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Experimental Investigation on Performance of Vapour Compression Refrigeration System with Integrated Sub-Cooling

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Abstract:
This paper presents an experimental investigation on performance of VCR system with integrated sub-cooling carried out by introducing counter flow tube – in – tube heat exchanger between compressor and condenser. The COP (coefficient of performance raised with condenser subcooling due to tradeoff between reducing compressor work and increasing refrigerating effect. Thermodynamic properties related with refrigerant effect like latent heat of vaporization and liquid specific heat were used to finding the superlative increasing in COP with condenser subcooling. Decreasing the condenser subcooling high latent heat of vaporization used in refrigerant. The performance and power required to run system is compared with conventional VCR System. The result shows that using heat exchanger as a pre cooler (or) Sub-cooler to condenser can improve 14% of COP and 27% Power consumption reduction when compared to the conventional VCR System.

Keywords - *COP, refrigerating effect, sub-cooling, superheating, tube – in – tube heat exchanger.*

I. INTRODUCTION

Now a days the applications of refrigeration and air conditioning systems is increasing due to requirement of comfort conditions to Human beings, industrial areas and in many organizations to keep equipment, food in safe conditions. So which is necessary to improve the performance of refrigeration systems without increasing effects of global warming and ozone depletion potentials.[1]Subcooling liquid before the expansion process can be obtained through different approaches. Ahamad al [2]. added extra component to subcool liquid in exit and inlet of compressor and condenser.We can obtain subcooling by various ways and with help of thermoelectric device we can achieve subcooling and condensate water was used to subcooling the water in exiting condenser. [3].So many ways are there for subcooling added heat sink cool heat exchanger was placed high pressure receiver between subcooler and condenser to separate vapour from liquid immediately in the way of subcooler [4]. A receiver is not important in shell and tube condensers because shell play a vital role like liquid vapor separater and with help of condenser we can get subcooling in system this is most advanced way for attaining subcooling without receiver [5].In the similar manner Shyam Agarwal et al. [6] computational Benefit the most from condenser sub cooling in comparison to R410 A (7.0%), R-134a. (5.9%) and R717 (2.7%) due to its smaller latent heat of vaporization and the value of cop maximizing due to sub cooling. Graeme maidment et al. [10] experimentally investigated the use of PCM in refrigeration systems. They conducted experiment on prototype with employing heat exchangers at different locations, with phase

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change material results shows that lowering the temperature of the sub cooled refrigerant up to 8% energy saving can be achieved and Cop of the system can be improved by 6%. R.K Ginusa et al.[11] the experimental analysis of double affect condensing unit. In VCR system the test was carried with two refrigeration cycles R-134 –as working fluid. And both cop and Refrigeration effects were observed. The cop of system up to 11% improved. At evaporation temperature of 15 0 c and condensation temperature of 35°C it can be concluded that use dedicated sub cooling cycle in VCR system is most efficient to simple VCR system.

Nomenclature

COP	coefficient of performance
q	Enthalpy difference across the evaporator ($KJ\ kg^{-1}$)
SH	superheated vapour region
SC	subcooled liquid region
T	temperature (ºC)
TP	two-phase region
w	specific compression work ($kJ\ kg^{-1}\ K^{-1}$)

Subscripts

avg	average
c	condenser
e	evaporator
fg	liquid vapor
in	inlet
p	constant pressure
out	outlet
sat	saturation
sub	subcooling

Greek

Δ	difference

II. SYSTEM DESCRIPTION AND MODELLING

The Experimental test rig is fabricated by incorporating the novel use of heat Exchanger between compressor and condenser without using conventional cycle as dedicated system. The Experimental system equipped with a domestic refrigeration system with components of compressor, condenser, Expansion Value (Capillary tube), Evaporator and Heat Exchanger (Tube – in – tube) as shown in figure: 1, is designed to operate with R-134a refrigerant as working fluid. The test rig is used to evaluate the co-efficient of performance and Refrigeration Effect; power consumed to run system and compared with the conventional VCR system, and effectiveness of heat exchanges is evaluated.

The following parameters were calculated.

1. Effectiveness of heat exchanger.
2. Degree of sub cooling to condenser and superheating to compressor.
3. Co-efficient of performance of system.

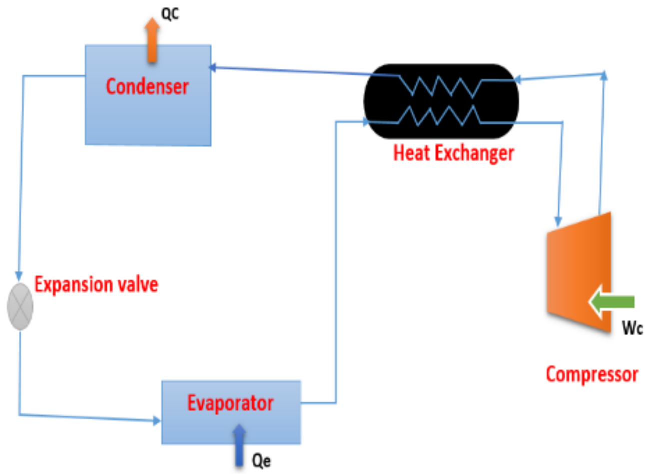

Figure:1 schematic diagram of experimental VCR system.

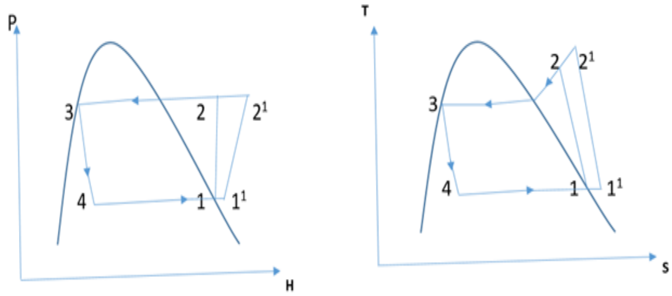

Figure: 2 P-h & T-s diagrams of experimental VCR system with integrated sub cooling

1-2-3-4 =Actual cycle of vapour compression refrigeration system

1^1-2^1-3-4- = experimental cycle of vapour compression refrigeration system equipped with heat exchanger.

Fig. 1 and 2 shows the P-h and T-s graphs belongs to subcooled and super-heated vapor compression refrigeration cycles. The heat was rejected by the condensate liquid passed through VCR cycles acted as subcooler. For producing low temperature in evaporator both cycles were coupled each other. For the analysis considered R134a two sections were preferred one by one in the system. The evaporator, subcooler compressor and condenser were parts in subcooled VCR cycle and evaporator was compressed. At elevated temperature and pressure compressor passed into the condenser and sub cooler. Expansion valve was used for passing liquid refrigerant from state 3-4. If evaporator reached low temperature liquid vapour mixture of refrigerant introduces. In second condenser vapour phase is converts in liquid and heat is consumes by it. At $1\text{-}1^1$ state mechanical subcooling is obtains by subcooler VCR cycle. Fig. 2 shows net specific refrigerant effect was produced by liquid condensate at $4\text{-}1^1$ state. COP was increased by raising in refrigerating effect and also in subcooler compressor work was decreased by COP

III. MATHEMATICAL ANALYSIS

By using the Experimental values of temperatures & pressures at different points which is measured by using T-type thermocouples and Borden pressure gauges in the cycle, calculated the performance parameters with the help of P-H chart of the Refrigerant R-134a,

1. The power supplied to run the compressor

P = VI ----------- (3.1)

2. Work of compressor required

$(\mathrm{W_{Comp}}) = m_r(h_2 - h_1)\mathrm{kJ/kg}$-------- (3.2)

3. Amount of Heat Rejected by the condenser

$Q_R = m_r(h_2 - h_3)kJ/kg$-------- (3.3)

4. Work done by the Expansion value (Capillary) is Zero

i.e. $h_3=h_4$------------- (3.4)

5. Amount of Heat Absorbed from space to sored (R.E)

$Q_A = m_r(h_1 - h_4)\ \ kJ/kg$---- (3.5)

6. Co-efficient of performance (Cop), which is defined as the ratio of Refrigeration Effect to the work required to run compressor.

$$COP = \frac{Refrigeration\ Effect}{Compressor\ Work}$$

$COP = \frac{Q_A}{W_C} = \frac{m_r(h_1-h_4)}{m_r(h_2-h_1)}$--------------------- (3.6)

7. Capacity of VCR System (TR) $= \frac{R.E\,/\,min}{210}$---- (3.7)

(One TR – 210 KJ/min)

8. Mass flow rate $(m_r) = \frac{Refrigeration\ effect/sec}{h_1-h_4}$ ------- (3.8)

A. Specifications of Refrigerant R-134a:

S.No.	Properties	R-134a
1.	Boiling Point	-26.3^0c.
2.	Freezing point	-103.3^0c
3.	Critical density	515.3 kg/m^3
4.	Critical Temp	213.9^0c
5.	Heat Capacity (Liquid)	1.44 kj/kgk
6.	Heat capacity (Vapour)	0.85 kj/kgk.
7.	O.D.P	0
8.	G.W.P	1200
9.	Auto ignition temperature	770 ^{O}C

Table 1: Specifications of Refrigerant R-134a

IV. DESIGN & PERFORMANCE OF HEAT EXCHANGER

Heat Exchanges are devices which are used for the process of heat exchanging between two fluids those are at different temperature levels .These are installed at different applications with different capacity like power plants ,food processing units ,refrigeration and air conditioning, chemical industries and space, aeronautical applications. In heat exchanges two fluids are flowing in shell side and tube side.(which are hot and cold fluids).When the two fluids are flows in same direction is called as co-current flow Heat exchanges, similarly the flow of fluids in opposite direction is called counter flow heat exchanger.

In this experiment tube - in - tube heat exchangers is employed with counter flow between compressor and condenser .The heat exchange process takes place between out let of compressor and outlet of evaporator as shown in above figure because the temperature difference between these two fluids are high so the heat exchanges process occurred.

High temperature refrigerant (or) super heater vapor

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refrigerant flowing through tube side and low temperature liquid refrigerant flowing through shell side. The temperature differences between these fluids were measured by using T-type thermocouples .The heat transfer rate(Q), over all heat transfer co-efficient(U) and the effectiveness of heat exchanger (Ɛ) which measured as the ratio of actual heat transfer to the maximum possible heat transfer between fluids were computed.

A. Specifications of heat exchanger:

1. Material used for inner tube = copper

(Thermal conductivity of copper K=388W/m ^{0}C)

Inner diameter (di) = 5.74 mm

Outer diameter (d_o) = 6.35 mm

2. Material used for outer tube = copper

Inner diameter (D_I) = 12mm

Outer diameter (D_O) = 12.7mm

3. Length of heat exchanger (L) = 350mm

4. Specific heat of liquid refrigerant (cp_l) = 1.44 Kj/kgk

5. Specific heat of vapor refrigerant (cp_v) = 0.85 Kj/kgk

B. Formulas and calculations of performance parameters:

1. Log mean temperature difference (LMTD):

LMTD = $\dfrac{Ti-To}{\ln\left(\dfrac{Ti}{To}\right)} = 15.1593^0 c$

Ti = $Th_i - Tc_o$ = (37.2-24.8) = 12.4^{0}c.

To = $Th_o - Tc_i$ = (32.4 – 14.1) = 18.3^{0}c.

Where,

Th_i = is hot fluid inlet temperature = 37.2 ^{0}C

Th_o = is hot fluid outlet temperature = 32.4^{0}C

Tc_i = is cold fluid inlet temperature = 14.1^{0}C

Tco = is cold fluid outlet temperature = 24.8^{0}C

2. Heat gained by cold fluid (Q_C)= m_c Cp_c (Tc_o – Tc_i)

Where,

m_c = Mass flow rate of cold fluid =0.016 kg/sec

Cp_c = specific heat of cold fluid=1.44 Kj/kgk

Tc_i = cold fluid for inlet temperature= 14.1^{0}C

Tc_o = cold fluid for outlet temperature=24.8^{0}C

Q_C= 0.016*1.44 (24.8-14.1) = 0.02304(10.7)

=0.2465KW

3. Heat lost by hot fluid(Q_h)= m_h Cp_h(Th_i – Th_o)

Where,

M_h =Mass flow rate of hot fluid = 0.016 Kg /sec

Cp_h = specific heat of hot fluid= 0.85 Kj/kgk

Th_i = Hot fluid for inlet temperature=37.2^{0}C

Th_o =Hot fluid for inlet temperature=32.4^{0}C

Heat lost by hot fluid (Q_h) = 0.016*0.85(37.2-32.4)

= 0.0136(4.8)

= 0.06528 KW

4. Average heat transfer (Q)

$$Q = \frac{Q_h + Q_c}{2} = \frac{0.06528 + 0.2465}{2} = \frac{0.31178}{2} = 0.15589KW$$

5. Overall heat transfer co-efficient based on inner surface area (U_i)

Q = U_iA_i (LMTD)

$$U_i = \frac{Q}{A_i(LMTD)}$$

Where,

A_i = inner surface area of inner pipe= $\pi.diL = 6.311x10^{-3}m^2$

L = Length of heat exchanger= 350x 10^{-3}m

d_i =Inner diameter of pipe= 5.74 x 10^{-3} m

Q=Average heat transfer=0.15589=155.89w

$$U_i = \frac{155.89}{(6.211\times10^{-3})\times(15.1593)} = 1629.44 \text{ W/m2 K.}$$

6. Overall heat transfer co-efficient based on outer surface area (U_0)

Q = U_0 A_0 (LMTD)

Where,

A_0 =outer surface area of pipe= π d_0 L= 695x10^{-3} m^2

L=Length of pipe= 350x10^{-3} m

d_0 =Outer diameter of pipe= 6.35 x 10^{-3} m

Q=Average heat transfer=155.89W

$$U_0 = \frac{Q}{A_0(LMTD)} = \frac{155.89}{(6.952\times10^{-3})\times(15.159)} = 1472.8419$$

W/m2 K.

7. Effectiveness (ε)

$$\varepsilon = \frac{Q}{Qmax} = \frac{155.89}{314.16} = 0.4962 = 0.5$$

Qmax = Cmin (Th_i – Tc_i)

Cmin = m_h Cp_h (or) m_cCp_c (which is minimum).

V. RESULTS &DISCUSSION

The main aim of constructing a test rig is to check the novel use of tube- in- tube Heat Exchanger between the compressor and condenser in vapour compression refrigeration systems and the performance will be compared with the conventional domestic VCR system. The test rig was used to measure the coefficient of performance and power consumption to run the compressor compared with conventional system.

In conventional vapour compression Refrigeration system showed similar performance by changing of heat exchanger. For improving the system groups of criterions were performed as follows:

1. The refrigerant inlet and outlet temperatures of compressor, Condenser, expansion -valve and evaporation.

2. The refrigerant inlet and outlet temperatures flowing through Heat Exchanger.

3. The refrigerant pressure in the compressor (suction pressure) and condenser pressure (Delivery pressure).

Figure: 3 Experimental test rig.

A. Performance parameters of conventional VCR:

S.no	Suction pressure(psi) (P_1=P_4)	Delivery pressure(psi) (P_2=P_3)	Time (Sec)	T_1 (^OC)	T_2 (^OC)	T_3 (^OC)	T_4 (^OC)	T_5 (^OC)	COP
1	18	250	900	21.6	34.0	29.4	18.1	23.7	2.63
2	17	250	1800	20.6	34.2	29.3	17.1	18.8	2.55
3	17	250	2700	20.6	34.1	29.3	16.8	16.2	2.67
4	17	250	3600	20.6	34.1	29.3	16.1	13.6	2.70

Table 2: Performance parameters of conventional VCR

T1 = Evaporator Outlet temperature.

T2 =Compressor outlet temperature.

T3 =Condenser outlet temperature.

T4 = Evaporator inlet temperature.

T5 = Cabin temperature.

Power required to run compressor (P) = voltage * current = 220 * 1 =220 Watts.

B. Performance parameters of conventional VCR with incorporation of heat exchanger:

S.no	Suction pressure(psi) (p_1=p_4)	Delivery pressure(psi) (P_2=P_3)	Time (sec)	T_1 (^OC)	T_2 (^OC)	T_3 (^OC)	T_4 (^OC)	T_5 (^OC)	T_6 (^OC)	T_7 (^OC)	COP
1	18	250	900	15.2	23.1	35.2	32.5	26.6	13.4	23.6	2.89
2	17	250	1800	15.1	25.2	36.7	32.9	26.3	13.0	19.8	2.95
3	17	250	2700	14.8	25.0	37.0	32.2	26.3	11.9	16.6	2.95
4	17	250	3600	14.1	24.8	37.2	32.4	26.1	11.8	13.8	2.97

Table 3: Performance parameters of Conventional VCR with heat exchanger.

T1 = Evaporator Outlet temperature.

T2 = Compressor inlet temperature.

T3 = compressor outlet temperature.

T4 = condenser inlet temperature.

T5 = Condenser outlet temperature.

T6 = inlet to evaporator.

T7 = cabin temperature.

Power required to run compressor (P) = voltage * current = 160* 1 =160 Watts

C. Comparison of COP and Power consumption of both conventional VCR and conventional VCR with incorporation of heat exchanger:

S.no.	Parameters	Conventional VCR	Modified VCR	% Improved
1	Inlet temperature to compressor	20.2	24.8	22%
2.	Inlet temperature to condenser	34.1	32.4	5%
3.	Degree of Sub Cooling	0	4.6^{0}c	-
4.	Degree of super heating	0	2^{0}c	-
5.	Cop	2.7	2.9705	14%
6.	Power to compressor	220v	160v	27%

Table 4: Comparison of COP and power consumption to run the system.

D. Variation in temperatures due to incorporation of heat exchanger in conventional VCR:

Figure 4 explores the difference in inlet temperatures of compressor and condenser of both conventional VCR system and conventional VCR system with Heat Exchanger. The results shows that the inlet temperatures of compressor and condenser varied from 20.6 ^{O}C to 24.8 ^{O}C and 34.1 ^{O}C to 32.2 ^{O}C due to incorporation of heat exchanger i.e. the inlet temperature of conventional VCR with heat exchanger is improved when compared with regular VCR system. Similarly the condenser inlet temperature of conventional VCR system with heat exchanger is reduced when compared with simple conventional VCR system.

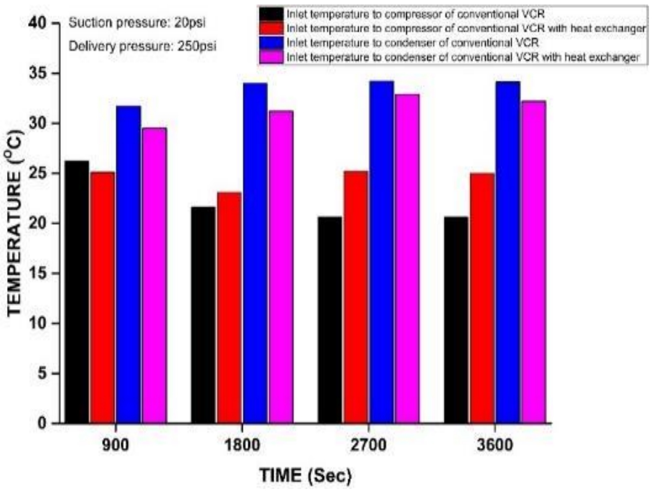

Figure 4: Variation in temperatures due to incorporation of heat exchanger in conventional VCR.

E. Effect of sub cooling temperature on performance of VCR system:

Figure 5 represents effect of sub-cooling temperature to condenser on performance of vapor compression refrigeration system with employing the Heat Exchanger. Which shows that the coefficient of performance (cop) increases with the increase in sub cooling temperature but the sub-cooling temperature increases with respect to effectiveness of Heat Exchanger i.e. pre-cooling temperature of condenser reaches maximum when effectiveness of Heat Exchanger reaches maximum respectively.

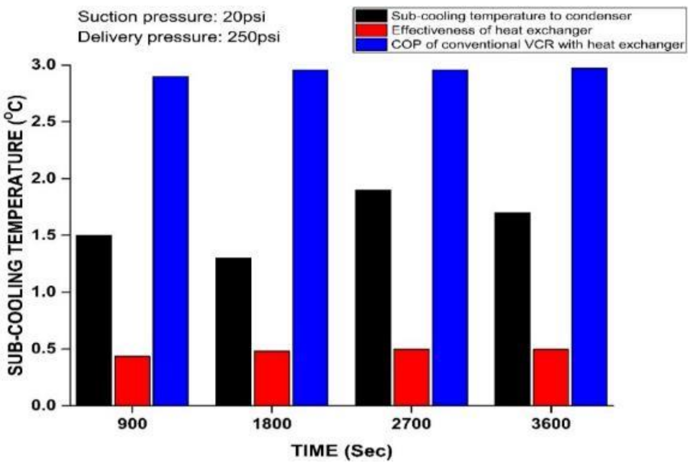

Figure 5: Effect of sub cooling temperature on performance of VCR system.

F. Effect of super heating temperature to compressor on performance of VCR system:

Figure 6 explores the effect of super heating temperature to compressor on performance of conventional VCR system with tube-in-tube Heat Exchanger. The result of Increasing super heating temperature shows that maximum co-efficient of performance (Cop) when compared with the normal conventional VCR System and effectiveness of heat exchanger also directly proportional to the super heating temperature i.e. degree of super heating increases with respect to increase effectiveness of Heat exchanger, finally degree of super heating improved 4.6^{O}C compared with the conventional VCR system.

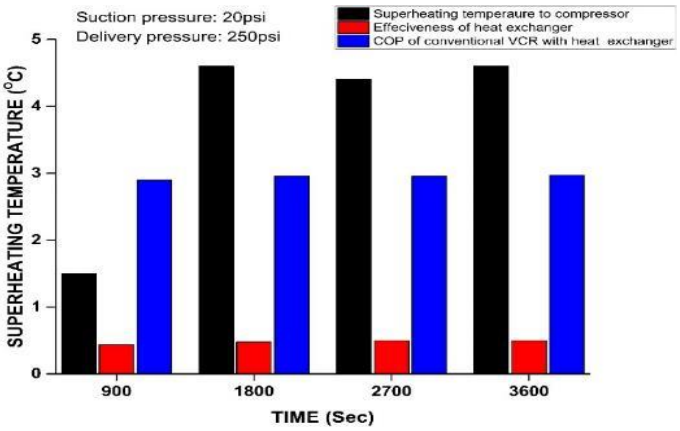

Figure 6: Effect of super heating temperature to compressor on performance of VCR system.

G. Comparison of cop of conventional VCR and conventional VCR with heat exchanger:

Figure 7 reveals the comparison of co-efficient of performance of both conventional VCR and conventional VCR with tube-in- tube Heat Exchanger. The result shows that the cop of experimental VCR improved 14% when compared with normal conventional VCR System i.e. the Cop of normal VCR System 2.7 and the conventional VCR System with heat exchanger reached maximum value of 2.97 which is higher than conventional VCR System.

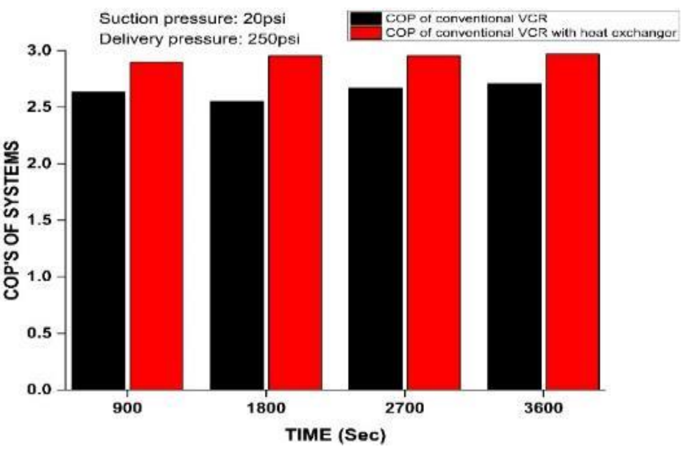

Figure 7: Comparison of cop of conventional VCR and conventional VCR with heat exchanger

H. Comparison of power consumption of conventional VCR and conventional VCR with heat exchanger:

Figure 8 represents the relative comparison of power consumption to run the compressor of both domestic VCR System and domestic VCR System with tube-in-tube Heat Exchanger. The results shows power requirement reduced from 220 Watts to 160 Watts when providing Heat Exchanger between compressor and condenser to exchange the heat between evaporator outlet and compressor outlet i.e. power consumption reduced to 27 % when compared with normal convention VCR System.

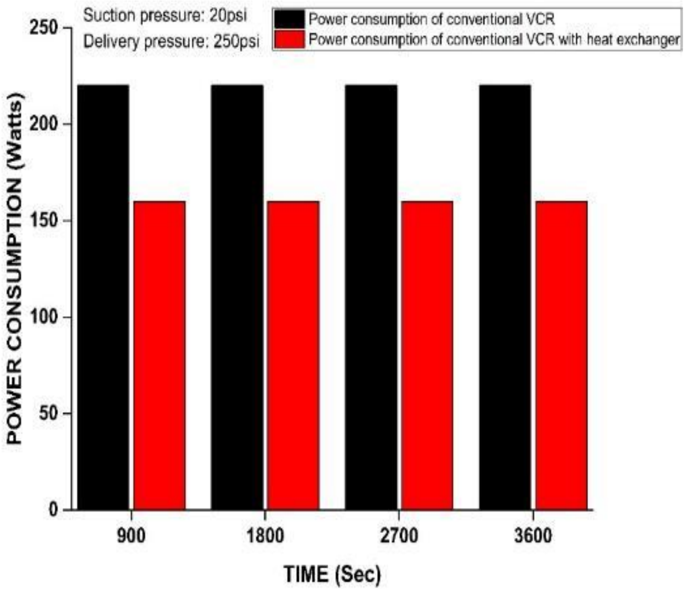

Figure 8: Comparison of power consumption of conventional VCR and conventional VCR with heat exchanger

VI. CONCLUSION

The experimental study on performance of domestic vapor compression refrigeration system introduced with tube - in – tube Heat exchanger shows the better performance compared with conventional VCR system. The superheated vapor coming out from compressor is sub-cooled by 5-6 ^{O}C Before entering into condenser and out let of evaporator is superheated by 8-10^{O}C by exchanging heat with outlet of compressor leads to increase in cop of system and refrigeration effect and reduction in power required to run the compressor. Which conclude that sub-cooling of refrigerant will give the maximum performance than conventional vapor compression refrigeration system. So which suggested to improve the performance of house -hold refrigerator.

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