Design of Compact Condenser for Waste Heat Recovery and Cop Enhancement of Refrigerator

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Abstract— Refrigerator has become an essential commodity rather than luxury item. The heat absorbed from space to be refrigerated (Evaporator) and the heat from the compressor is added to refrigerant is rejected to the surrounding through a condenser. This heat can be recovered and used for the various purposes. Paper represents research work on a design of compact condenser (shell and tube type) for effective heat recovery in minimum possible time and cop enhancement of the domestic refrigerator. The modified condenser can mounted in the vacant space just above the compressor. Therefore vacant space is utilized and handling problems due to bare copper tube is also reduced. Natural circulation of water eliminates use of pump. Cad modeling and matlab programming are performed for ease in manufacturing and to determine the dimensions of the proposed condenser. By the experimental investigation it is found that this modification in existing system increases the performance of system to 28.61%. It is observed that temperature of cold water rises to 50oC just within 20 minutes. This hot water can be used for various purposes like dish washing, bath, laundry etc. Therefore the proposed system makes the household refrigerator to be work as both refrigerator and water heater.

Key words: Compact Condenser, Waste Heat Recovery

I. INTRODUCTION

Energy saving is one of the key issue not only from the view of energy conservation but also for environment. Energy conservation is now faced with the challenged of applying the latest technology for facilities and improvement that can be justified on its own merit. Energy conservation is the technique to be adopted to face energy crisis under these circumstances. Waste heat before rejecting to the environment, we utilize a part of this energy for shifting of refrigerator due to bare copper tubes of condenser. Therefore there is much scope for recovery of this waste heat.

The main objectives of research work are is to extract the heat from the domestic refrigerator by designing a compact condenser. Recover the heat in minimum possible time. And Increase the COP and overall efficiency of the system. Power consumption or LPG consumption can be eliminated for water heating. Hot water can be used for geyser, laundry, and dish washing like applications.

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.

G.G Mominand Y.A.Patil [3] has found that performance of the system can be increased by using thermosyphon technique for water circulation. It also eliminates the need of pump for circulation of water. Y.A.Patil and H.M. Dange[1] discussed on waste heat recovery from an refrigerator by using a typical waste heat recovery unit. S.C.Walavade [5] has shown the effective and simple way of heat recovery by dividing the condenser and mounting it in metal cabin. P.Emulalai [7] has done a case study on waste heat recovery by using hot oven and heater chamber at compressor outlet. Tarangagarwali[8] has given the cost effective method of cop enhancement by mounting the condenser coil in iron galvanized box. In this paper the efforts are made to replace the box with compact WHRU and improving the heat transfer rate between refrigerant and water.

III. SYSTEM DESCRIPTION

The cold water from the water tank sent to the condenser thorough the mass flow meter. The amount of water going to the condenser can be adjusted with the help of mass flow meter. Water absorbs the heat which is rejected by the refrigerant in the condenser and leaves it as hot water. The manually operated control valve is assembled to the exit line.
of hot water. So by closing this valve the time for which the water remains in the condenser can be adjusted and desired hot water temperature can be obtained. The working of system is same as vapor compression refrigeration cycle.

Fig. 2: Block diagram for setup
The dimensions of condenser are determined by mathematical modeling. It is found that the shell diameter and length is 6 cm and 40 cm respectively. The length of condenser is slightly less than width of refrigerator. So we can imagine the compactness of condenser.

A. System Specification

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>R-134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling capacity</td>
<td>365 Btu/hr</td>
</tr>
<tr>
<td>Power input – Rated</td>
<td>100 watts</td>
</tr>
<tr>
<td>Refrigerant Control</td>
<td>Capillary</td>
</tr>
<tr>
<td>Compressor Cooling</td>
<td>Static</td>
</tr>
<tr>
<td>Evaporator temperature range</td>
<td>-34 to -12 °C</td>
</tr>
<tr>
<td>Displacement/revolution</td>
<td>4.00 cc</td>
</tr>
<tr>
<td>No of cylinders</td>
<td>One</td>
</tr>
<tr>
<td>Evaporating temperature</td>
<td>-10°C</td>
</tr>
<tr>
<td>Condensing temperature</td>
<td>40 °C</td>
</tr>
<tr>
<td>Liquid sub cooling temperature</td>
<td>32 °C</td>
</tr>
<tr>
<td>Return gas temperature</td>
<td>32 °C</td>
</tr>
<tr>
<td>suction temperature</td>
<td>32 °C</td>
</tr>
<tr>
<td>Suction (Evaporator) pressure</td>
<td>0.27579 Bar</td>
</tr>
<tr>
<td>Discharge (Compressor)pressure</td>
<td>13.7895</td>
</tr>
</tbody>
</table>

Table 1: System Specification

B. Mathematical Modeling

1) Coefficient of Performance (COP)
From steam table at pressure 0.27579 bar
\[ h_1 = 366.94 KJ/kg \]
\[ s_1 = 1.7826 KJ/kgK \]
From steam table at pressure 13.7895 bar
\[ S_2 = 1.7065 KJ/kgK \]
\[ h_2 = 424.08 KJ/kg \]
From steam table at pressure 13.7895 bar
\[ h_b = 247.45 KJ/kg \]
\[ S_b = 2.35 \text{Cp log} (T_2/T_1) \]
\[ T_2 = 67.61°C \]
\[ h_2 = h_2' + \text{Cp} (T_2 - T_1') \]
\[ h_2 = 448.929 KJ/kg \]
\[ \text{COP} = \frac{h_1 - h_3}{h_2 - h_1} \]
\[ \text{COP} = 1.128 \]

2) Total heat rejected by the condenser (Q)
Refrigerating Effect = \( h_1 - h_3 \) = 92.49 KJ/kg
a) For compressor
Motor power = 1/8 HP = 92 watt ≈ 100 watt
\[ \text{COP} = \frac{Q}{W} \]
\[ Q_1 = 112.8 \text{ watt} \]
\[ Q_2 = Q_1 + W = 212.8 \text{ watt} \]
Mass flow rate of refrigerant
\[ m_e = \frac{Q_2}{\text{Cp} * \Delta T} = 0.002301 \text{ kg/s} \]
Heat available at condenser for Rejection
\[ Q = m_e * (h_2 - h_1) = 401.47 \text{ watt} \]

3) Mass flow rate of water required (m_w)
a) For mass flow rate of water
\[ Q = m_w * \text{Cp} * \Delta T \]
For to achieve desired temperature of hot water we can calculate the mass flow rate required of inlet water
For \( \Delta T = 20°C \)
\[ m_w = 0.004794 \text{ kg/s} \]

4) Logarithmic mean temperature difference (LMTD)
\[ T_{c1} = 25°C \]
\[ T_{c1} = 67.61°C \]
\[ T_{c2} = 45°C \]
\[ T_{c2} = 37°C \]
a) For counter flow heat exchanger
\[ \Delta T_1 = T_{c1} - T_{c2} = 22.61°C \]
\[ \Delta T_2 = T_{c2} - T_{c1} = 12°C \]
\[ \text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} = 16.7486°C \]

5) Overall heat transfer coefficient (U)
a) For hand \( h_i \) calculation
\[ T_{\text{mean}} = \frac{T_{\text{in}} + T_{\text{out}}}{2} = 31°C \]
Properties of water at 31°C
b) For water side
\[ h_{f} = 2431 \text{ KJ/kgK} \]
\[ \mu = 0.165 \text{ kg/m} \text{s} \]
\[ \text{Heat transfer coefficient for water side} (h_i) \]
\[ h_i = 0.725 \left[ \frac{K_{f}^{2} g h_{f} + K_{f}^{3}}{\mu \cdot D \cdot (T_1 - T_0)} \right] \]
\[ \text{Heat transfer coefficient for water side} (h_i) = 475.98 \]
c) For refrigerant side
\[ h_{f} = 179.1 \mu = 1.83 \times 10^{-3} \text{ Km} \]
\[ \text{Similarly heat transfer coefficient for refrigerant side} (h_i) = 225.38 \]

6) Total Area required for heat recovery (A)
\[ Q = U * A * \text{LMTD} \]
\[ A = 0.16488 \text{ m}^2 \]
\[ R = \frac{T_{c1} - T_{c2}}{T_{h2} - T_{h1}} \]
\[ S = \frac{h_{b2} - h_{b1}}{T_{c1} - T_{c2}} \]
\[ R = 0.4533 \]
\[ S = 0.7183 \]

Fig. 3: Modeling
From graph

\[ f_t = \text{Temp correction factor} = 0.85 \]

New LMTD = 16.7486 * 0.8 = 14.2361 °C

New Area = \[ \frac{Q}{U_{\text{new LMTD}}} = 0.1939 \text{ m}^2 \]

7) Length of copper tube required (L)

Area = \[ \pi \times do \times L \times N_t \]

8) Total no of copper tubes required (N_t)

No of turns \( N_t = \frac{L}{\text{Fixed distance } \times \text{Lissajous}} \) = 21.42 ≈ 22

9) Tube pitch (P_t)

\[ P_t = 1.25 \times do = 0.75 \text{ mm} \]

10) Bundle diameter (D_b)

\[ D_b = do \times \left( \frac{N_t}{K_1} \right)^{1/n_1} \]

For 1 pass: Triangular Pitch

\[ D_b = 4.33 \text{ cm} \]

11) Bundle diameter clearance (BDC)

BUNDLE DIAMETER = 10 mm

12) Shell diameter (D_s)

Shell diameter (Ds) = \( D_b + BDC = 5.33 \text{ cm} \)

13) Baffle spacing (B_s)

\[ B_s = 1.8 \times D_s = 9.6 \text{ cm} \]

Fig. 5: Actual model of shell and tube condenser

C. Observation Table

<table>
<thead>
<tr>
<th>Time in Minutes</th>
<th>Compressor Outlet Temperature</th>
<th>Water Outlet Temperature</th>
<th>Evaporator Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40.1</td>
<td>33.2</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>43.3</td>
<td>39.5</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>46.2</td>
<td>43</td>
<td>9.5</td>
</tr>
<tr>
<td>15</td>
<td>48.6</td>
<td>46.9</td>
<td>4.1</td>
</tr>
<tr>
<td>20</td>
<td>49.8</td>
<td>47.9</td>
<td>2.2</td>
</tr>
<tr>
<td>25</td>
<td>50.4</td>
<td>48.3</td>
<td>0.8</td>
</tr>
<tr>
<td>30</td>
<td>51.8</td>
<td>48.2</td>
<td>-0.1</td>
</tr>
<tr>
<td>35</td>
<td>52.3</td>
<td>47.9</td>
<td>-0.3</td>
</tr>
<tr>
<td>40</td>
<td>52.8</td>
<td>48</td>
<td>-0.1</td>
</tr>
<tr>
<td>45</td>
<td>52.9</td>
<td>47.4</td>
<td>-0.5</td>
</tr>
<tr>
<td>50</td>
<td>56.1</td>
<td>48.2</td>
<td>-0.9</td>
</tr>
<tr>
<td>55</td>
<td>58.3</td>
<td>48.5</td>
<td>-1.2</td>
</tr>
<tr>
<td>60</td>
<td>58.3</td>
<td>48.7</td>
<td>-1.4</td>
</tr>
<tr>
<td>65</td>
<td>60</td>
<td>49.3</td>
<td>-1.4</td>
</tr>
<tr>
<td>70</td>
<td>59.9</td>
<td>49.7</td>
<td>-1.3</td>
</tr>
<tr>
<td>75</td>
<td>61</td>
<td>49.9</td>
<td>-1.4</td>
</tr>
<tr>
<td>80</td>
<td>60</td>
<td>49.6</td>
<td>-1.6</td>
</tr>
</tbody>
</table>

From the observations we can see that the temperature of water increase to 48°C within 20 minutes only. Maximum temperature of water which can be achieved is 50°C.

IV. RESULTS AND CALCULATIONS

A. Cop Calculations

Time required for 10 impulse = 60 sec

Trial duration = 10 minutes

Energy meter constant=3200 imp/kw hr

\[ = \frac{1000 \times (3600/3200)}{1125} \text{ watt} \]

\[ = 0.1875 \text{ kw} \]

For 25 liters load on system

Cop of old system:

\[ \text{Refrigerating effect produced} = \frac{25 \times 4.187 \times 1.25}{(60 \times 10)} \]

\[ = 0.2180 \text{ kw} \]

\[ \text{Cop} = \frac{\text{refrigerating effect}}{\text{work supplied}} = 1.162 \]

Similarly cop of new system

Time for 10 impulse = 84 sec

New cop = 1.6277

\[ \% \text{ improvement in cop} = \left( \frac{\text{new cop} - \text{old cop}}{\text{new cop}} \right) \times 100 \]

\[ = 28.61 \% \]
System takes only 20 minutes to raise the temperature of water to 48°C. Maximum temperature which can be obtained is 50°C as per earlier researches; system takes 2 hours of time to raise the temperature to 50°C.

The green color represents the condenser. The condenser is mounted just above the compressor. The surface area required for this condenser is much lesser than air cooled condenser. So it saves lot of space which is wasted for mounting air cooled condenser.

**B. Actual Experimental Setup**

![Fig. 5: CAD modeling of setup](image)

![Fig. 5: Actual Experimental Setup](image)

**Fig. 7: Graph 2 Load vs Actual COP graph**

Actual COP of the system with compact condenser is more than system with existing air cooled condenser system. COP has improved to 28.61%.

### V. CONCLUSION

- The maximum temperature achieved in the water storage tank at 25 liter load is 50 °C within 20 minutes.
- Power Consumption is reduced by using water cooled (HRU) condenser instead of air cooled.
- COP of system increased to 28.61%
- The designed condenser is much compact and can be adjusted easily in the vacant space available above compressor.
- It reduces the handling problems of refrigerator and reduces chances of leakage of refrigerant from bare copper tube.
- Recovery of heat from the condenser reduces the heat load to surrounding and it makes surrounding comfortable.

### REFERENCES


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