DESIGN AND ANALYSIS OF LIQUID SUCTION HEAT EXCHANGER IN A VAPOUR COMPRESSION REFRIGERATION SYSTEM

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Abstract - *Performance enhancement of the vapour compression refrigeration systems to gain better refrigerating effect and COP is the current need. This study investigates the effect of adding a liquid-suction heat exchanger on the performance of a vapour compression refrigeration system using R134a. In this application the liquid line is usually placed in contact with the suction line, forming a counter flow heat exchanger. The liquid line is welded to the suction line in the lateral configuration. The temperature of the vapour refrigerant coming out from the evaporator is less than the temperature of the liquid coming out from the condenser. Before the expansion process, heat is transferred from the liquid line to the suction line. As a consequence this in turn reduces the refrigerant quality at the inlet of the evaporator and therefore increases the refrigerating capacity. The LSHE is designed using SOLIDWORKS software for the VCR system and the design is based on the rate of sub-cooling and super-heating. Next to that an analysis is done using ANSYS WORKBENCH on the stream of ANSYS fluent simulation on LSHE to analyze the temperature distribution and velocity of fluid flow. The results revealed that the liquid- suction heat exchanger has a significant effect on the system performance as it influences the sub-cooling and super-heating temperatures. A theoretical analysis has been carried out on the effect of liquid suction heat exchanger on the cooling performance of VCR system. The main objective of this project is to evaluate the performance of modified system with liquid-suction heat exchanger and system without liquid-suction heat exchanger by using R134a and compare their performance improvement with the existing system.*

***Key Words*:** *LSHE, R134a, ANSYS WORKBENCH, SOLIDWORKS, VCR system, performance improvement.*

1. INTRODUCTION

Vapour compression Refrigeration system is an improved type of air refrigeration system. The ability of certain liquids to absorb enormous quantities of heat as they vaporize is the basis of this system. Compared to melting solids (say ice) to obtain refrigeration effect, vaporizing liquid refrigerant has more advantages. To mention a few, the refrigerating effect can be started or stopped at will, the rate of cooling can be predetermined, the vaporizing temperatures can be governed by controlling the pressure at which the liquid vaporizes. Moreover, the vapour can be readily collected and condensed back into liquid state so that same liquid can be re-circulated over and over again to obtain refrigeration effect. Thus the vapour compression system employs a liquid refrigerant which evaporates and condenses readily. The System is a closed one since the refrigerant never leaves the system. The coefficient of performance of a refrigeration system is the ratio of refrigerating effect to the compression work; therefore the coefficient of performance can be increased by increasing the refrigerating effect or by decreasing the compression work. The

Vapour compression refrigeration system is now- a-days used for all purpose refrigeration. It is generally used for all industrial purposes from a small domestic refrigerator to a big air-conditioning plant.

1.1 METHODS OF ENERGY SAVING IN REFRIGERATION SYSTEM

There are many methods of energy savings in the refrigeration systems, from simple to complex methods. There are four methods of savings in the refrigeration systems are:

1. Liquid Suction Heat Exchanger (LSHX)
2. Dedicated Mechanical Sub-Cooling (DMS)
3. Integrated Mechanical Sub-Cooling (IMS)
4. Condensate Assisted Sub-Cooling (CAS)

It is one of the simple methods that can be used to increase the cooling capacity (CC) of refrigeration systems. By increasing the CC improves the COP of the systems.

2 .OBJECTIVE OF THE STUDY

Many experimental and theoretical studies have been reported for the improvement in the performance of the vapour compression refrigeration system ranging from simple to complex. Methods such as using a sub-cooler, inverter, ejector as an expansion device, and using Nano-particle in compressor lubricant or in refrigerant are in research. In this project, by using a liquid suction heat exchanger, the performance of a vapour compression refrigeration system is theoretically analyzed.

2.1 PROBLEM STATEMENT

The problems statement describes the existing difficulties in the vapour compression refrigeration system as follows:

- COP is less and power consumption is comparatively higher which results in excess energy consumption.
- It is difficult to control the single phase vapour to the compressor.
- The formation of flash gas at the inlet of the expansion device may occur frequently.

2.2 AIM OF LIQUID SUCTION HEAT EXCHANGER IN THE VCR SYSTEM

Among many possible variations of the basic refrigeration cycle, the cycle with the Liquid Suction Heat Exchanger (LSHE) is probably used most often. Liquid Suction Heat Exchanger is introduced in the vapour compression refrigeration system for the following reasons:

- To improve the performance (COP) of the system.
- To prevent the formation of flash gas at the valve hole to the expansion device.
- The remaining liquid is fully evaporated in the liquid-suction before reaching compressor.
- The high pressure refrigerant is sub cooled at the expense of superheating the vapour entering the compressor.
- It may often employ for protecting system components.
- It helps to ensure the single-phase liquid to the expansion device and single phase vapour to the compressor.
- In residential refrigerators, it is used to heat the suction line above the dew-point temperature of ambient air, thus preventing condensation of the water vapour on the outside of the water vapour on the outside of the suction line.
- Employing an intra-cycle heat exchanger alters refrigerant thermodynamic states in the cycle, which may have significant (positive or negative) performance implications.
- For any fluid and system, an LSHX increases refrigerant temperature at the compressor inlet and outlet, i.e. short coming.
- The volumetric capacity may increase for some fluid application combinations, while for others they may decrease.

3. LITERATURE REVIEW

[1] Domanski et al-Numerically investigated the performance of 38 different VCRC refrigerants that use LSHX. They reported that refrigerants with low vapor molar heat capacity did not improve the COP as compared to basic cycle (without sub-cooling) when LSHX was applied. They also reported that by using refrigerants with very low heat capacity, the COP of the system decreased when the LSHX was applied.

[2] Klein et al-Introduced a relative capacity change index (RCI) formula to calculate the CC improvement of using LSHX. The correlation between RCI and the effectiveness of heat exchanger, where the effectiveness can be defined as the ratio of actual to maximum possible heat transfer in the heat exchanger. It shows that by applying LSHX in VCRC with eleven refrigerants, three refrigerants decrease their CC, namely R22, R32 and R717; and the other eight refrigerants increase their CC.

[3] Navarro-Esbri et al-Experimentally investigated the effect of sub- cooling using LSHX in VCRC by using R22, R134a and R407C as working fluids. Besides studying the influence of sub-cooling on the performance, they also investigated the impact of mass flow rate. Experimental results showed that the mass flow rate reduction occurred for R22 and R134a refrigerants when LSHX was applied. However, although the mass flow rate decreased, the COP did not decrease because the increment of cooling capacity by using LSHX was slightly higher than the mass flow rate. Different results were exhibited by R407C, in which the mass flow rate and cooling capacity increased. As a result, the COP improvement of R407C was the highest for the compression ratio below 5.

[4] Mastrullo et al-Numerically investigated the advantage of applying LSHX in VCRS. They investigated 19 ozone friendly refrigerants in their study and varied the evaporating and condensing temperatures. They introduced a simple chart that allows the estimation of the effectiveness of using LSHX in the VCRC for various working fluids and specified operating conditions. For example, for a system using R22 as working fluid for evaporating and condensing temperatures of -20ºC and 45 ºC, respectively, the point from these conditions is above the curve of R22. As a result, the use of LSHX improves the system performance. However, if the point from the two conditions (evaporating and condensing temperatures) is below the curve, the benefit of using LSHX disappears. They also found that the advantage of LSHX depends on the combination and operating conditions. The author also highlighted the effect of ambient temperature on discharge temperature, compressor work and percentage improvement in COP. The effectiveness of LSHX increases with an increase in ambient temperature.

[5] Later, Potter and Hrnjak-Carried out an extension experimental investigation to study the effect of sub cooling on various parameters in the air conditioning system using R134a and R1234yf. The parameters of the air conditioner being studied included isentropic efficiency, compression ratio, condenser pressure drop, suction line pressure drop, saturation temperatures at the evaporator exit and compressor inlet and COP. The experimental results showed that the presence of LSHX in the air conditioner increased the COP up to 18% and 9% for R1234yf and R134a, respectively. The results also showed that there were changes in some parameters due to the presence of sub-cooler using LSHX. Because of COP is the ratio of CC to compressor power, as a result the increase in COP depends on their increments. Most working fluid generate COP improvement of the system when the LSHX sub-cooling is applied, and only few refrigerants (R717, R32 and R407C) showed COP reduction when using LSHX sub- cooling.

[6] B.O. Bolaji, M.A. Akintunde and T.O. Falade-Selected five environment-friendly refrigerants (R23, R32, R134a, R143a and R152a) and investigated theoretically their performance in a liquid suction heat exchanger refrigeration system. The liquid suction heat exchanger was used to evaluate the impact of selected refrigerants on the exchanger effectiveness, system capacity and coefficient of performance (COP) and found that the relationship between relative capacity index and sub-cooling heat exchanger effectiveness was nearly linear were as the refrigerant flow rate decreases with the increasing effectiveness of the heat exchanger. They also presented the chart for evaluating the possible thermodynamic advantage of adopting a liquid suction heat exchanger.

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4. METHODOLOGY

The methodology provides us the sequence operations carried out in this project by chronological order.

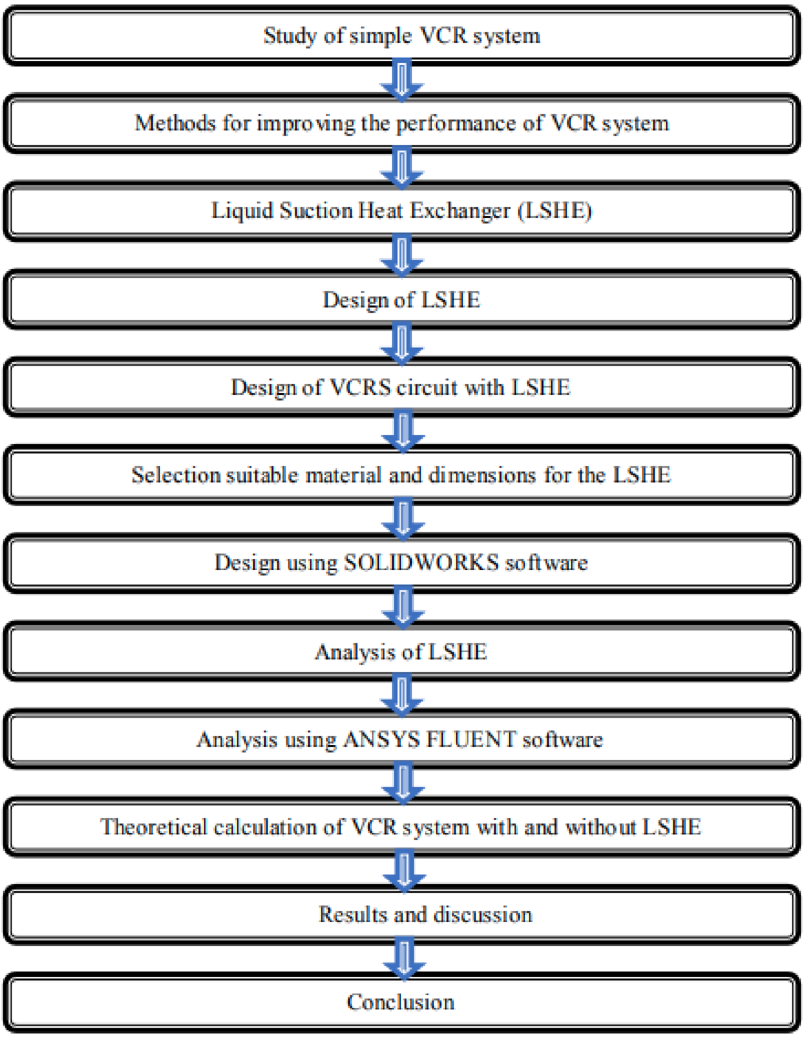


Fig.1.1 Methodology

5. DESIGN OF HEAT EXCHANGER

- A LSHE is a counter flow heat exchanger in which the warm refrigerant liquid from the condenser exchanges heat with the cool refrigerant vapour from the evaporator.
- Required degree of sub-cooling and superheating may not be possible, if one were to rely only on heat transfer between the refrigerant and external heat source.
- In the present works the copper is selected for both liquid and suction line of the heat exchanger because maximum heat transfer and make the fabrication process quite easy i.e. joining of same materials by gas welding.

Fig.1.2 Liquid Suction Heat Exchanger

5.1 DESIGN OF LSHE CIRCUIT

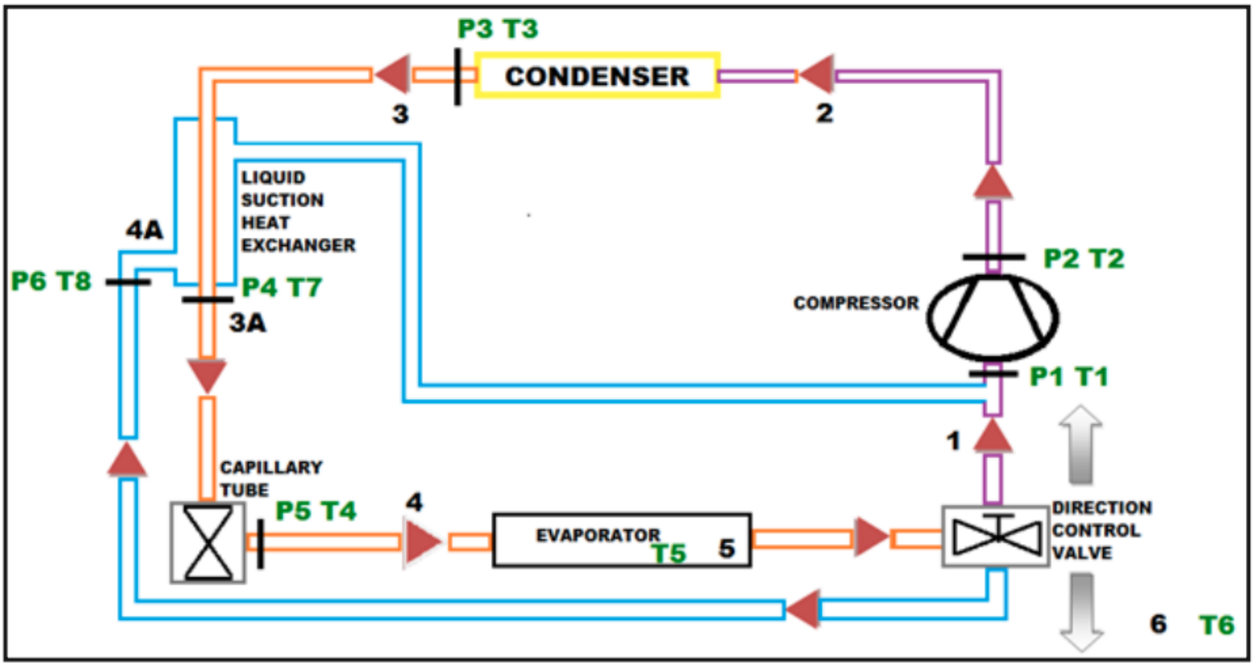


Fig.1.3 Circuit diagram of VCRS with LSHE

5.2 POINTS AND PROCESS OF VCRS WITH LSHE CIRCUIT

VCRS WITHOUT HEAT EXCHANGER			VCRS WITH HEAT EXCHANGER*
Temperature Indications	T1	-	Compressor inlet /Cold fluid outlet*
	T2	-	Compressor outlet
	T3	-	Condenser outlet / Hot fluid inlet*
	T4	-	Expansion outlet
	T5	-	Chiller temperature
	T6	-	Surrounding air
	T7=T3A*	-	Hot fluid outlet*
	T8=T4A*	-	Cold fluid inlet*
Pressure Indications	P1	-	Before compression /Cold fluid outlet pressure*
	P2	-	After compression
	P3*	-	Hot fluid inlet pressure*
	P4=P3A*	-	Before expansion /Hot fluid outlet pressure*
	P5	-	After expansion
	P6=P4A*	-	Cold fluid inlet pressure*

Table 1.1 Points of VCRS with and without LSHE

VCRS WITHOUT HEAT EXCHANGER		VCRS WITH HEAT EXCHANGER*	
Process - 1-2-3-4-1		**Process - 1-2-3-3A-4-4A-1***	
1-2	Isentropic Compression	1-2	Isentropic Compression
2-3	Constant pressure heat rejection	2-3	Constant pressure heat rejection
		3-3A	Sub-cooling
3-4	Throttling process	3A-4	Throttling process
4-1	Constant pressure heat addition	4-4A	Constant pressure heat addition
		4A-1	Superheating

Table 1.2 Process of VCRS with and without LSHE

5.3 SPECIFICATIONS OF DOMESTIC REFRIGERATOR

The domestic refrigerator selected for the project has the following specifications:

1.Compressor:			Dimensions	:	120x120x38 mm
Type	:	Hermetically Sealed Compressor	Metal body	:	4.5 inches
Compression level	:	Single-stage	Weight	:	250 grams
Refrigerant	:	Freon (R134a)	Coil length	:	0.96 m
Cylinder position	:	Vertical	Coil diameter	:	5 mm
Cooling type	:	Air	**3.Capillary Tube:**		
Lubrication	:	Oil	Coil diameter	:	2.5 mm
Voltage	:	220-240V / 50-60Hz	Length	:	185 cm
Motor type	:	CSIR	**4.Evaporator:**		
Starting capacitor	:	80UF	Type	:	Cylindrical
Power	:	1168 W / 1.5 HP	Radius	:	0.1 m
Displacement	:	12 cm^3	Height	:	0.2 m
2.Condenser:			Fluid used	:	Water
Cooling medium	:	Fan	Density of the fluid	:	1000 kg/m^3
Power source	:	AC / 220V	Capacity	:	6.28 kg

Table 1.3 Specification of VCR system

5.4 RATE OF SUPERHEATING AND SUBCOOLING

The rate of superheating and sub-cooling for the existing vapour compression refrigeration system is fixed as 5°C and 3°C. It is taken based the following performance parameters as follows:

- ❖ The work of compression is decreased drastically above the fixed level of superheating and sub-cooling.
- ❖ The theoretical power of the compressor is decreased drastically above the fixed level of superheating and sub-cooling.
- ❖ The suction temperature of the compressor is too high to the normal operating condition.
- ❖ The inner parts of the compressor may affect due to friction and it reduce the life of the compressor.
- ❖ At the certain range the performance the VCR system doesn't increases it remains constant or decreases.

5.5 CALCULATION FOR THE DESIGN OF LSHE

The following parameters are calculated for the selection of suitable dimensions and design of liquid suction heat exchanger.

❖ **HEAT TRANSFER**

- Heat transfer in hot fluid flow:

  $Qh = m_h \times C_{ph} \times (T_{hi} - T_{ho}) = 0.1 \times 1500 \times (48 - 45) = 450W$

- Heat transfer in cold fluid flow:

  $Qc = m_c \times C_{pc} \times (T_{co} - T_{ci}) = 0.1 \times 820 \times (25 - 20) = 410W$

- Heat transfer:

  $Q = (Q_h + Q_c) / 2 = 430$ W

❖ **OVERALL HEAT TRANSFER COEFFICIENT (U)**

- $U = Q / (a \, x \, lmtd) = 430 / (0.0942 \, x \, 24) = 190.2$ W/ m^2.K

❖ **PRESSURE DROP IN LSHE**

- $u = q \times A = (1 \times 10^{-4}) \times (0.0942) = 7.85 \times 10^{-9}$ m/sec
- $Dp = (4 \, x \, F \, x \, e \, x \, U^2 \, x \, Nhp) / d_I = (4 \, x \; 4.22 \, x 10^{-3} \, x \, 4.25 \, x \, (0.0249)^2 \, x \, 1) \, 0.01 = 4.45 \times 10^{-3}$ N/m^2

5.6 DIMENSIONS OF THE LSHE

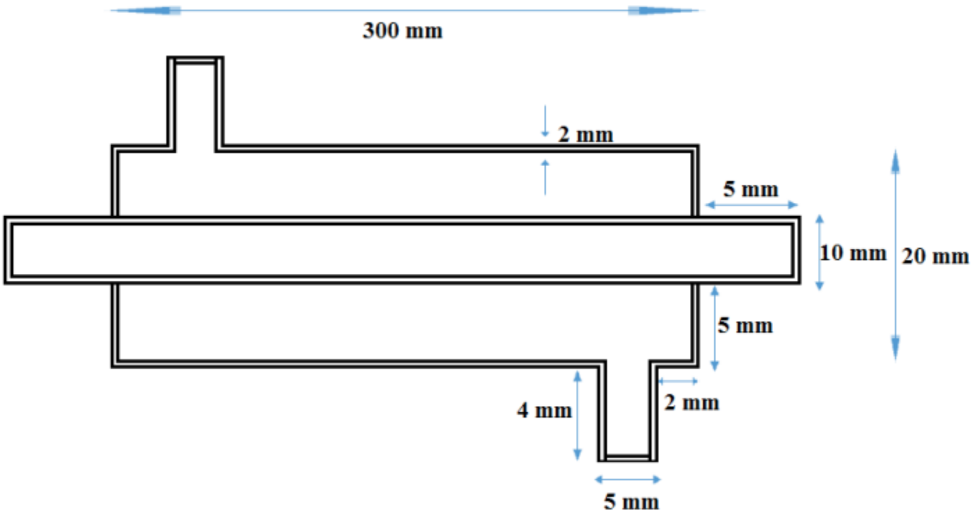


Fig.1.4 Dimensions of the LSHE

5.7 DEIGN OF LSHE USING SOLIDWORKS

The model is designed in the SOLIDWORKS 2021 based on the design calculation of the liquid suction heat exchanger.

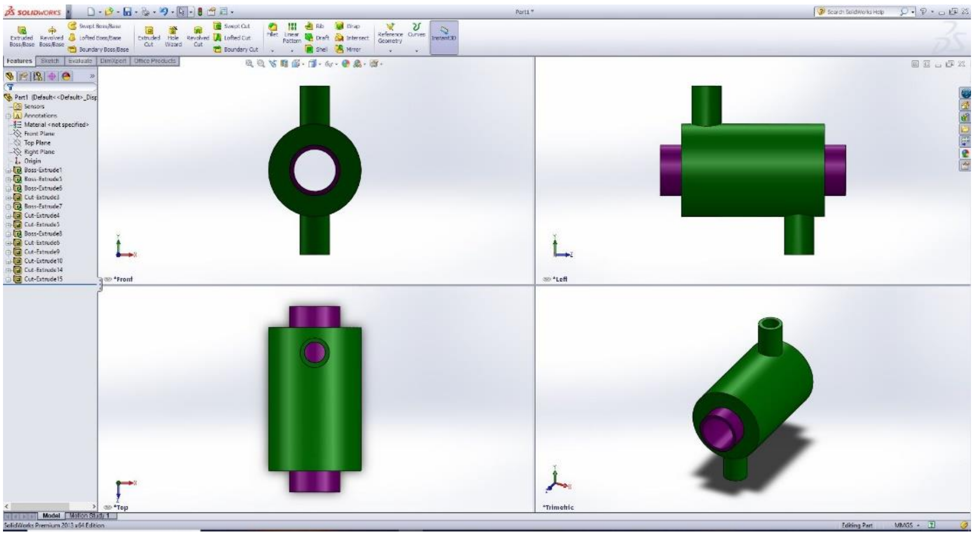


Fig.1.5 Solid model of LHSE in grid view

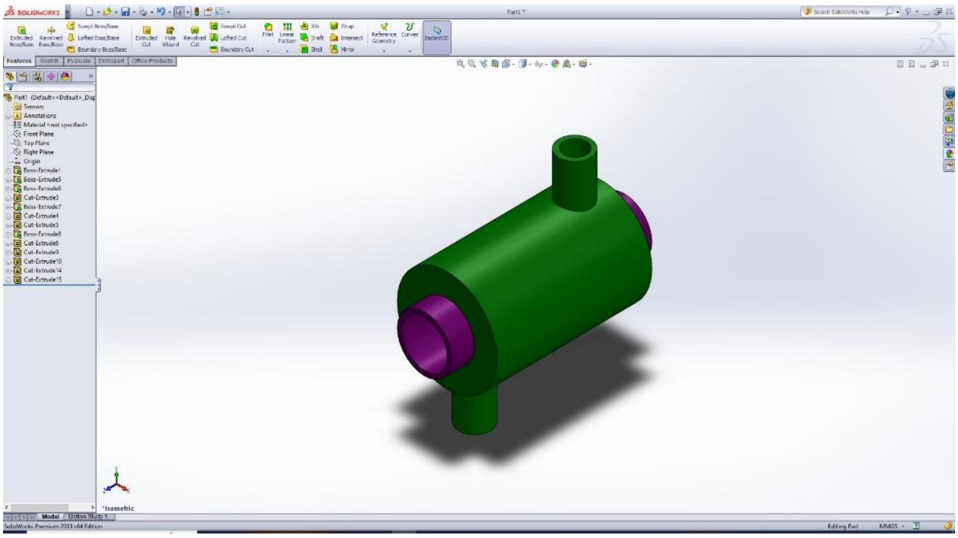


Fig.1.6 Designed model of LHSE

6. ANALYSIS

After designing Liquid suction heat exchanger in ANSYS workbench, we have done the analysis in fluid fluent CFD. The material we have used for the design of pipes is copper. The two fluids used are R134a (liquid) as a hot fluid and R134a (Vapour) as a cold fluid. The inlet temperature of hot fluid is 321K and after it passes through the heat exchanger its temperature at the outlet is 318K. The inlet and outlet temperatures of cold fluids are 293K and 298K respectively. The number iterations for the analysis of fluid flow is taken as 200.The results are given below.

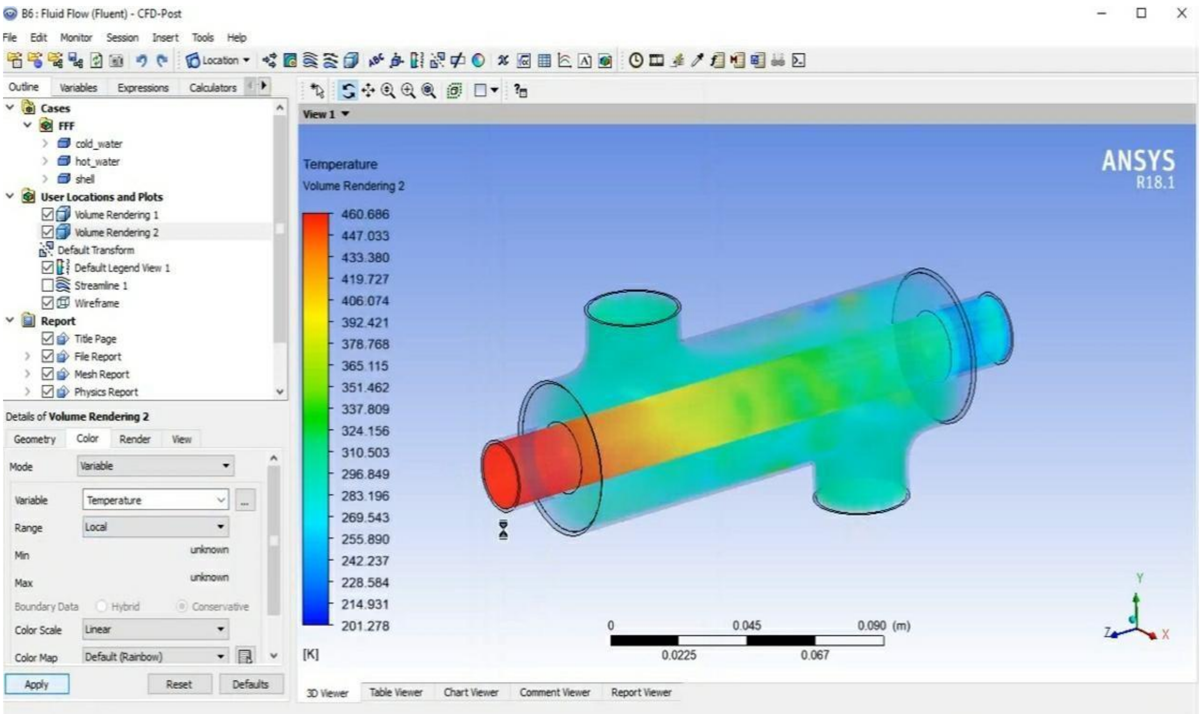


Fig.1.7 Temperature distribution of LSHE

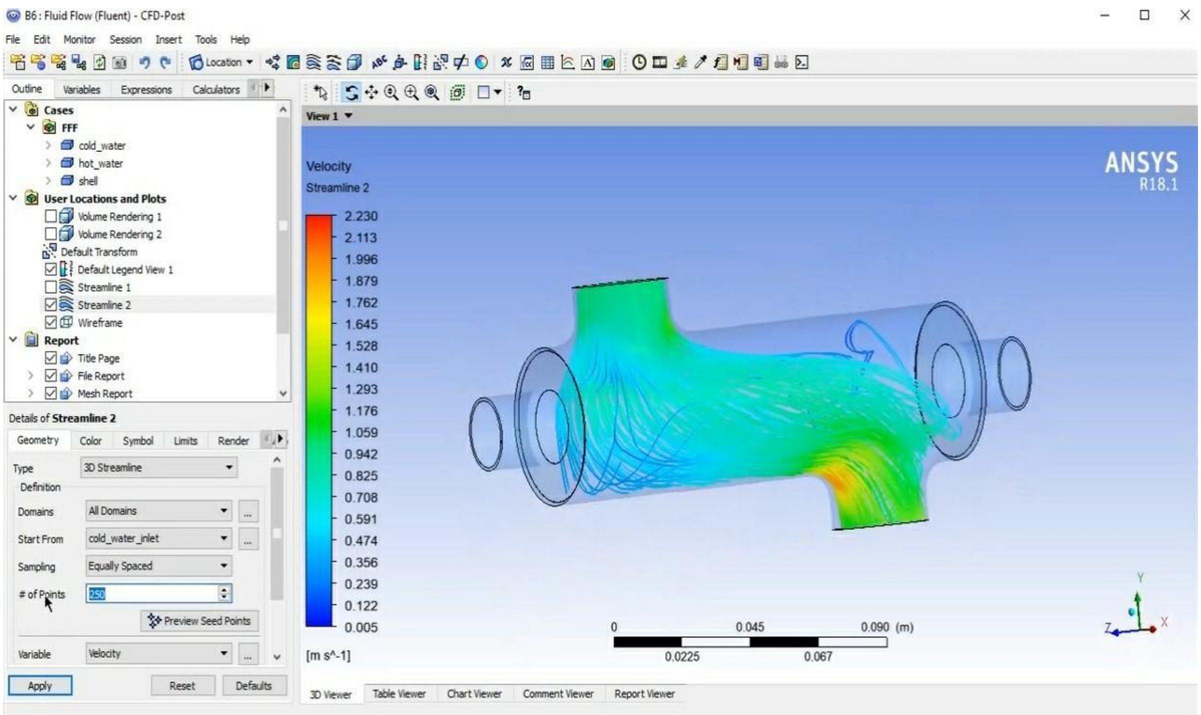


Fig.1.8 Velocity of fluid flow in LSHE

Using CFD methodology, this study explores the heat transfer and flow characteristics of liquid suction heat exchanger for counter flow. The outlet temperature of the fluids depends up on the mass flow rate of both fluids and varies when we alter flow rate. When the area of contact between the fluid and pipe increases heat transfer rate also increases significantly. From this we can observe that heat transfer rate is directly dependent on area through which the fluid flows. Thus from the velocity result above, we can conclude that the velocity of the fluid after the fluid temperature increase is high while the velocity of the fluid is getting low. And the from this we can say velocity and temperature are directly proportional and in our analysis the counter flow gives better heat transfer rate in which the temperature of the hot fluid at the outlet is almost equal to the temperature of the cold fluid at the inlet .

7. THEORETICAL CALCULATION

The temperature, pressure and enthalpy at state points for the VCR systemusing R134a without heat exchanger are taken and given in the following table:

Parameters	Points	Units	VCRS without LSHE	VCRS with LSHE
Compressor suction temperature	T_1	°C	20	25 **(5°C Superheating)**
Compressor discharge Temperature	T_2	°C	59	59
Condenser outlet temperature	T_3	°C	48	48
Expansion outlet temperature	T_4	°C	15	12 **(3°C Sub cooling)**
Evaporator temperature (Initial)	T_{5i}	°C	30	30
Evaporator temperature (Final)	T_{5f}	°C	7.8	4.8
Atmospheric temperature	T_6	°C	25	25
Compressor suction pressure	P_1	bar	1.07	1.03
Compressor discharge pressure	P_2	bar	9.89	9.8
Total running time	Δt	sec	1800	1800
Enthalpy (Using T_1 & P_1)	h_1	kJ/kg	398	403
Enthalpy (Using T_2 & P_2)	h_2	kJ/kg	445	445
Enthalpy (Using T_4 & P_2)	h_3	kJ/kg	225	223
Enthalpy (Using T_4 & P_2)	h_4	kJ/kg	225	223

Table 1.4. Readings of VCR system without heat exchanger

7.1 PERFORMANCE CALCULATIONS

1) Capacity of the evaporator

   r = radius of the evaporator = 0.1m,

   ρ = Density of the water = 1000 kg/m^3,

   H = height of the evaporator = 0.2m

   M = $\pi r^2 \rho h$ = 3.14 x 0.1^2 x 1000 x 0.2 = 6.28 kg

2) Net Refrigeration effect (NRE) = h_1 - h_4 = 398 - 225 = 173 kJ/kg
3) Mass flow rate to obtain one TR (m_r) = 210/ NRE = 210/173 = 1.213 kg/min
4) Work of Compression = h_2 - h_1 = 445 - 398 = 47 kJ/kg
5) Heat Equivalent of work of compression per TR = m_r x (h_2 - h_1) = 1.213 x 47 = 57.011 kJ/min
6) Theoretical power of compressor = 57.011/60 = 0.95 kW
7) Coefficient of Performance (COP) = (h_1 - h_4)/(h_2 - h_1)= 173/47 = 3.68
8) Heat to be rejected in condenser = h_2 - h_3 = 445-225 = 220 kJ/kg
9) Heat Rejection per TR = m_r x (h_2 - h_3) = 1.213 x 220 = 266.86 kJ/min
10) Heat Rejection Ratio = 266.86/210 = 1.27
11) Compression Ratio = P_2/P_1 = 9.89/1.07 = 9.24

8. RESULT AND DISCUSSION

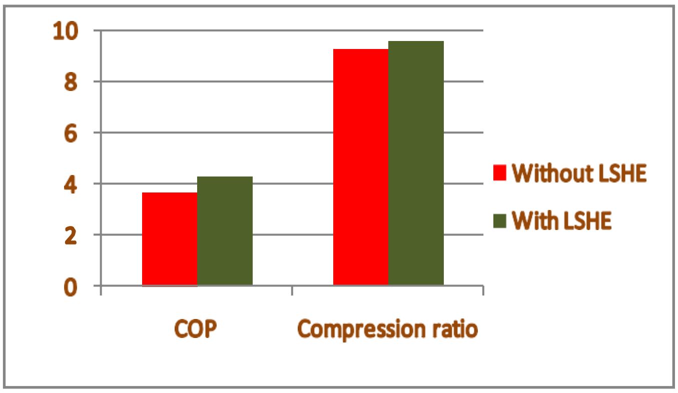
In this study, we compare the performance of the VCR System with and without Liquid Suction Heat Exchanger (LSHE). The following results were obtained from the above analysis:

Sl. No	Parameters	Unit	VCRS without LSHE	VCRS with LSHE	Percentageof Variation	Effect on the Performance	Notations
1.	Net Refrigeration effect (NRE)	kJ/kg	173	180	3.88	Increases	
2.	Mass flow rate to obtain one TR (m_r)	kg/min	1.21	1.16	4.13	Decreases	
3.	Work of Compression	kJ/kg	47	42	10.63	Decreases	
4.	Heat Equivalent of work of compression per TR	kJ/min	57.01	49.01	14	Decreases	
5.	Theoretical power of compressor	kW	0.95	0.81	14.73	Decreases	
6.	Coefficient of Performance (COP)	-	3.68	4.28	14	Increases	
7.	Heat to be rejected in condenser	kJ/kg	220	222	0.9	Increases	
8.	Heat Rejection per TR	kJ/min	266.86	259.07	2.91	Decreases	
9.	Heat Rejection Ratio	-	1.27	1.23	3.14	Decreases	
10.	Compression Ratio	-	9.24	9.51	2.83	Increases	

Table.1.5. Comparison on the results of VCRS with and without LSHE

The results were plotted in the bar chart to understand the comparison between the Vapour Compression Refrigeration System (VCRS) with and without Liquid Suction Heat Exchanger (LSHE).

8.1 EFFECT ON THE COP OF THE SYSTEM

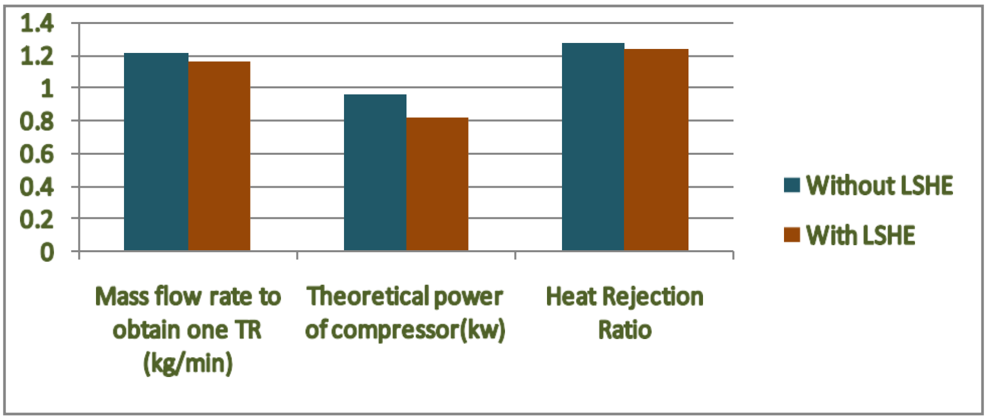


Graph.1.1 Effect on COP of the system with and without LSHE

Referring the graph 1.1 in the present work system with Liquid suction heatexchanger using R134a as a refrigerant,

- There is 14 % increment in COP of the system compared with existingsystem.
- There is 2.83 % increment in compression ratio of the system comparedwith existing system.

8.2 EFFECT ON THE THEORETICAL POWER OF COMPRESSOR

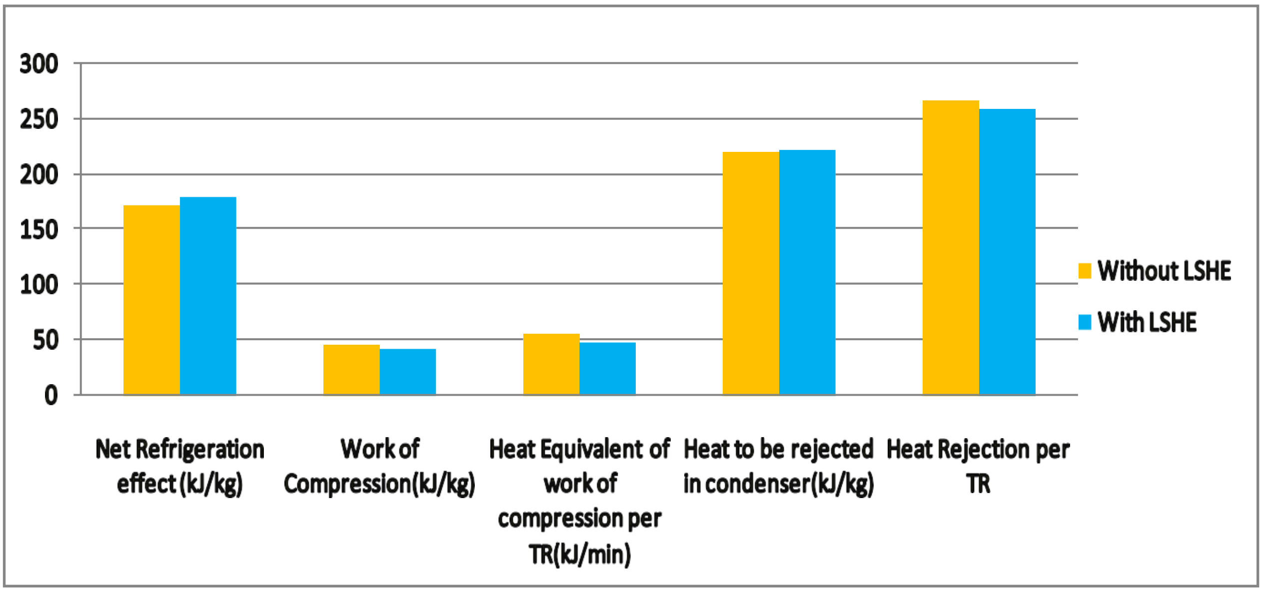


Graph.1.2. Effect on compressor power of the system with and without LSHE

Referring the graph 1.2 in the present work system with Liquid suction heat exchanger using R134a as a refrigerant,

- There is 14.73 % decrement in compressor power compared with existing.
- There is 4.13 % decrement in mass flow rate to obtain one TR (m_r) compared with existing.
- There is 3.14% decrement in heat rejection ratio compared with existing.

8.3 EFFECT ON THE NET REFRIGERATION EFFECT (NRE) ANDWORK OF COMPRESSION:



Graph.1.3 Effect on the Net refrigerating effect of the system with and without LSHE

Referring the graph 1.3 in the present work system with Liquid suction heat exchanger using R134a as a refrigerant,

- There is 3.88% increment in refrigerating effect compared with existing.
- There is 10.63% decrement in compressor work compared with existing.
- There is 2.91% decrement in heat rejection per TR compared with existingsystem.
- There is 0.9% increment in heat to be rejected in the condenser comparedwith existing system.
- There is 14% decrement in heat equivalent of work of compression per TRrejection compared with existing system.

9. CONCLUSION

Due to the increasing demand of refrigerator and the limited energy resources, there is an urgent need of improving the performance of vapour compression refrigeration system. Various methods can be used to improve the performance of the system. In the present work, the Liquid Suction Heat Exchanger (LSHE) method is reviewed as one of the sub-cooling methods. A complete design and analysis of LSHE has been made using SOLIDWORKS and ANSYS workbench based on requirement in the performance improvement in the existing VCR system. Under closer evaluation from the theoretical analysis, it can be summarized that:

- Due to the superheating process, the mass flow rate of refrigerant going into the compressor decreases. But if we assume that the mass flow rate is constant then according to our study, we concluded that on increasing the degree of sub-cooling, the COP of the VCR system is increased by 14 % on installing a liquid suction heat exchanger in case of R-134a refrigerant.
- Although the compressor power is only slightly affected by the change in state ofthe refrigerant entering the compressor, the refrigerant mass flow rate is reduced by 4.13 %.
- It also presented that R134a has high response to increase the refrigerant effect by 3.88 % when the liquid-suction heat exchanger used.
- Minimizes risk of liquid refrigerant presence at the compressor inlet whichincreases compressor life.
- Heat to be rejected in condenser is increased by 0.9 % on installing the LSHE onthe VCR system using R134a.
- The superheating and sub-cooling effects were recorded with high value when the R134a was used in modified and no-modified systems.
- Installation of Liquid Suction Heat exchanger with existing Refrigeration is a very easy process. And costing is very less comparing to improvement in the refrigeration effect.
- But COP does not always increase with the increase in the amount of sub-cooling because a point comes when it attains a maximum value & after that, it decreases due to increase in compressor work but Refrigerating effect continued to be on improving if refrigerant entering condition is maintained the saturated liquid at the entry to the expansion device.

From the above discussions, it can be concluded that the adoption of the liquid suction heat exchanger is a profitable choice and the performance of vapour compression refrigeration system of domestic refrigerator can be increased and the benefits of the LSHE on system performances depend on the combination of operating conditions and fluid properties.

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NOMENCLATURE

d	-	Tube diameter	$\mathbf{N_{hp}}$	-	Number of hairpins
l	-	Length of the tube	**U**	-	Overall heat transfer coefficient
$\mathbf{T_{ho}}$	-	Hot fluid outlet temperature	$\mathbf{C_p}$	-	Specific heat capacity of fluid
$\mathbf{T_{hi}}$	-	Hot fluid inlet temperature	***Q***	-	Heat transfer
$\mathbf{T_{co}}$	-	Cold fluid outlet temperature	**Lmtd**	-	Log mean temperature difference
$\mathbf{T_{ci}}$	-	Cold fluid inlet temperature	**a**	-	Area
e	-	Density of fluid	**U**	-	Mean velocity
u	-	Velocity of fluid	**R**	-	Reynolds's number
m	-	Mass flow rate of fluid	**F**	-	Friction coefficient
q	-	Discharge of fluid	$\mathbf{D_p}$	-	Pressure drop