Design and Analysis of Water Cooled Condenser

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Abstract

The domestic refrigerator is one of the most commonly used components in today's household. It is provided with a hot-wall condenser, which results for about 7 to 8 kW-hr of power consumption per month [1]. This paper consists of exergy analysis of this domestic refrigerator, working on eco-friendly refrigerant R-600a, to check for exergy destruction in the components. Exergy is the amount of available energy. Exergy destruction thus gives for maximum amount of un-utilized energy in the system. Exergy analysis gives maximum exergy destruction in the compressor followed by the condenser [2]. The hot-wall condenser was thus replaced by a water-cooled condenser. The aim of the present work is to improve the performance and efficiency of the domestic refrigerator by a change in condenser by exergy analysis of the systems. Also performance is evaluated by performing various tests according to the IS 15750:2006 conventions and checking for COP, exergy destruction, exergy efficiency, system pressure ratio, evaporator temperature and cooling time of the refrigerator [3].

Keywords - exergy, domestic refrigerator, water-cooled condenser, temperature, pressure, COP.

I. INTRODUCTION

Domestic refrigerators are major energy consuming appliances in household environment. The domestic refrigerator operates on the Vapour-Compression (VCR) Cycle. It consists of the following components – A compressor, a hot-wall condenser, a capillary tube and an evaporator. The system uses R600a as the environmentally-friendly refrigerant. Researchers have also reported better working of hydrocarbon refrigerants like R600a and R290 than hydrofluorocarbons like R134a. The traditional energy analysis which leads to an incomplete thermodynamic analysis of the system. An exergy based analysis which suits well between the classical thermodynamic approach based on the first law and the exergy approach based on the second law for the evaluation of a refrigeration system. The exergy analysis of the modern refrigerator is a basic step to find out the amount of losses in each component of the vapour compression cycle.

Mahmood Mastani Joybari, Mohammad Sadegh Hatamipour, Amir Rahimi, Fatemeh Ghadiri Modarres et al. [2] (2013) in their study, carried out exergy analysis out for 145 g of R134a. Then, R134a was replaced by 60 g of R600a, compressor was changed to a HC type one and exergy analysis was applied to the refrigerator to improve its performance. According to the results, R600a charge amount, compressor COP and condenser fan rotational velocity were selected for Taguchi design. It was found that at optimum condition, the amount of charge required for R600a was 50 g which is 66% lower than R134a one; Besides, R134a is about two times more expensive than R600a which makes R600a use economically beneficial. Exergy analysis of a refrigerator showed that the compressor had the highest amount of exergy destruction followed by the condenser, capillary tube, and evaporator and superheating coil.

Selladurai and Saravana kumar et al. [4] (2013) compared the performance between R134a and R290/R600a mixture on a domestic refrigerator which is originally designed to work with R134a and found that R290/R600a hydrocarbon mixture showed higher COP and exergetic efficiency than R134a. In their analysis highest irreversibility obtained in the compressor compare to condenser, expansion valve and evaporator.

Arif Hepbasli et al. [5] (Dec. 2006) used EXCEM method based on the quantities exergy, cost, energy and mass and applied it to a household refrigerator using the refrigerant R134a and R600a. His study concluded that the greatest irreversibility occurred in the compressor, followed by the condenser, capillary tube, and evaporator and superheating coil. The test was conducted in accordance with EN 28187. The ratios of exergy loss rates to capital cost values are obtained to vary from 2.949×10^{-4} to 3.468×10^{-4} kW US^{-1}. The exergy efficiency values are also found to range from 13.69 to 28.00% and 58.15 to 68.88% on the basis of net rational efficiency and product/fuel at the reference state temperatures considered, respectively.

Arora and Kaushik [6] did a detailed exergy analysis in the vapour compression cycle and developed a computational model to calculate COP, exergy loss, exergy efficiency, and efficiency defects for R502, R404, and R507A. They reported that R507a is a better substitute to R502a than R404a.

Ahmet Kabul, Onder Kizilkan, Ali Kemal Yakut [7] performed energy and exergy analyses for a vapour compression refrigeration system with an internal heat exchanger using a HC, isobutene (R600a). For a refrigeration capacity of 1 kW and cold chamber temperature of 0°C, energy and exergy balances are taken into account to determine the performance of the refrigeration system. It is seen that the compressor has the highest irreversibility rate, and the evaporator has the lowest. Also from the result of the analysis, it is found that condenser and evaporator temperatures have strong effects on energetic and exergetic performances of the system.

Gaurav, Raj Kumar [8] studied the comparison of energy and exergy analysis for R134a, R152a, R290, R600 and R600a in refrigerator. They analysed the domestic refrigerator with alternative refrigerants for computing coefficient of performance, exergy destruction ratio, exergy efficiency and efficiency defect. It is established that in the present work efficiency defect is maximum in condenser and lowest in evaporator.

P. Saji Raveendran, S. Joseph Sekhar [9] studied the performance of a domestic refrigeration system with brazed plate heat exchanger as condenser, and working with refrigerants such as R290/R600a and R134a using experimental method. The result showed that the system with water-cooled brazed plate heat exchanger reduces the per day energy consumption of a system from 21% to 27% and increases the COP from 52% to 68%, when compared to conventional system. The compressor discharge temperature and dome temperature are also dampened.

Based on the above studies, exergy analysis of the domestic refrigerator was carried out for the refrigerant R600a. During the test, condenser temperature is maintained at 316K and evaporator temperature is varied. Exergy destruction is checked for in each component of the refrigerator. Based on the results, the condenser is changed and a newly designed water cooled condenser is placed instead of the hot wall condenser. Comparative tests are carried out with the system based on the exergetic analysis as well as IS conventions. Factors like COP, exergy destruction, exergy efficiency, system pressure ratio, evaporator temperature and cooling time are checked for the both the systems.

A. Experimental Apparatus and Test Procedure:

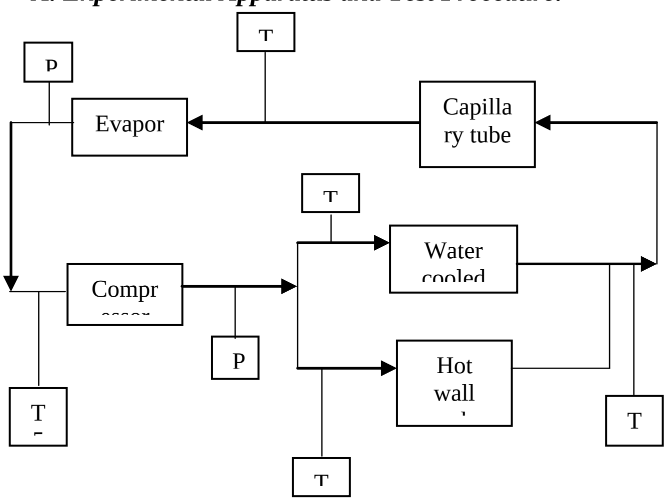


Figure 1: Experimental Apparatus Line Diagram

Figure 1 shows the line diagram of the experimental setup. The photographic diagram of the test apparatus is shown in Figure 2. The apparatus consists of a hermetically sealed inverter compressor with 253 W nominal input power at 240 V and 50 Hz, a hot-wall condenser, a water cooled condenser designed and put in parallel to the hot-wall unit, a capillary tube and filter, and an evaporator. The compressor is a variable speed compressor which regulates its working speed with response to the cooling load applied, thus making it possible to save energy at part load. The water-cooled condenser designed for the system is a closed box type serpentine coiled counter flow heat exchanger. The Figure 3 shows the designed water cooled condenser. A8W, 12V pump is used to regulate flow through the water cooled condenser. The water temperature is kept in check by using a simple designed cooling tower. In actual practice the water can be used to wash utensils whenever required, by providing a suitable tapped connection.

The refrigerator was instrumented with two compound pressure gauges with an accuracy of ±0.25% at the inlet and outlet of the compressor for measuring the suction and discharge pressures and at the inlet and outlet of the capillary tubes. Four calibrated K-type temperature sensors with an accuracy of ±1 K were provided in the compressor outlet, condenser outlet, evaporator inlet, and inlet of the compressor. The power consumption of the compressor was measured by using an energy meter with 0.01 kWh of accuracy. The temperature sensors were attached to a data acquisition and recording system which periodically recorded the system readings.

Initially, the test rig was thoroughly checked by

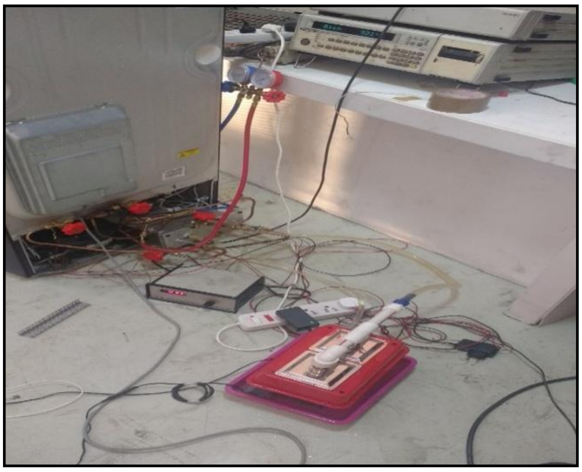


Figure 2: Apparatus Setup Photographic View

flushing with nitrogen gas at 10 bar to check for leakages as well as eliminate impurities, moisture, and other foreign materials inside the system, which may affect the accuracy of the experimental results. The evacuation was carried out with the help of a vacuum pump and refrigerant R600a was charged into the system with the help of charging unit. The system was charged with about 60g of the refrigerant [2]. Temperatures and pressures are recorded at frequent intervals. The power consumption of the refrigerator during tests was measured after attaining the steady-state condition. The measured values were used to study the performance characteristics of the refrigerator.

II. EXERGY ANALYSIS

The exergy or available energy of a system is the maximum work that could be derived if the system were allowed to come to equilibrium with the environment. It is a consequence of the second law of thermodynamics. Unlike energy, exergy is not conserved, once it is lost, it is lost forever. The exergy analysis is widely accepted as a useful tool in obtaining the improved understanding of the overall performance of any system and its components.

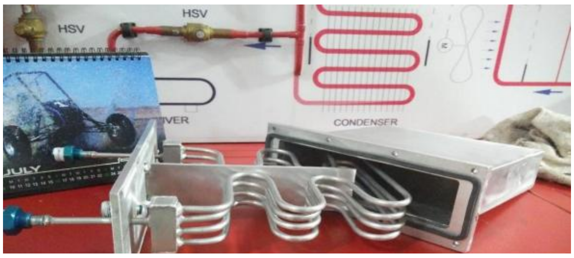
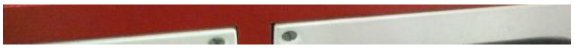


Figure 3: The designed water cooled condenser



Exergy analysis also helps in taking account the important engineering decisions regarding design parameters of a system. The term exergy destruction is used when the potential for the production of work is destroyed within the system boundary.
For the present system, the component wise exergy balance equation can be written as below:

a) *Compressor*

$$(\mathrm{EX_D})_{comp} = E_{x1} + W_c - E_{x2} = m_r(T_o(s_2 - s_1))$$

b) *Condenser*

$$(EX_D) = E_{x2} - E_{x3} = m_r(h_2 - T_0 s_2) - m_r(h_3 - T_0 s_3)$$

c) *Expansion Device*

$$(EX_D)_{exp} = E_{x3} - E_{x4} = m_r(T_0(s_2 - s_1))$$

d) *Evaporator*

$$(EX_D)_{evap} = E_{x4} + Q_e\left(1 - \frac{T_0}{T_r}\right) - E_{x1} = m_r(h_4 - T_0 s_4) + Q_e\left(1 - \frac{T_0}{T_r}\right) - m_r(h_1 - T_0 s_1)$$

The total exergy destruction in the system is the sum of exergy destruction in different components of the system and is given by

e) Total exergy destruction is given by

$$(EX_D)_{Total} = (EX_D)_{comp} + (EX_D)_{Cond} + (EX_D)_{exp} + (EX_D)_{evap}$$

f) *Exergy Efficiency*

$$\eta_{exergy} = \frac{Q_e}{W_c}[(1 - \frac{T_0}{T_r}]$$

The exergy analysis of the system was done based on the above formulations. On the basis of first law, the performance of refrigeration cycle is based on the coefficient of performance, which is defined as the ratio of net refrigerating effect (cooling/heating load) obtained per unit of power consumed. It is expressed as:

$$COP = \frac{Qe}{Wc}$$

According to IS 15750:2006 conventions, pull down and energy consumption tests were carried out on the system. For these tests surrounding temperatures were maintained at 316K and 305K respectively. Load was applied using a regulated air heater inside the refrigerator compartment and temperature time graphs were plotted.

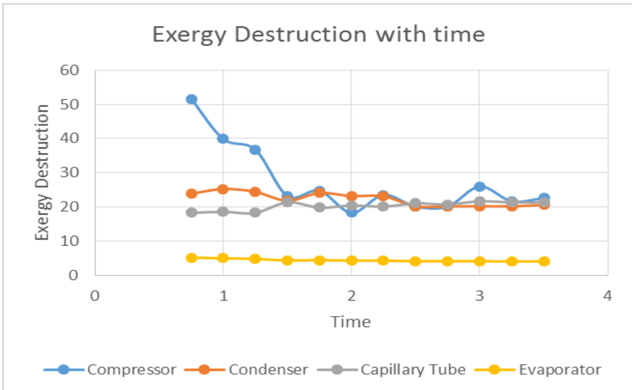


Figure 4:Exergy Destruction with Time is Domestic Refrigerator

III. RESULTS AND DISCUSSIONS:

The graph in fig. 4 shows the exergy destruction in various components of the refrigerator along with time. Exergy loss becomes stable with time to a great extent. As seen the compressor has maximum exergy losses at 34.32 kJ/kg. This is followed by the condenser at 22.6 kJ/kg, capillary at 18.65 kJ/kg and at the evaporator at 4.73 kJ/kg.
Thus condenser losses amount to 28.14% of total losses. Thus a change of design of condenser is necessary to minimize losses.

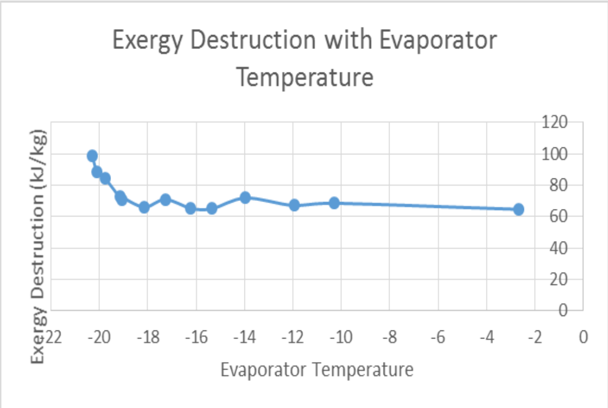


Figure 5: Overall Exergy Destruction at various evaporator temperatures

The figure 5 shows the exergy losses at changing evaporating temperature. The graph shows that with the increase in evaporator temperature, the values of exergy efficiency will increase, whereas total irreversibility rate was decreased. This means that an increase in evaporator temperature affects the system positively. Optimum evaporator temperature is the temperature at which maximum exergy is obtained. Extrapolation reveals operating system at 1-4 °C for minimum exergy losses.
The plot given in fig. 6 gives the compartment temperatures during pull down test for the hot wall condenser. The refrigerator took about 3.5 hours to reach the designated minimum testing temperature of -15°C for the freezer as shown.

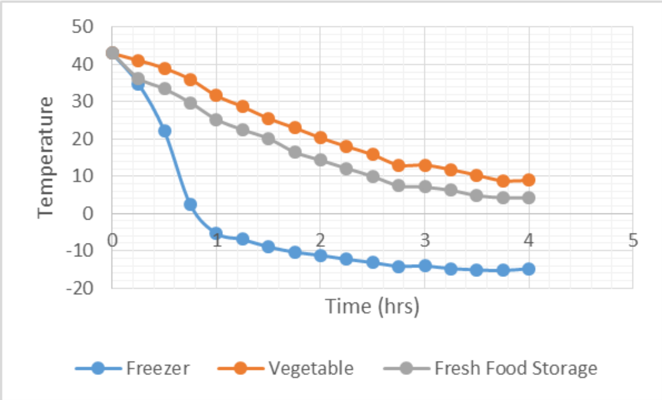


Figure 6: Pulldown Test Time vs Temperature Plot - Hot Wall Condenser

The plot in fig. 7 gives the compartment wise temperatures of pull down test for the water cooled condenser which was designed. As seen the temp of -15°C is reached in only 1.2 hrs. Thus the pulldown time of the water cooled condenser is 66% lesser than the hot wall condenser. As a result the water cooled condenser is more efficient than the hot wall condenser.

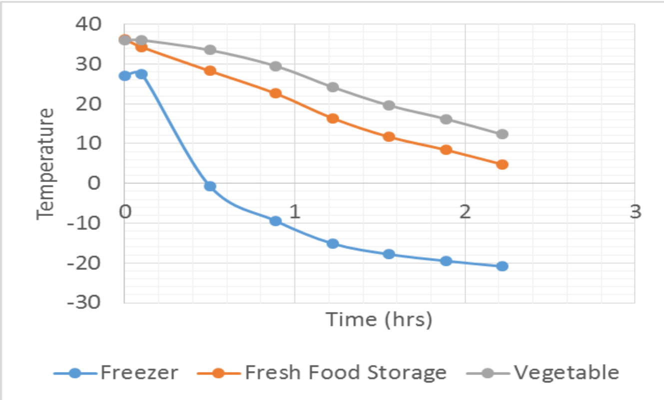


Figure 7: Pulldown Test Time vs Temperature Plot - Water Cooled Condenser

The plot given in fig 8 gives the COP vs evaporator temperatures plot of the refrigerator. COP reaches at 2.5 as seen from the graph for the hot wall condenser at -15°C. For the same temperature, COP is about 3.2 for the water cooled condenser. As seen from the graph, water cooled condenser always gives a higher COP than the hot wall condenser by an average value of 1. Thus the water cooled condenser is more efficient as it requires lesser compressor duty than the hot wall condenser.

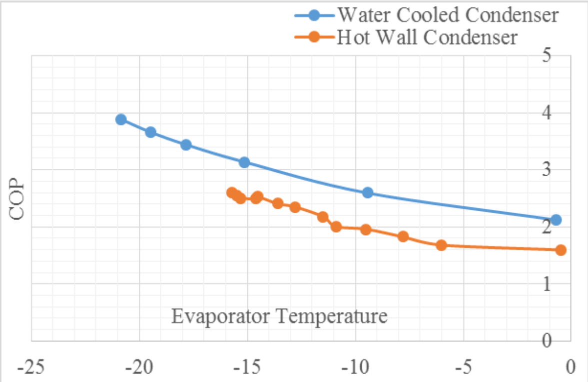


Figure 8: Comparison of COP at various evaporator temperatures

IV. CONCLUSIONS

An exergy analysis was conducted in a single-evaporator domestic refrigerator between the evaporation and condensation temperatures ranging from -20 to 60°C by using R600a refrigerant. Based on both experimental study and exergy analysis, we find,

- Exergy analysis of the modern refrigerator gives maximum exergy destruction of 41.2% in the compressor followed by 28.14% in the condenser. This makes condenser design a good idea in order to save energy in the system.
- The pulldown test of the hot wall condenser needed 4.5 hrs to reach a minimum temperature of -16 in the freezer. With the water cooled condenser cooled condenser, it only takes about 1.5 hours to reach that temperature.
- The Water cooled condenser has a great potential in power saving. It consumes only 78W average power as compared to the 100W consumed by the hot walled condenser.
- The water cooled compressor is a compact one with only 4.3 metres of total coil length while the length for the hot wall condenser is 21 metres.
- COP of the system is much higher than the COP of hot walled condenser. The Water cooled condenser gives an average COP of 3.55 compared to 2.20 of hot walled condenser.

Thus it can be concluded that the water cooled condenser is a much better option than the hot wall condenser.

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