Cost-Effective COP Enhancement of a Domestic Air Cooled Refrigerator using R-134a Refrigerant

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Abstract—This paper presents a cost-effective method to increase the COP and utility of a domestic refrigerator using R-134a refrigerant. A cabin was installed on the top of a domestic refrigerator with condenser coils of refrigerator serving as heating coils inside the cabin. Known quantity of water was heated by the condenser coils (due to convection currents) thereby increasing the overall COP of the refrigerator. Further, the utility was increased since it can serve the purpose of cooking (oven), geysers etc. Besides, the refrigerator may be used as conventional refrigerator by keeping the cabin door open in case of absence of heat sink. It was concluded that we can increase the COP upto 11% just by using a cabin on the top of the refrigerator unit. Further increase in COP is possible; however enhancements will involve higher costs.

Keywords--Clausius statement, cost effective design, modified refrigerator, R134a refrigerant, Waste heat recovery

I. INTRODUCTION

Our society depends on the roots of 3E viz. Energy, Economy, and Environment. Every country needs to keep all energy options open to satisfy the growing demand. Sun generates the entire energy in universe. All other forms of energy such as wind, tidal etc. are basically derived from solar energy itself. Energies created by the humans are through nuclear fission and fusion. This energy does not depend on sun but it is limited by the availability of radioactive material, danger of radioactivity, uncontrolled reaction etc. Hence, there will always be a need to create and utilize energy more efficiently.

Waste heat recovery is the collection of heat which is created as an undesired by-product of the operation in everyday processes such as refrigeration, air-conditioning etc. Waste heat losses arise both from equipment inefficiencies and from thermodynamic limitations (second law of thermodynamics). A waste heat recovery unit (WHRU) is an energy recovery heat exchanger which recovers heat from hot stream which is generally a by-product of any process. For functioning of an apparatus like refrigerator etc., this heat has to be rejected into the environment (Clausius statement [1]).

Hence, before rejecting this energy into the environment, we utilize a part of this energy in heating applications. Various waste heat sources are available such as domestic and urban waste which includes heat losses in cooking appliances, heat losses in air conditioners, heat losses in HVAC systems etc. Waste heat recovery system can be used in various applications but in present study, we shall focus on the use of waste heat recovery in air cooled domestic refrigerator.

The vapor compression refrigeration process includes 4 stages i.e. compression, condensation, expansion and evaporation. Out of these stages, heat rejection takes place in condensation process. This heat is rejected into the atmosphere (waste heat) and hence there is an opportunity to recover and re-use that heat so that overall system efficiency can be maximized (as shown in Figure 1.).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Schematic diagram of modified refrigeration system}
\end{figure}

We can use various refrigerants for this purpose but our study is focused on R-134a because of the various advantages such as minimum ozone depletion, higher COP and cooling capacity (for majority of test conditions), higher pressure ratios etc. [2].
II. LITERATURE REVIEW

A number of experimental studies have been done to recover the lost heat in domestic refrigerator systems. Many of these studies have been done by using different refrigerators modifications such as water-cooled condensers, different refrigerants, waste heat recovery systems etc.

Although there have been many prototypes build; however there is still a need to develop a cost-effective method to harness this waste energy. Some of the previous studies are as follows:

1. Slama [3] developed two prototypes viz. refrigerator coupled with water heater and floor heating setup. It was concluded that temperatures upto 60°C and 50°C (water and floor-heating) can be reached without modifying the temperature of the evaporator (approximately −20°C). Further, the elimination of the grid of the condenser creates an advantage by avoiding its heating thereby; reducing the electricity consumption.

2. Mukuna and Kilfoil [4] investigated the technical feasibility of combined refrigerator/heat exchanger and geyser system. It was concluded that 0.8 % of the total input energy in the geyser was saved in cycling mode of the refrigerator and continuous mode of the geyser. However, the refrigerator’s effectiveness was reduced because the refrigerant was not cool enough.

3. Zhu et al. [5] proposed a domestic cooling and heating unit (DCAHU). It was an integration of the air conditioning, the refrigerator, and the water heater. Economic analysis was done on the basis of summer and winter conditions. The system realizes multiple working modes with recovery of waste heat and thus reducing energy requirement.

4. Clark et al. [6] studied waste heat recovery of domestic refrigerator after modifying it in two conditions i.e. no water use condition conducted up to five days and with water use pattern i.e. high, low, medium conducted up to 5 to 9 days. It was concluded that to achieve higher efficiency, these modifications should be incorporated in large refrigerating units.

5. Patil and Dange [7] modified a domestic 190 liter refrigerator to recover the waste heat by installing a water tank containing the condenser coils of refrigerator. Experiment showed that maximum temperature increment was up to 40 degree centigrade. But major drawback with this type of arrangement was that it had no mobility and cannot be used for domestic purposes.

6. Kaushik and Singh [8] studied the feasibility of heat recovery from the condenser of a vapors compression refrigeration system through a Canopus heat exchanger (CHE). It was placed between the compressor and condenser components. It was concluded that a heat recovery factor of order 2.0 and 4.0 of condenser heat can be recovered through the Canopus heat exchanger under typical temperature conditions.

7. O’Brien et al. [9] designed a prototype refrigeration-cum-hot water heating system for domestic use. The system used heat energy rejected from the compressor and condenser of a vapour-compression refrigerator by storing it in a heat sink. It was concluded that the system performed better as the prototype than it did as a hot water heater but needs to be improved further to fully explore its expected potential.

8. Sreejith [10] investigated the effect of different types of compressor oil in a domestic refrigerator with water cooled condenser. The experiment was done using HFC134a as the refrigerant, Polyester oil (POE) oil and SUNISO 3GS mineral oil. It was concluded that the HFC134a/SUNISO 3GS mineral oil system worked normally and efficiently in the household refrigerator with water-cooled condenser and the energy consumption of the HFC134a refrigerator using SUNISO 3GS mineral oil as the lubricant reduced the energy consumption of the household refrigerator between 8% and 11% for different loads.

9. Momin et al. [11] recovered waste heat from condenser unit of a household refrigerator to improve the performance of the system by using a thermo siphon. It was found that after recovering heat from the condenser of the conventional refrigerator, its performance was improved than conventional refrigerator. It was concluded that the theoretical COP of the system was more than the system running with air cooled condenser.

10. Crown et al. [2] discussed the findings of 'An experimental study designed to show the effect of changing refrigerants on the performance of a refrigeration system'. It was concluded that COP and cooling capacity of R-134a proved to exceed that of R12 for the majority of test conditions. The values of COP and capacity for R134a were maximum of 5.4% and 6.8% higher than those for R-12, respectively.
III. DESIGN AND FABRICATION OF EXPERIMENTAL SETUP

The main objective of this experiment is to develop a cost-effective design to minimize the heat losses and to maximize the overall performance of the system. For that purpose we have designed and assembled a cabin at the top of the domestic refrigerator. Design and specifications of the components are as follows-

i. Cabin was made of galvanized iron sheet having inner dimensions 45.5 x 34.5 x 45.5 cm with thickness as 2.5 cm from each side. Insulating material used in the cabin for insulation was thermocol. Figure 2 shows the cabin (insulated from 5 sides) which was installed above the domestic refrigerator. The cabin door may be kept open when there is no heat sink.

ii. A 165 litre domestic refrigerator was modified by removing its condenser coils. Copper coils of diameter 4.36 mm and length 620 cm were installed inside the cabin (also served as condenser coils for the refrigerator). These coils were made in turns so that they occupy minimum space with maximum surface area. Two sets of such coils were made and were mounted at top and bottom of the cabin as shown in Figure 3. This cabin was installed over the top of the refrigerator. The evaporator used in the refrigerator was of plate type.

iii. Refrigerant which was used during entire experiment was R-134a with boiling temperature of -26.3 °C and density of 4.25 kg/m³ [12].

IV. PROCEDURE

The entire experiment was divided into two main parts i.e. measurement of COP of the refrigerator and determination of amount of waste-heat (condenser coils) absorbed by the water inside the cabin

a) For determination of the COP of refrigerator, two parameters are required i.e. power absorbed by the compressor and heat absorbed by the evaporator coils in the refrigerator. Before taking any readings it was ensured that the refrigerator was started at least 2 hours before. It was done to ensure that the refrigerator was working on its normal capacity. The portion of the refrigerator below the freezer was also separated using an insulating material to achieve better accuracy.
To calculate the power absorbed by the compressor, a digital multi-metre was used. Values of current and voltage were recorded. Hence, the power absorbed by the compressor was calculated as:

\[
\text{Power absorbed by the compressor} = \text{voltage} \times \text{current} \times \text{power factor (taken as 0.8)}
\] Eq. (1)

To determine the cooling capacity, a beaker with a known quantity of water was kept inside the refrigerator. The decrement in temperature of the water was recorded with variation in time. Hence COP of the refrigerator was calculated by the formula:

\[
\text{COP (refrigerator)} = \frac{\text{absorbed by the evaporator per unit time}}{\text{power supplied to the compressor}}
\] Eq. (2)

b) For determination of waste heat, known quantity of water was kept inside the cabin. After ensuring that the refrigerator was running at its normal capacity, increment in temperature of water was recorded with variation in time. Hence the rate at which the waste heat can be extracted from the condenser was calculated. The modified COP of the refrigerator was calculated by considering this waste heat as useful energy since it can be used in various applications such as geysers, cooking purposes etc. the formula used is as follows

\[
\text{COP (modified refrigerator)} = \frac{\text{heat absorbed by the evaporator per unit time}}{\text{Power supplied to the compressor} - \text{heat absorbed by water per unit time}}
\] Eq. (3)

V. RESULTS AND DISCUSSIONS

As discussed earlier, calculations are divided into two parts i.e. COP (original) and heat absorbed (in condenser coils). For COP calculation, decrement in the temperature of water was recorded at interval of 15 minutes. Initial temperature of water was 30.1°C. The decrement in temperature with time is plotted Figure 4.

From above Figure, we can conclude that the decrement in the temperature is exponential with coefficient of regression value close to 1 which also corresponds to theory of heat transfer (exponential cooling) [13]. Now, for calculation of amount of heat extracted, a graph is plotted between amount of heat extracted and time at interval of 15 minutes as shown in the Figure 5. To calculate the average amount of heat extracted, curve fitting with high regression coefficient (close to 1) was applied and integrated within specific limits to calculate the average value.

Average amount of heat extracted is 19.3 watts. The power supplied to the compressor is calculated as:

\[
\text{Power} = 225 \text{V} \times 0.88 \times 0.8 \times \text{power factor} = 158.4.
\]

Hence;

\[
\text{COP (Refrigerator)} = \frac{19.3}{158.4} = 0.122
\]

Value of COP is very low because the domestic refrigerator used in the experiment was ‘old and used’. To calculate the amount of waste heat added to the water in the cabin, two sets of temperature readings (incremental) were taken against time at 15 minutes interval as shown in the Figure 5. As discussed above, same concept of exponential curve fitting was applied to verify the data (as shown in Figure 6). Average amount of heat added (waste heat) was calculated using the same concept of curve fitting (Figure 7).
Figure 6. Plot of temperature of water with variation in time

Figure 7. Plot of heat added to water with variation in time

Two values of average amount of heat added (waste heat) were obtained as 15.7 and 15.9 Watts. Average amount of heat added to the water is taken as 15.8 Watts.

Improved COP = 19.3 / (158.4 - 15.9) = 0.135

Improvement in COP = \( \frac{COP \text{ (improved)}}{COP \text{ (original)}} \times 100 \)

Eq. (4)

=\( \frac{(0.1354 - 0.1219)}{0.1219} \times 100 = 11.07\% \)

VI. UNCERTAINTY ANALYSIS

It is very important to determine the uncertainty of an experiment in order to provide solution within required limit of uncertainty. For the present study, a method of estimating uncertainty by Kline and McClintock [14] has been used. Using this method, uncertainties have been calculated as:

i. Uncertainty in power measurement = 1.2 %
ii. Uncertainty in volume measurement = 1.7 %
iii. Uncertainty in heat added per second calculations = 2.5 %

VII. CONCLUSION

In present study, a cost effective method has been suggested to improve the overall efficiency and utilization of a domestic refrigerator by installing its condenser coils inside a cabin. The heat rejected (usually to atmosphere) was recovered by heating water in a beaker. This recovered heat energy may be utilized in various day to day activities such as geysers, cooking (ovens) and industrial applications such as boilers etc. Hence overall efficiency and utility of the system can be improved.

It is important to understand that the COP of the refrigerator will increase with increase in overall temperature of heat sink. Hence, it is suggested to maintain a flow of the fluid which is to be heated with small temperature difference (5-10 °C). In case of absence of heat sink, the doors of the cabin may be kept open to ensure proper heat dissipation in air/surroundings. Hence, in these cases, the refrigerator may also work as conventional refrigerators.

On the basis of above study it can be concluded that overall efficiency of a domestic refrigerator can be increased up to 11.07 % by modifying the refrigerating system as above. This efficiency may further be improved by using a heat exchanger, fluids with higher specific heat capacity etc. However, these enhancements will involve high costs due to which it may not be a cost-effective solution for domestic purposes.

REFERENCES

APPENDIX A

I. Uncertainty Analysis

A precise method of estimating uncertainty in experimental results has been suggested by Kline and McClintock [14]. For a set of measurements the uncertainty in each measurement are measured and then used to calculate uncertainty in the experiment. If R is a function of the independent variables x₁, x₂, x₃, . . . , xₙ and Wᵣ be the uncertainty in result with w₁, w₂, . . . , wₙ as uncertainty in independent variables; then

\[ W_R = \left[ \left( \frac{\partial R}{\partial x_1} \right)^2 w_1^2 + \left( \frac{\partial R}{\partial x_2} \right)^2 w_2^2 + \ldots + \left( \frac{\partial R}{\partial x_n} \right)^2 w_n^2 \right]^{1/2} \]  \hspace{1cm} \text{Eq. (A1)}

On the basis of above principle, we have estimated the uncertainty in experiment as:

i. Uncertainty in power measurement:

\[ V = 225 \pm 1 \text{V and A} = 0.88 \pm 0.01 \text{A (values measured on multi-meter)} \]

\[ P = VI\cos\phi = 225 \times 0.88 \times 0.8 = 158.4 \]  \hspace{1cm} \text{Eq. (A2)}

Using uncertainty principle:

\[ (dP)^2 = \left( \frac{\partial P}{\partial V} \right)^2 (dV)^2 + \left( \frac{\partial P}{\partial I} \right)^2 (dI)^2 \]  \hspace{1cm} \text{Eq. (A3)}

\[ \frac{\partial P}{\partial V} = I\cos\phi = 0.88 \times 0.8 = 0.704 \]

\[ \frac{\partial P}{\partial I} = V\cos\phi = 225 \times 0.8 = 180 \]

\[ dP = \sqrt{(0.704 \times 1)^2 + (180 \times 0.01)^2} = 1.93 \]

Hence % uncertainty in power = \( \frac{(1.93/15.8) \times 100}{1} = 1.2\% \)

ii. Uncertainty in volume measurement:

Let f be a function where \( f = l \times b \times h = 22 \times 12 \times 7.1 \) = 1874.4 cm³ (base value)

Using Uncertainty principle

\[ (df)^2 = \left( \frac{\partial f}{\partial l} \right)^2 (dl)^2 + \left( \frac{\partial f}{\partial b} \right)^2 (db)^2 + \left( \frac{\partial f}{\partial h} \right)^2 (dh)^2 \]  \hspace{1cm} \text{Eq. (A4)}

\[ (df)^2 = (bh \,(dl))^2 + (lh \,(db))^2 + (lb \,(dh))^2 \]  \hspace{1cm} \text{Eq. (A5)}

\[ (df) = ((22 \times 12 \times 0.1)^2 + (22 \times 7.1 \times 0.1)^2 + (7.1 \times 12 \times 0.1)^2)^{0.5} = 31.83 \]

Hence % uncertainty in volume measurement = \( \frac{31.83/(22 \times 12 \times 7.1)}{100} = 1.7\% \)

iii. Uncertainty in heat added per second calculations:

Taking specific heat capacity of water as 4.18 KJ/kg K and \( \Delta T \) as 3.9 °C

\[ Q = ms\Delta T/t = (1.61 \times 4.18 \times 1000 \times 3.9)/900 = 29.16 \] (base value)  \hspace{1cm} \text{Eq. (A6)}

\[ (dQ)^2 = \left( \frac{\partial Q}{\partial \Delta T} \right)^2 (d\Delta T)^2 + \left( \frac{\partial Q}{\partial t} \right)^2 (dt)^2 \]  \hspace{1cm} \text{Eq. (A7)}

\[ (dQ)^2 = \left( \frac{ms}{t} \right)^2 \left( \frac{\partial (ms\Delta T)}{\partial t} \right)^2 = \left( \frac{ms\Delta T}{t^2} \right)^2 (dt)^2 \]  \hspace{1cm} \text{Eq. (A8)}

\[ (dQ)^2 = (1.61 \times 4.18 \times 1000 \times 0.1/900)^2 \]

\[ = (1.61 \times 4.18 \times 1000 \times 3.9 \times 1/900)^2 \]

\[ (dQ)^2 = (1.61 \times 4.18 \times 1000/900)^2 \times (0.1)^2 - (3.9/900)^2 = 0.55 \]

Hence; \( dQ = 0.74 \)

Percentage error = \( (0.74/29.16) \times 100 = 2.5\% \)