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

Vinayak Nathjogi[1] Shruti Suryawanshi[2] Abhijit Khude[3] Dilbar Sayyad[4] Prof S.B.Teli[5]
[1,2,3,4,5]Department of Mechanical Engineering
[1,2,3,4,5]Smt. Kashibai Navale College of Engineering, Vadgaon, Pune

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 500c 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 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.

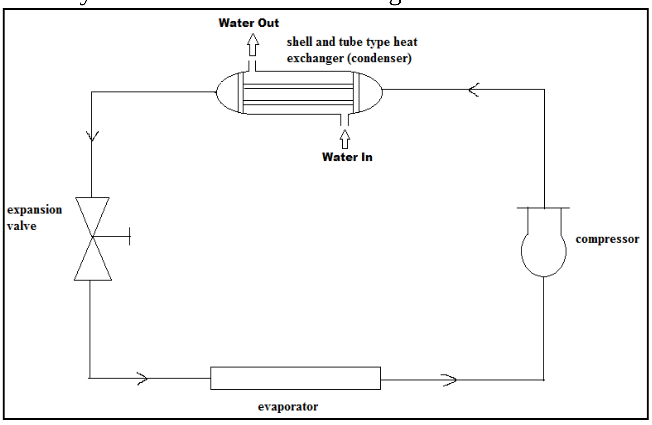

Fig. 1: Block Diagram of WHRS

There are some problems with air cooled refrigerator. Refrigerator needs to be place away from the wall for proper ventilation. There is handling problem also for shifting of refrigerator due to bare copper tubes of condenser. These problems can also be solved by using this system.

We can used various refrigerants but generally R-134a is most preferable substitute for R-12 and has 74% less GWP than R-12. Now a day's refrigerator is used in almost all middle class families, general stores for food preservation. In such refrigerator the refrigerant which is working medium , absorbs the heat from refrigerated space as well as the heat is added to it during compression . This total heat is then rejected to the atmosphere, through 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 geysers, 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.Elumalai [7] has done a case study on waste heat recovery by using hot oven and heater chamber at compressor outlet. Tarangagarwal[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.

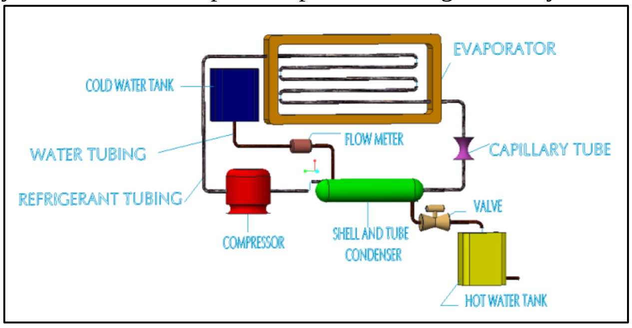

Fig. 2: Block diagram for setup

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*

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

Table 1: System Specification

B. *Mathematical Modeling*

1) *Coefficient of Performance (COP)*

From steam table at pressure 0.27579 bar

h_1=366.94KJ/kg

s_1=s2=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_4=hf_3=274.45 KJ/kg

$S_2 = S_2' + 2.3Cp \log (T_2 / T_2')$

T_2= 67.61℃

$h_2 = h_2' + Cp (T_2 - T_2')$

h_2 = 448.929 KJ/kg

$$COP = \frac{h1-h4}{h2-h1}$$

COP = 1.128

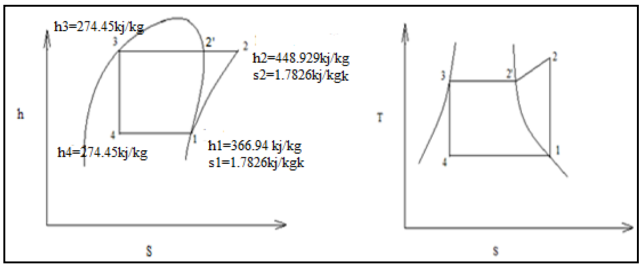

Fig. 3: Modeling

2) *Total heat rejected by the condenser (Q)*

Refrigerating Effect = h1– h_{f3} = 92.49 KJ/kg

a) For compressor

Motor power = 1/8 HP =92watt ≈ 100watt

$$COP = \frac{Q}{W}$$

Q1 = 112.8 watt

$Q_2 = Q_1 + W$ = 212.8 watt

Mass flow rate of refrigerant

$$m_r = \frac{Q2}{RE} = 0.002301 \text{ kg/s}$$

Heat available at condenser for Rejection

$$Q = m_r * (h_2 - h_3) = 401.47 \text{ watt}$$

3) *Mass flow rate of water required (m_w)*

a) For mass flow rate of water

$$Q = m_w * Cp_w * \Delta T$$

For to achieve desired temperature of hot water we can calculate the mass flow rate required of inlet water

For ΔT = 20°C

m_w = 0.004794 kg/s

4) *Logarithmic mean temperature difference (LMTD)*

T_{c1} = 25 °C T_{h1} = 67.61 °C

T_{c2} = 45 °C T_{h2}= 37 °C

a) For counter flow heat exchanger

$\Delta T_1 = T_{h1} - Tc_2$ = 22.61 °C

$\Delta T_2 = T_{h2} - Tc_1$ = 12 °C

$$LMTD = \frac{\Delta T1 - \Delta T2}{\ln(\frac{\Delta T1}{\Delta T2})} = 16.7486$$

5) *Overall heat transfer coefficient (U)*

a) For $h_i$and h_o calculation

$$T_{mean} = \frac{Twin+TRout}{2} = 31°C$$

Properties of water at 31°C

b) For water side

hf_g= 2431 KJ/kK$_f$ =0.165μ = 0.798 * 10^{-3} kg/mD = 0.053m = 53mm

Heat transfer coefficient for water side (h_i)

$$h_i = 0.725 \left[\frac{\rho^2 * g * hfg * Kf^3}{\mu * D * (To-Ti)}\right]$$

Heat transfer coefficient for water side (h_i) = 475.98

c) For refrigerant side

hf_g= 179.1 μ=1.83*$10^{-4}$$K_f$= 0.00342

Similarly heat transfer coefficient for refrigerant side (h_r) = 225.38

Fouling factor for Refrigerant (f_r) =0.00017

Fouling factor for water (f_w) =0.00017

$$\frac{1}{U} = \frac{1}{hi} + \frac{1}{hr} + \frac{\mu}{K} + f_r + f_w$$

U= 145.38 w/m^{2}k

6) *Total Area required for heat recovery (A)*

Q = U * A * LMTD

A = 0.16488 m^2

$$R = \left[\frac{Tc1-Tc2}{th2-th1}\right] \qquad S = \left[\frac{th2-th1}{Tc1-th1}\right]$$

R= 0.4533 S= 0.7183

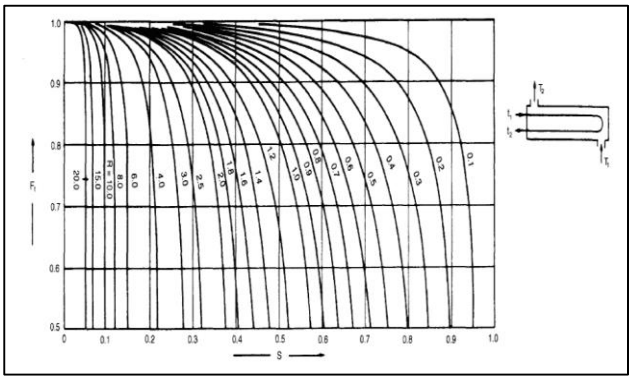

Fig. 3: Temperature correction factor: one shell pass; two or more even tube 'passes

From graph

f_t = Temp correction factor = 0.85

New LMTD = 16.7486 * 0.8 = 14.23631 ºC

$$\text{New Area} = \frac{Q}{U*newLMTD} = 0.1939\ m^2$$

7) Length of copper tube required (L)

$$\text{Area} = \pi * Do * L * Nt = 10.286\ m^2$$

8) Total no of copper tubes required (N_t)

$$\text{No of turns } Nt = \frac{L}{Fixeddistance'L'isassumed} = 21.42 \cong 22$$

Tubes

9) Tube pitch (P_t)

Pt = 1.25 * do=0.75 mm

10) Bundle diameter (Db)

$$Db = do * \left(\frac{Nt}{K1}\right)^{1/n1}$$

For 1 pass: Triangular Pitch

K_1= 0.319 n_1= 2.412

Db= 4.33 cm

11) Bundle diameter clearance (BDC)

Bundle diameter clearance (BDC) = 10 mm

12) Shell diameter (Ds)

Shell diameter (Ds) = $Db + BDC$= 5.33 cm

13) Baffle spacing (Bs)

Baffle spacing (Bs) = 1.8 * Ds= 9.6 cm

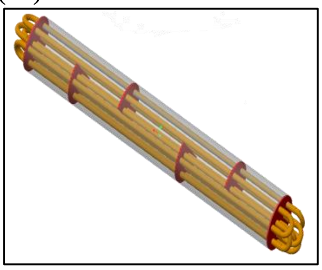

Fig. 4: CAD modeling of shell and tube condenser

CAD model is designed as per the dimensions obtained from mathematical modeling. CREO software is used for the designing.

Fig. 5: Actual model of shell and tube condenser

C. Observation Table

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

Table 2: Observation Table

From the observations we can see that the temperature of water increase to 48^0c within 20 minutes only. Maximum temperature of water which can be achieved is 50^0c.

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

= 1000*(3600/3200)

= 1125 watt

Work supplied to compressor = $\frac{1125*10}{60}$ watt

=0.1875kw

For 25 liters load on system

Cop of old system:

Refrigerating effect produced =

$$\left(\frac{\text{mass of water} * \text{cp} * \text{temperature rise for 10 minutes}}{\text{trial duration in seconds}}\right)$$

=25*4.187*1.25)/(60*10)

= 0.2180 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

$$\%\ \text{improvement in cop} = \left(\frac{\text{new cop} - \text{old cop}}{\text{new cop}}\right) * 100$$

= 28.61 %

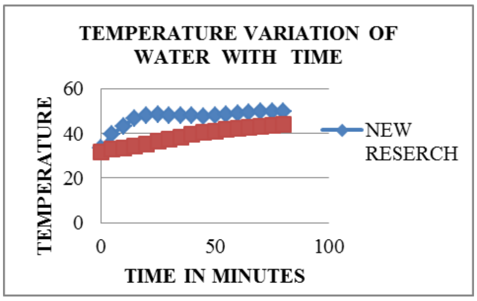

Fig. 6: Graph Time vs Temperature rise graph

System takes only 20 minutes to raise the temperature of water to 48^0c. Maximum temperature which can be obtained is 50^0c.as per earlier researches; system takes 2 hours of time to raise the temperature to 50^0c.

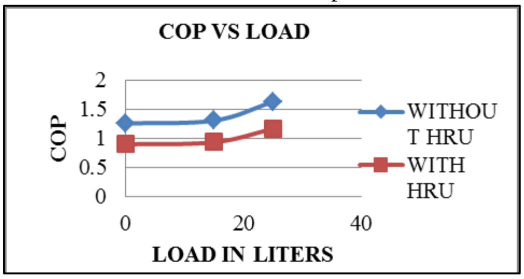

Fig. 7: Graph 2 Load vs Actual COP graph

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

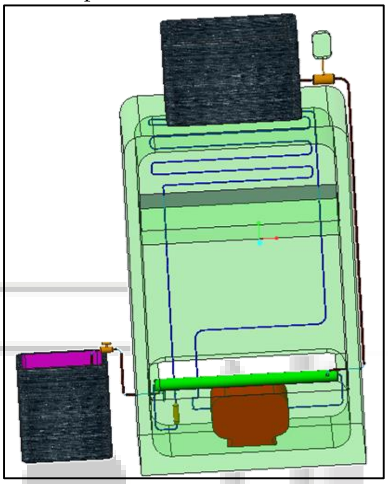

Fig. 5: CAD modeling of setup

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

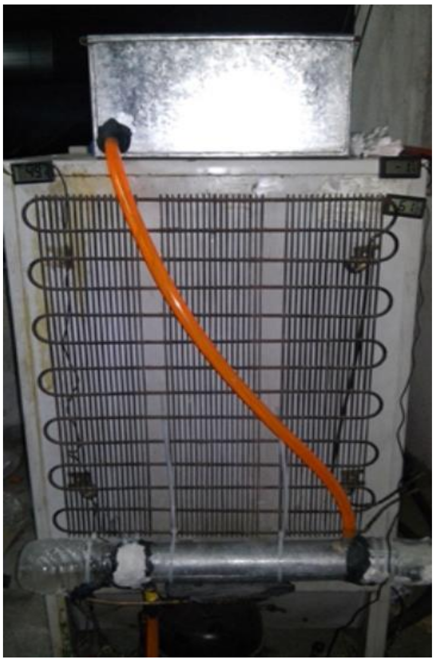

Fig. 5: Actual Experimental Setup

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.

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