devices to control the flow rate of refrigerants is the capillary tube. This is a simple tube of 1.2 mm internal diameter, Although the device lacks active function (mechanical or electrical) to actively adjust to any sudden change in the load conditions, it is still in use as a result of its simplicity low cost and requirement of low compressor starting torque [11, 12]. Therefore, the design is based on the used of capillary tube as an expansion device.

The pressure-enthalpy (p-h) diagram of a simple vapour compression refrigeration cycle is shown in Fig. 1. In this theoretical vapour compression cycle, the refrigerant enters the compressor at state 1 at low pressure, low temperature, and saturated vapour state. From state 1 to 2, the refrigerant is compressed by the compressor and is discharged at state 2 as a high pressure, high temperature and super heated vapour. At state 2, it enters the condenser where it releases heat to the environment. The refrigerant leaves the condenser at state 3 at high pressure and saturated liquid state. From state 3, the refrigerant enters the expansion devise where its pressure is reduced from high pressure (condenser pressure) to low pressure (evaporator pressure). After this it enters the evaporator at state 4 where it absorbs heat from the conditioned space and it leaves the evaporator at low pressure, low temperature and saturated vapour (state 1).

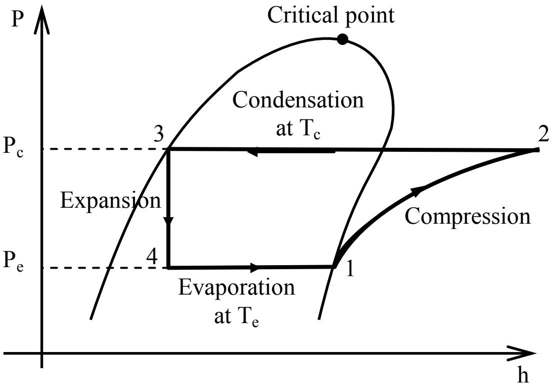

Fig. 1. Simple vapour compression refrigeration cycle on p-h diagram.

In the theoretical cycle, it is also assumed that there is no super heating in the suction line and no sub-cooling in the liquid line. It also assumed that steady states and uniform flow conditions exist throughout the elements of this simple vapour compression refrigeration cycle and changes in kinetic, potential energies, and heat loss from the compressor are negligible. Therefore specific work of compression (W_{comp}) for the compressor is given as [13]:

$$W_{comp} = h_2 - h_1 \tag{1}$$

where h_1 and h_2 (kJ/kg) are enthalpies at the compressor inlet and exit, respectively.
During compression process, the refrigerant is considered as ideal gas and the specific work of compression (W_{comp}) can be expressed by [14, 15]:

$$W_{comp} = \frac{C_p T_{comp,i}}{\eta_{is}} \left(r_p^{\frac{\gamma-1}{\gamma}} - 1 \right) \tag{2}$$

$$\text{and} \quad r_p = \frac{P_2}{P_1} \tag{3}$$

where r_p = pressure ratio; P_1 = evaporator pressure (N/m^2); P_2 = condenser pressure (N/m^2); $T_{comp,i}$ = temperature at compressor inlet (K); η_{is} = isentropic efficiency of the compressor; C_p = specific heat at constant pressure (kJ/kg.K); and γ = specific heat ratio of the refrigerant.

The isentropic efficiency of the compressor is given as [16]:

$$\eta_{is} = \frac{\dot{W}_{is}}{\dot{W}_{input}} \tag{4}$$

where, $\dot{W}_{is}$ = isentropic work of compression per second (W); and $\dot{W}_{input}$ = compressor power input (W). During the throttling process in the expansion device, it is assumed that there is no heat transfer to the environment [17], which results in:

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

The refrigeration capacity of the cycle can be calculated from the rate of enthalpy change in the evaporator:

$$Q_e = h_1 - h_4 \tag{6}$$

Where Q_e is the specific refrigeration load of the refrigeration cycle in kJ/kg. The rate of heat rejection (Q_e) can be calculated from the rate of enthalpy change in the condenser:

$$Q_c = h_2 - h_3 \tag{7}$$

The coefficient of performance of the refrigeration cycle (COP_{system}) is the ratio of the specific refrigeration load (Q_e) to the specific work of compression (W_{comp}), therefore,

$$COP_{system} = \frac{Q_e}{W_{comp}} \tag{8}$$

The coefficient of performance of the Carnot refrigeration cycle (COP_{Carnot}) is the ratio of the minimum temperature (T_e) to the difference between the maximum and the minimum temperatures in the cycle ($T_c - T_e$), therefore,

$$COP_{Carnot} = \frac{T_e}{T_c - T_e} \tag{9}$$

The relative efficiency is obtained using Eq. (10) [18]:

$$\eta_r = \frac{COP_{system}}{COP_{Carnot}} \tag{10}$$

2.3. Equipment Description

The refrigeration system was constructed as instructional laboratory apparatus. The schematic diagram of the apparatus is shown in Fig. 2 and the general view is shown in Fig. 3. The temperature and pressure of the working fluid (R134a) were measured at the four different points indicated in Fig. 1 and 2. In addition, the mass flow rate of the refrigerant was measured using a flow meter. The measurements of the temperature and pressure at points 1 to 4 allow the determination of the various thermodynamics properties needed to demonstrate thermodynamics principles such as the first and second laws.

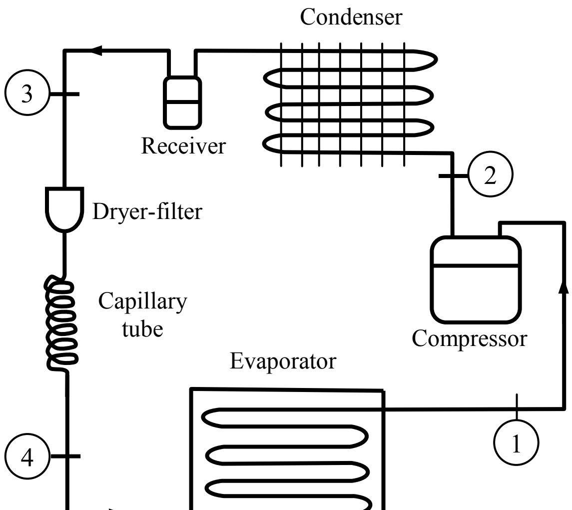

Fig. 2: Schematic diagram of an experimental apparatus for demonstrating vapour compression refrigeration system

All the components are fixed rigidly on the board. The compressor chosen is a reciprocating type, power 0.746 kW, and swept volume 30.4 cm^3. The evaporator is a bare plate with inner coil tube for refrigerant flow. The tube inner diameter is 6.8 mm and tube length is 6.6 m. The dimension of the evaporator is 0.58 x 1.27 m. The evaporator is connected at one end to the capillary tube and at other end to the compressor.

The choice of the capillary tube was based on the following requirements; adequate capacity, and ability to provide the required pressure drop to tolerate the refrigerant and to operate within the temperature range. The required length of capillary tube depends mostly on the size of the system. The required length has reported by Kim *et al*. [11]. In this work, the model chosen was from Alco Products. It is coiled capillary tube, pipe inner diameter 1.2 mm, outer diameter 1.9 mm, tube length 1000 mm and coiled diameter 52 mm.

Fig. 3: General view of the experimental apparatus for demonstrating vapour compression refrigeration system

Dryer-filter and receiver were connected in between capillary tube and condenser as shown in Fig. 2. Condenser is finned-tube, pipe inner diameter 6.8 mm, outer diameter 7.6 mm and tube length 8.4 m. The condenser is fixed together by the side of compressor, which formed a compact assembly of a condensing unit. All joints were brazed. The tube was sized as recommended by ASHRAE guide lines for line sizing [19].

After all the components were assembled, the copper lines were checked for leaks then the system was charged with refrigerant (R134a). In addition, the copper lines were insulated and wrapped with duct tape. The control system consisted of an on/off switch actuated by temperature-sensing bulls, to regulate the temperature of the evaporator. Since the operating point is 6°C, the control system will turn the motor on at 7°C and off at 5°C.

3. Results and Discussion

Tests were carried out on the apparatus and a sample of the data obtained is shown in Table 1. The data represent the final measurements taken before the compressor was started by the control system, as a result of the temperature of the evaporator reaching the operating point. The following parameters: refrigeration capacity (Q_e), rate of heat rejection (Q_c), coefficient of performance (COP), and relative efficiency (η_r) were evaluated with the aid of the measured parameters, refrigerant properties table [20] and Eqs. (1 to 10). A summary of these results is shown in Tables 2 and 3.

Table 1. Temperature and pressure of refrigerant measured at various state points shown in Figures 1 and 2.

State Point	Position	Temperature (°C)	Pressure (kN/m²)
1	Compressor inlet	-5.6	238
2	Condenser inlet	48.6	828
3	Capillary tube inlet	32.8	828
4	Evaporator inlet	-12.5	182
-	Evaporator surface	5.2	-

Table 2. Results of heat gain and loss from the system

Parameter	Rate of heat (W)
Refrigeration capacity, Q_e	915.8
Rate of heat rejection, Q_c	1152.5
Compressor power input, $\dot{W}_{input}$	236.8
Isentropic work per second, $\dot{W}_{is}$	205.3

Table 3. Results of performance parameters of the system

Parameter	Value
Refrigerant flow rate	0.00245 kg/s
COP_{carnot}	6.96
COP_{system}	3.87
Relative efficiency (η_r)	55.6%
Isentropic efficiency (η_{is})	86.7%

The different in pressure and temperature between evaporator inlet and compressor inlet as shown in Table 1, which is a deviation from the ideal refrigeration system, is due to pressure losses in lines and fittings, and small amount of super heat between the evaporator output and compressor inlet in order to ensure that no liquid enters the compressor. The compressor suction and discharge pressure were monitored and the readings were taking during the normal running of the compressor before it was stopped by the control system as a result of the temperature of the evaporator reaching the operating point. The curve of the pressure ratio against the computed isentropic efficiency is shown in Fig. 4. The figure shows the characteristic curve for the compressor used. As shown in this figure, the isentropic efficiency first increased at the start of compressor with increase in pressure ratio and decreases gradually for rest of the operating period.

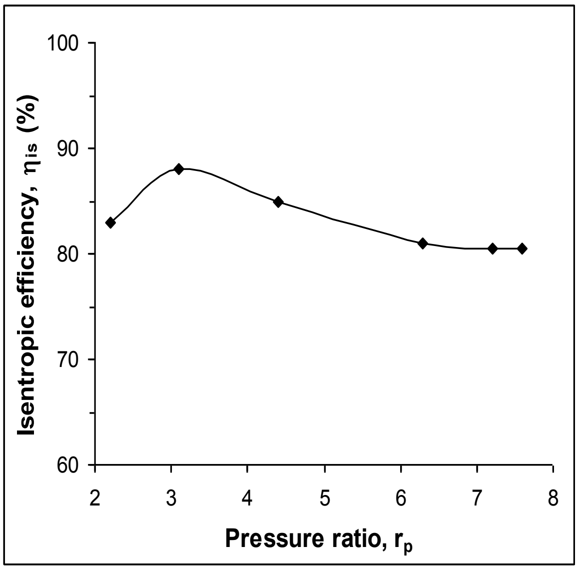

Fig. 4: The curve of the pressure ratio against the isentropic efficiency

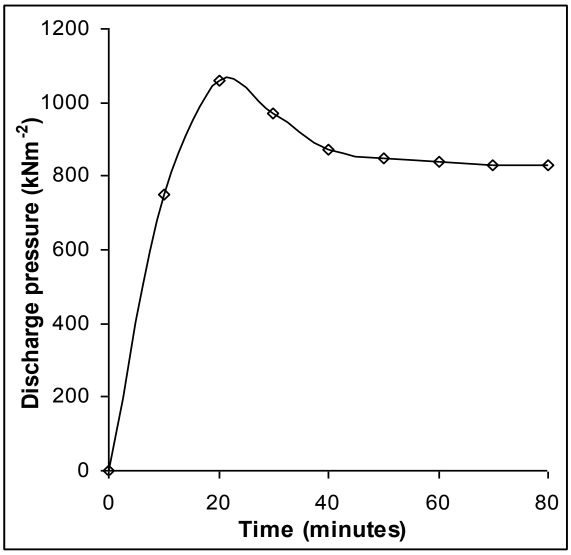

Fig. 5: The variation of discharge pressure with time

Fig. 5 shows the variation of discharge pressure with time. As shown in the figure, the maximum short-time discharge pressure within the first 20 min of starting the compressor runs up to 1060 kPa, after which the pressure reduced and stabilized. At steady state conditions the discharge pressures was 830 kPa. The performance of the system was obtained for different ambient air temperatures. Figs. 6 and 7 show the relationships between the refrigeration capacity and the COP obtained with ambient air temperature, respectively. As shown in these figures, the refrigeration capacity and the COP reduce as ambient air temperature increases. The average refrigeration capacity and COP obtained for the system were 915.8 W and 3.87, respectively.

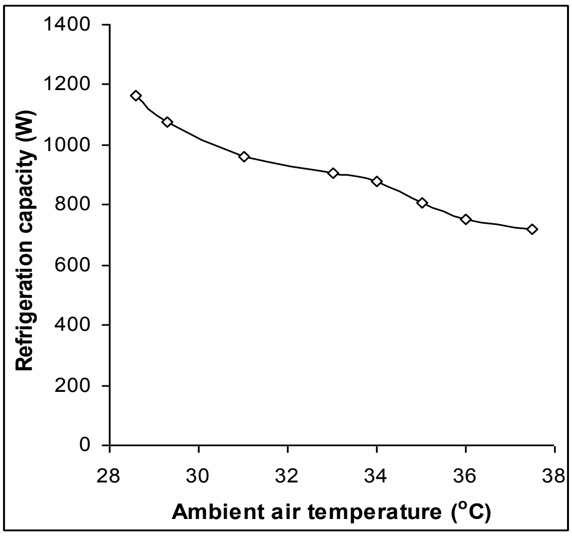

Fig. 6: The variation of refrigeration capacity with ambient air temperature

3. Conclusion

The vapour compression refrigeration system is of paramount importance in food and drug preservation, air conditioning, heat pumps as well as other industrial and commercial processes. In this work, an experimental apparatus for demonstrating vapour compression refrigeration system and thermodynamics principles was design, constructed and tested. The apparatus is portable and can be used for laboratory experiments and classroom demonstrations. It will help students of engineering disciplines to have a thorough understanding of both the practical aspects of refrigeration and the thermodynamic processes affecting the performance of the cycle. The sample results showed that the apparatus is well designed for its intended purpose of demonstrating basic principles and laws of thermodynamics. The effect of compressor pressure ratio on system performance was investigated and the result obtained showed that the higher the pressure ratio the lower the isentropic efficiency of the system for the larger part of the operating period. The steady state discharge pressure obtained was 830 kPa. Also, the result obtained showed that the higher the ambient air temperature the lower the refrigeration capacity and the COP of the system. During the test, the average refrigeration capacity, the system COP and the Carnot cycle COP obtained were 915.8 W, 3.87 and 6.96 respectively, while the relative and isentropic efficiencies obtained were 55.6 and 86.7%, respectively.

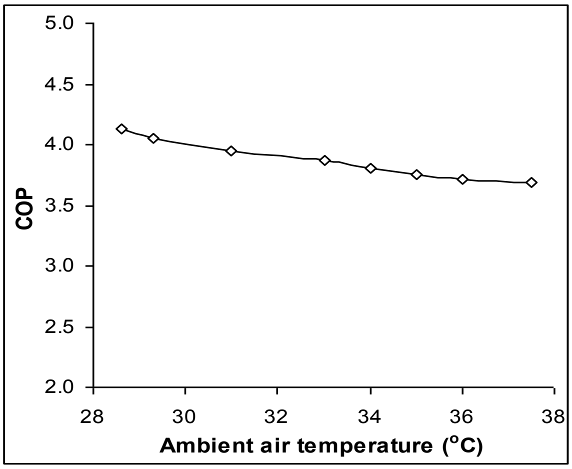

Fig. 7: The variation of COP with ambient air temperature

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