ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 5, Issue 8, August 2018

Experimental Result Evaluation & Effects of Mass Flow Rate of Refrigerant on the Performance of Domestic Refrigerator with Water Cooled Spiral Tube Condenser

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Abstract: Refrigerator has become an essential commodity rather than luxury item. It is one of the home appliance utilizing vapour compression cycle in it process. Performance of this system becomes main issue and many researches are still ongoing to evaluate and improve efficiency of the system. Sub cooling of refrigerant after condenser and Superheating of refrigerant before entering in the compressor are two methods which help to improve the COP of refrigeration system. This paper presents effect of evaporative condenser on COP of domestic refrigerator. The purpose of this article is to compare the COP of refrigerator by using water cooled condenser and evaporative condenser of same length and same diameter. This experiment is carried out on domestic refrigerator test rig. In this study, an innovative, evaporative condenser for residential refrigerator was introduced. A vapour compression cycle incorporating the proposed evaporative condenser was tested to evaluate the cycle performance.

Keywords: Water Cooled Condenser, Vapour Compression System, Coefficient of Performance (COP), sub cooling and superheating

I. INTRODUCTION

Refrigeration is a process where the heat moves from low temperature reservoir to high temperature reservoir. Heat which is rejected by the condenser of a refrigerator is of low quality which means the temperature is low. Majority of refrigerator works on vapour compression refrigeration system. The system consist of compressor, condenser, expansion valve and evaporator. The performance of the system depends on the performance of all components of the refrigeration system.

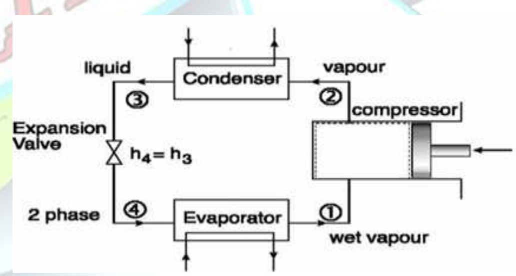

Fig 1.1: Vapour compression refrigeration system

The aim of the present work is to improve the performance and efficiency of the domestic refrigerator by adopting two easy ways.

1. Sub-cooling
2. Super heating

Super heating involves super heating of refrigerant after evaporator while Sub cooling includes sub cooling of refrigerant before entering in to expansion device.

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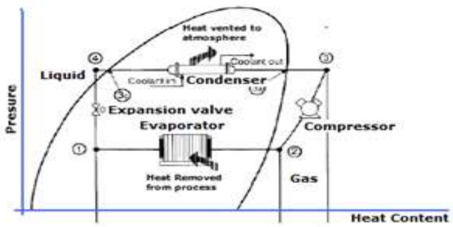

Fig 1.2: VCR cycle

Condensers and evaporators are basically heat exchangers in which the refrigerant undergoes a phase change. Next to compressors, proper design and selection of condensers and evaporators is very important for satisfactory performance of any refrigeration system.

- **Methods of sub cooling:**

Refrigerant can be sub cooled by following methods

a) By improving and carrying out modifications in condensers so that sub cooling arrangement is included.

b) By installing internal and external heat exchangers to provide sub cooling.

- **Advantages of sub cooling:**

a) Refrigeration is improved when a liquid refrigerant is sub cooled by a circulation of cold water in the heat exchanger or by some other methods. As a general rule, a 1% increase in refrigeration can be achieved for every 2 degrees of liquid sub cooling obtained. Due to this characteristic, design of condensers have been changed to achieve obtain liquid sub cooling.

b) Production of flash gas is reduced during the process of expansion.

c) Greater latitude is achieved in management of piping and location of evaporator

- **Classification of condensers:**

Based on the external fluid, condensers can be classified as

a) Air cooled condensers
b)Water cooled condensers, and
c) Evaporative condensers

- **Water Cooled Condensers:**

In water cooled condensers water is the external fluid. Depending upon the construction, water cooled condensers can be further classified into:

1. Double pipe or tube-in-tube
2. Shell- and- coil type
3. Shell-and-tube type

II. PROJECT EXPLANATION

Objectives of our project works are:

- ❖ Development of Refrigerator test set up with water cooled condenser
- ❖ Heat transfer analysis of condenser with and without TES & water cooled condenser
- ❖ Testing and performance evaluation
- ❖ Comparative analysis of refrigerator with and without water cooled condenser

1) Problem Specification and Solutions:

During literature review we noticed following problems encountered with air cooled condenser of domestic refrigerator.

- ❖ To enhance COP of domestic refrigerator
- ❖ Less effective space available for rejection of heat
- ❖ No action of centrifugal force
- ❖ Frictional losses
- ❖ Length of the coil

There are following solutions that can be use to enhance the COP of the domestic refrigerator.

- ❖ Provide centrifugal force to improve volumetric flow
- ❖ Use spiral or helical coil tube to increase turbulences
- ❖ Increase diametric ratio (d/D) of helical coil tube condenser
- ❖ Minimize frictional losses
- ❖ Providing sub cooling to improve the refrigerating effect

2) Construction:

Following are the different Components of modified Refrigerator:

a) Compressor, b) Water cooled spiral tube Condenser
c) Expansion device, d) Evaporator, e) Water pump,
f) Thermocouples(7), g)Pressure gauges(3), h) Voltmeter,
i) Refrigerant (R134a), j) Ammeter, k) Pipes, l) Sump,
m) Water jacket (shell coil condenser)

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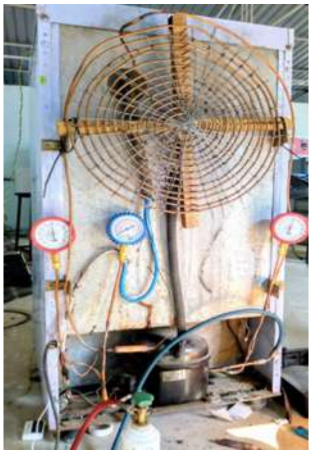

Fig. (a)

Fig. (b)

Fig. (a)- Domestic refrigerator with air cooled spiral tube condenser
Fig. (b)- Domestic refrigerator with water cooled spiral tube condenser

Water-Cooled Spiral Coil Tube Condenser:

Water-cooling systems have seen considerable use for years, though they are also on the rise in smaller businesses and some residential applications. The system operates through a network of water coils used to transfer the heat from the condenser coils. These systems typically work in-tandem with a cooling tower in order to circulate out and exhaust heat.

A Water-cooled condenser utilizes water coils to transfer the heat from the condenser coils. A waterline, separate from the water used to make ice, brings the water into the cabinet. The water circulates through the system, efficiently removing the heat. This hot water is then drained out of the ice machine unit. In an establishment where the surrounding air temperatures are typically 80 degrees to 100 degrees Fahrenheit on a regular basis, such as in a commercial kitchen, a water-cooled condenser may make more sense since an air-cooled unit would soon be overtaxed trying to cool the condenser with excessively warm air. Particularly in states where the climate is hot for many months, a water-cooled condenser can function more effectively, meaning a longer lifetime for your ice machine equipment.

Water-cooled systems are often chosen because:

They operate at better efficiencies- Overall a water-cooled condenser unit will typically consume far less overall energy, which can lead to savings on energy costs and consumption.

Extended lifespan- Because of the efficiency of the medium and the lack of weather-exposed parts, a water-cooled system will typically last years longer, assuming maintenance is not neglected.

Can operate better at higher temperatures- Industries such as manufacturing industries may find that water-chilled systems operate more effectively in high-temp.

3) Working principle:

The Working of a Domestic Refrigerator with Spiral tube condenser is as same as Straight tube Condenser. The vapour leaving from the Evaporator has low pressure and low temperature and send to the Compressor where it is compressed to high pressure and high temperature. This vapour refrigerant is condensed in the Condenser at constant pressure and temperature. Due to Spiral shape of Condenser there will be the more turbulence flow which increases the mass flow rate inside it. The high temperature and high pressure liquid refrigerant thus expanded in the Expansion device and loses it temperature and flows through the evaporator where latent heat was absorbed and gets evaporated. Same the process is repeated further.

Advantages of spiral tube condenser:

- High heat transfer rate which enhances COP
- More mass flow rate
- Total length compared to straight tube condenser is less
- More frictional resistance
- Sub-cooling takes place easily than Super heating
- Low frictional losses
- Easy design

4) Design of water cool spiral tube condenser:

Now

Total length of the tube use in straight tube condenser

$L_{available}$= Number of passes×Length of one pass+No of semicircular bends × Perimeter of semicircular bends

$=17\times42.5+17\times(\pi d_b)/2$

$=17\times42.5+17\times(\pi\times4)/2$

$=829.314cm$

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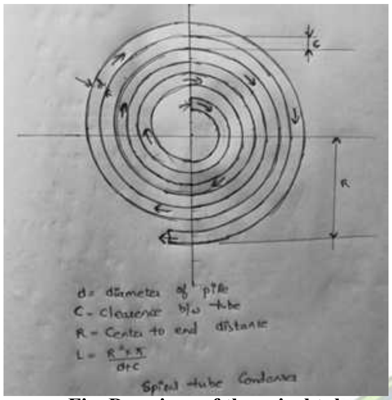

Fig. Drawings of the spiral tube condenser

For making connections we provide extra length

L_{ext}=86+16 =102

Now

Total length = $L_{available} + L_{ext}$

=829.5+102

=931.5

~940cm

Now for spiral => ~950cm (assume)

We assume the maximum radius of spiral is 43cm as per width available at back side of the refrigerator also we set minimum diameter as 2a+p

Where

a- starting distance point of the spiral from its centre

P- Distance advanced bend in two points per ½ turns

For convenient we performance

a=2cm &p=1.5cm

From construction of the spiral we know total length of the spiral

$L=\sum^{n}_{i=1}$

$L=L_1+L_2+L_3+L_4+L_5$ +----------+L_n

$L=\sum^{n}_{i=1}$

But $L=\frac{\pi D}{2}$

D → diameter of the semicircular section of the spiral

Diameter varying each ½ revaluation we know the reaction at the D with a&p

D_n=2a+np

L_n=π/2 (2a+p) + π (2a+2p)+π/2 (2a+3p)+π/2(2a+p)+----------+π/2(2a+np)

=π [2na+ (p+2p+3p+4p+------+np)]

Where,

n→ number of semicircular

But 'n' is depending upon width

W=np+2a

=2a+np

Where w=width available

As we set D_{max}=43cm

43=np+2a

For p=1.5 &a=2

43=n×1.5+2×2

$n=\frac{43-4}{1.5}$

n=26

L=π/2[2na+p(1p+2p+35p+--+np)]

L= π/2 [2na+p(351)]

L= π/2[2×26×2+1.5×351]

L=990cm consider

Or

L=π/2 [2na+p(1+2+3+----+n)]

$L=\pi/2\left[2na+p\times\left(\frac{n(n+1)}{2}\right)\right]$

$L=\pi/2\left[2\times2\times26\times2+1.5\left[26+\frac{26+1}{2}\right]\right]$

L=990cm

But we have L=940

$940=\pi/2\left[2\times1.5\times n+\frac{n(n+1)}{2}\right]$

$L=\pi/2\left[2an+p\left(\frac{n(n+1)}{2}\right)\right]$

We assuming

a=1,1.5,2,2.5,------

p=0.5,1.0,1.5,2----

n→?

W=2a+np

Now, for

1. a=1cm, p=0.5cm

$950=\pi/2\left[2an+p\left(\frac{n(n+1)}{2}\right)\right]$

$950=\pi/2\left[2\times1\times n+\frac{0.5(n2+n)}{2}\right]$

$950=\pi/2\left[2n+\frac{0.5n2+0.5n}{2}\right]$

950=π/2[(4n+0.5n2+0.5n)/2]

$950=\pi/4[0.5n^2+4.5n]$

n=44

2. a=1.5cm, P=1cm

$950=\pi/4(n^2+7n)$

n=31

3. a=2cm, p=1.5cm

N=25.406~26

4. a=2.5cm, p=2cm

$950=\pi/2[2\times2.5\times n+2(n^2+n)/2]$

n=21

L=π/2[2an+p(n(n+1)/2]

$N=\frac{b2\pm\sqrt{b2}-4ac}{2}$

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W=2a+np
We have $width_{max}$=43cm
W=2a+np
Checking for width

1. W=2×1+44×0.5=24cm
2. W=2×1.5+31×1=34cm
3. W=2×2+26×1.5=42.1cm
4. W=2×2.5+21×2=47cm

Final dimension obtained by trial and error method
We get
L = 950cm
n = 26
a = 2cm
p = 1.5cm

$$L=\pi/2\ \left(2\times2\times25.04+1.5\times25.4\left[\frac{25.4+1}{2}\right]\right)$$

L=949.58
L~950cm

III. EXPERIMENTATION

1) Procedure

- ❖ Unplug the Power supply from refrigerator.
- ❖ Then discharge the refrigerant which is inside copper tube.
- ❖ Attach pressure gauges and thermocouples at where to which readings are to be taken.
- ❖ After attachment of pressure gauges and thermocouples, again supply the refrigerant to the unit.
- ❖ Check whether any leakages are there, if not take the readings of straight tube condenser with 6L water, 60W and 100W bulb load variation corresponding temperatures and pressure and note down.
- ❖ Again discharge the refrigerant and take out the straight tube and fix the spiral tube condenser.
- ❖ Supply the refrigerant to the unit and braze it correctly without any leakages.
- ❖ Now take the pressure and temperature readings with 6L water, 60W, 100W bulb load variation.
- ❖ Calculate the properties like enthalpies at various nodes with respect to temperature from P-h chart.
- ❖ Calculate the COP and mass flow rate for both condensers and compare the COP.

TABLE 1
SPECIFICATION OF THE REFRIGERATOR

Refrigerant	R-134a
Evaporator	Helical rectangular coil
Length	829.31cm
Refrigerant Control	Capillary tube
Compressor Cooling	Static
Evaporating Temp Range	-24˚C to -12˚˚C
Displacement/ revolution	4.00˚CC
No. of cylinder	One
Evaporating Temperature	-23.3˚˚ C
Condensing Temperature	65˚ C
Condenser	
Pitch	4cm
No of passes	17
Height of condenser	66.5cm
Inside diameter of tube	3mm
Outside diameter of tube	3.7mm

2) Sample Calculation for Spiral Tube Condenser:

From experimentation we obtaining number of observation table and out of it we have giving one sample calculation.
For maximum COP reading :- (at 6 lit. water load)
Assumption made for calculating amount of heat transfer from the condenser
1. Efficiency of compressor is 95%.
2. Negligible variation in mass flow rate.
3. Flow inside the condenser tube is turbulent.
COP=8.5, Tei=-2.7, Tcdi=53.2^{0}c, Tcdo=31.2^{0}c, h1=410kJ/kg.K, h2=430kJ/kg.K , h3=h4=240kJ/kg.K
We have
Wc= η_{comp}. X V X I
= 0.95 ×230 × 0.8
= 174.8 watt
= 0.1748 kW
But,
Wc= m × (h2-h1)
0.1748=m × (430-410)
m=0.00874 kg/sec
Now,
For finding heat transfer coefficient and heat transfer rate
Followings are the properties of R134a taking from data table at bulk mean
temperature
Tb = (Tci+Tco)/2
= (53.2+31.2)/2
= 44.8^{o}c
=45^{o}c
From data hand book at 45°c
ρ_v= 57.66 kg/m3

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$\mu = 1.486 \times 10{-}5$ kg/ms
Pr = 1.058
K = 0.01664W/mK
C_v = 1184 J/kg K
We know that,
$m = \rho_v.A.V$
We have

$V = \frac{m}{\rho v.A}$

$A = \frac{\pi}{4} \times d^2$

$= \frac{\pi}{4} \times (5 \times 10^{-3})^2$

$= 1.96 \times 10^{-5} m^2$

$V = \frac{0.027}{57.66 \times 1.96 \times 10^{-5}}$

= 23.89 m/sec

But,

$Re = \frac{\rho v.V.d}{\mu}$

$= \frac{57.66 \times 23.89 \times 5 \times 10^{-3}}{1.486 \times 10^{-5}}$

$= 463.49 \times 10^3$

= 463419.72> 2300

Hence flow is turbulent
Also when,
0.6 <Pr> 100
$2500 < Re > 1.25 \times 10^6$
And, L/D > 60
Then we can use the following relation

$Nu = 0.0233\, Re^{0.8} Pr^{0.3}$

$= 0.0233 \times 463491.7^{0.8} \times 1.058^{0.3}$

= 808.23

We have

$Nu = \frac{hd}{K}$

$808.23 = \frac{h X\, 5X\, 10^{-3}}{0.01664}$

$h = 2689.79 \frac{w}{m^2\, K}$

$= 2.689 \frac{kw}{m^2\, K}$

Heat transfer rate of condenser coil is given as,
$Q = h.As.\Delta Tm$
Where
As be the surface area of the coil

$A_s = \pi \times d \times L$

$= \pi \times 5 \times 10^{-3} \times 950 \times 10^{-2}$

$= 0.149 m^2$

Also

$Q = m.Cpv.\Delta Tf$

$= 0.027 \times 1184 \times (53.2 - 31.2)$

= 703.296watt

= 0.703296 kw

For wall temperature

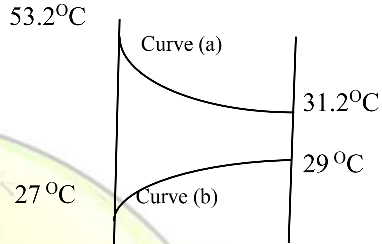
$h.As.\ \Delta T_m = Q$

$0.703296 = 2.689 \times 0.149 \times (\frac{Tci+Tco}{2} - Tw)$

$0.7.3296 = 2.689 \times 0.149 \times (\frac{53.2+31.2}{2} - Tw)$

$T_w = 40.44°C$

By using LMTD method



Curve (a) shows temperature difference of refrigerant
Curve (a) shows temperature difference of cooling water

$\theta_m = \frac{\theta 1 - \theta 2}{\ln(\frac{\theta 1}{\theta 2})}$

$= \frac{(53.2-27)-(31.2-29)}{\ln(\frac{53.2-27}{35-29})}$

$\theta_m = 9.687°C$

but,

$Q_r = U.As.\ \theta_m$

$\therefore U = \frac{Qr}{A\ .\theta m}$

$U = \frac{703.296}{As \times 9.687}$

here,
A_s=Surface area

$= \pi \times d \times L$

$= \pi \times 5 \times 10^{-3} \times 9.50$

$= 0.1492 m^2$

$\therefore U = \frac{703.296}{0.149 \times 9.687}$

$U = 487.26 \frac{W}{m^2 K}$

Neglecting tube thickness as

$t \lll L$

$\therefore \frac{1}{U} = \frac{1}{hi} + \frac{1}{ho} + Rfi + Rfo$

where

Rf_i and Rf_o is the internal fluid and external fluid fouling resistance and its values taken from heat transfer data book

$Rf_i = 0.0001725 \frac{m^2 K}{w}$..................(.as internal fluid is refrigerant)

$Rf_o = 0.0003525 \frac{m^2 K}{w}$..................(.as external fluid is air)

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ISSN 2394-3785 (Online)
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$$\therefore \frac{1}{ho} = \frac{1}{U} - \frac{1}{hi} - Rfi - Rfo$$

$$\therefore \frac{1}{ho} = \frac{1}{487.26} - \frac{1}{2689.79} - 0.0001754 - 0.0003525$$

$$\frac{1}{ho} = 0.001152$$

$$\therefore ho = \frac{1}{0.001152}$$

$h_o = 868.055 \frac{W}{m^2 K}$

for frictional factor (f)

as we know that,

$$f = \frac{\Delta P}{\frac{L}{d} \times \frac{1}{2} \times \rho v \times V^2}$$

$$= \frac{1 \times 10^5}{\frac{9.50}{0.005} \times \frac{1}{2} \times 57.66 \times 23.89^2}$$

$$f = 0.003$$

3) Comparative Performance Analysis

Comparative Graphs:

3.1 Time vs COP

For 6lit water load:

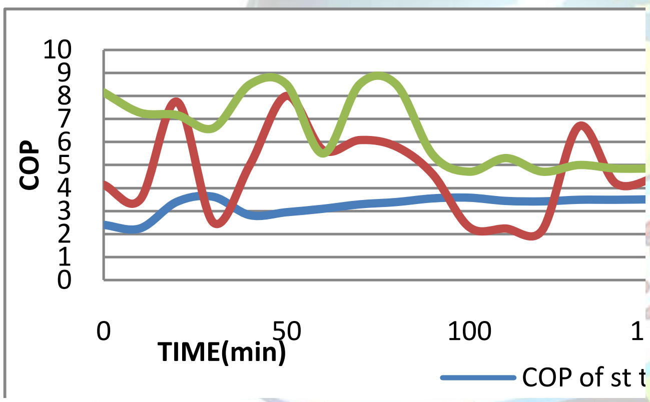

Fig 9.1 Shows variation in COP with respect to time for with or without water cool spiral tube condenser for 6L water load.

From the graph we can see that blue colour indicates straight tube and red colour indicates spiral tube condenser. With spiral tube condenser we got very high COP values compare to straight tube condenser.

For 60Watt load:

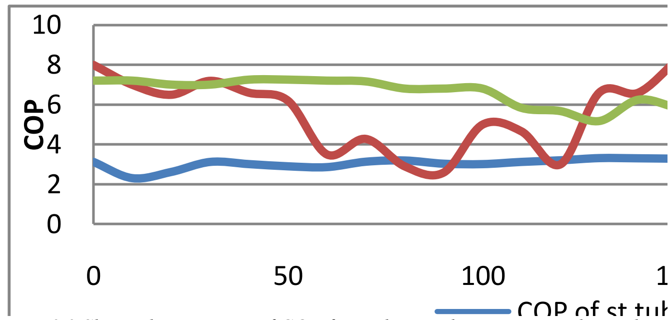

Fig 9.2 Shows the variation of COP for with or without water cool spiral tube condenser for 60W

In the graph we can see that when 60 W load is applied, the COP of straight tube condenser is much less than spiral tube condenser. Due to spiral tube condenser there will be more heat rejection takes place which enhances COP.

For 100 Watt load:

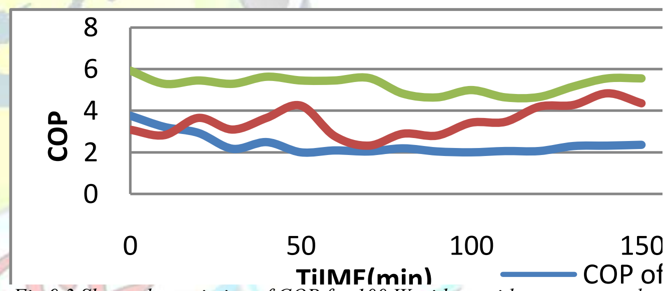

Fig 9.3 Shows the variation of COP for 100 W with or without water cool spiral tube condenser.

3.2 Time vs m_r

For 6lit water load:

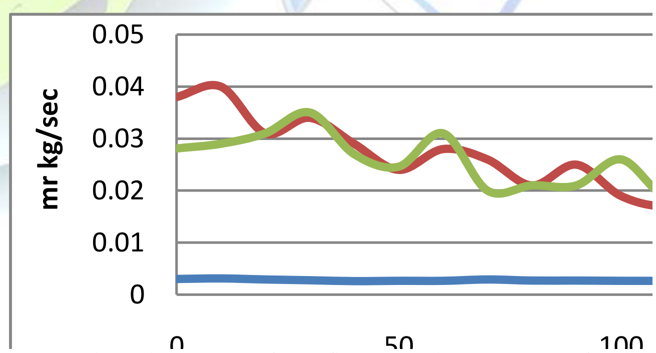

Fig 9.4 Shows the variation of mass flow rate with respect to time for 6lit water load with and without water cool spiral tube condenser.

For 60 Watt load:

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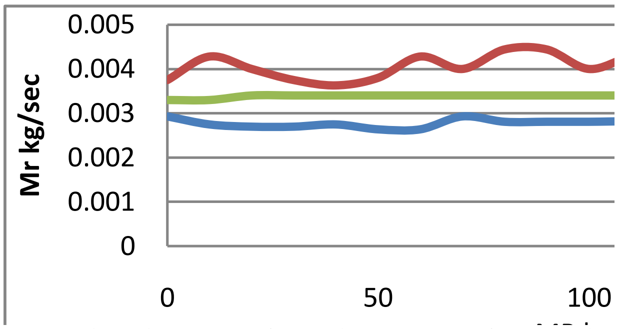

Fig 9.5 Shows the variation of MR with respect to time for 60W with and without water cool spiral tube condenser.

For 100 Watt load:

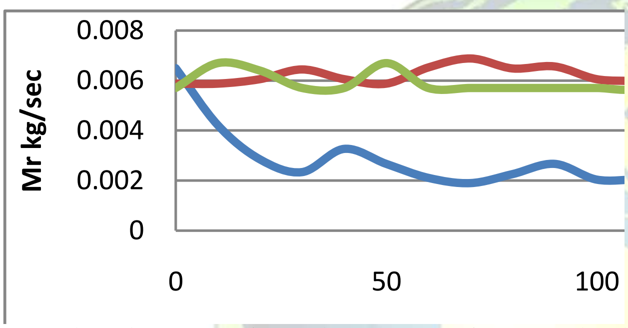

Fig 9.6 Shows the variation of MR with respect to time for 100W with and without water cool spiral tube condenser.

3.3 Time vs Heat rejection in condenser (Qr)

For 6lit water load:

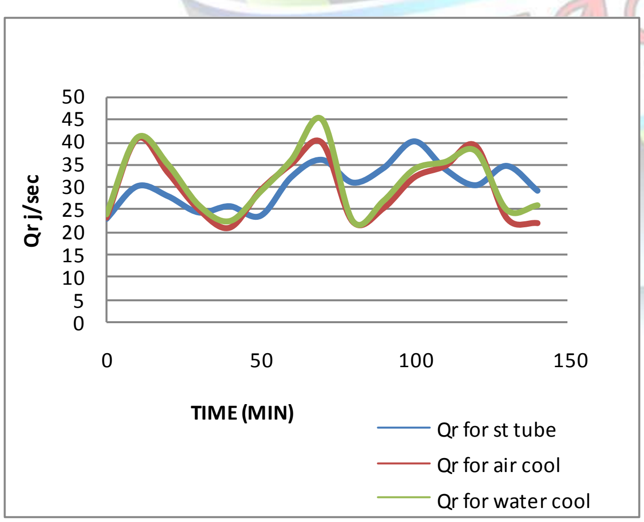

Fig 9.7 Shows the variation of Heat rejection for 6L water load with and without water cool spiral tube condenser

For 60 Watt load:

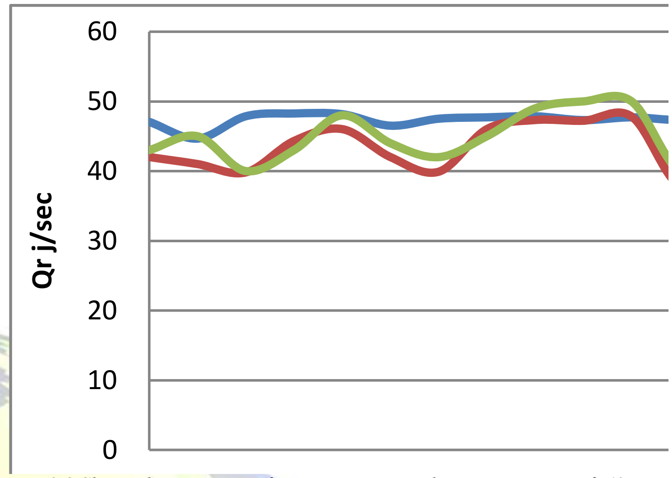

Fig 9.8 Shows the variation of Heat rejection with respect to time of 60W load with and without water cool spiral tube condenser

For 100Watt load:

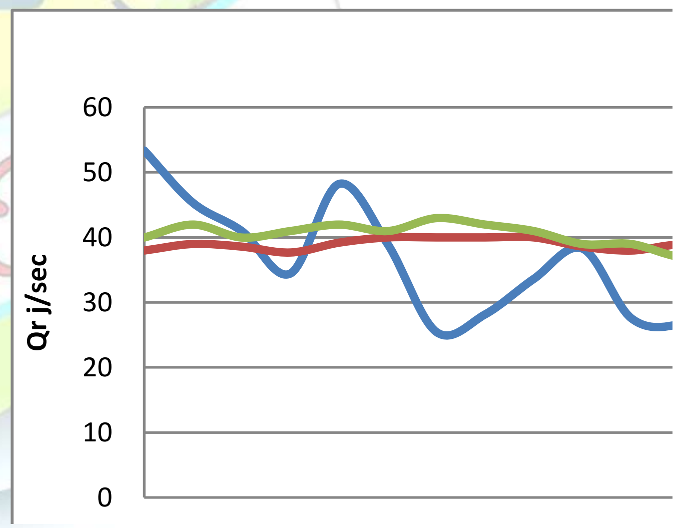

Fig 9.9 Shows the variation of Qr with respect to time for 100W load with and without water cool spiral tube condenser

IV. Result and Discussion

Table shows testing results among straight tube, air cool spiral tube, water cool spiral tube condenser

TABLE 2
RESULT TABLE

CONDENSER TYPE	LOAD	M_R (kg/sec)	COP
STRAIGHT TUBE	6Lit	0.00268	2.6
	60W	0.00027	2.4
	100W	0.00026	2.35
AIR COOLED SPIRAL TUBE	6Lit	0.025	5.38
	60W	0.0004	4.03
	100W	0.00055	4.5
WATERCOOLED SPIRAL TUBE CONDENSER	6Lit	0.0281	6.75
	60W	0.003	5.57
	100W	0.0058	5.15

From various graphs plotted above shows comparatively difference among the performance of refrigerator with straight tube condenser, air cooled spiral tube condenser, water cooled spiral tube condenser. Finally above results are obtained which shows that higher COP with increment in the mass flow rate in case of Water cooled spiral tube condenser as compare to Straight tube and Air cooled spiral tube condenser.

V. Conclusion

After testing the refrigerator having 150lit capacity with straight tube condenser, spiral tube air cooled condenser and spiral tube water cooled condenser we conclude that

1. After comparing the COPs of straight tube, spiral tube air cooled and spiral tube water cooled condenser, it has been found spiral tube water cooled condenser gives maximum COP value which indicates the improved performance of the refrigerator.

2. Due to the spiral shape of the condenser there is existence of centrifugal action which helps to increase the mass flow rate of refrigerant inside the condenser coil, which is further responsible for to increases the heat transfer rate.

3. It is possible to get maximum COP for domestic refrigerator by using spiral tube water cooled condenser but frictional resistance and pressure drop are play vital role for selecting the number of turns and pitch distance between two turns.

4. Pressure drop range is must be below 6 bar and frictional factor value is must be below 3 because increase in the value of pressure drop and frictional factor increases load on compressor.

Acknowledgment

This paper has been supported by coordinator of R&D cell, Mechanical Engineering Department, Kshatriya college of Engineering- Armoor, Nizamabad, (Dist).

We would like to thank my advisor and teacher, Dr.MVS Murali Krishna without his knowledge and guidance this study would not have been possible.

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ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 5, Issue 8, August 2018

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