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Development of the simulation technique for performance estimation of domestic refrigerator

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ABSTRACT

The objective of this paper is to develop simulation technique for refrigerator. It works on the principle of vapor compression refrigeration cycle. R600a is preferable for sealed system. Energy consumption can be reduced by selecting proper equipment's. The total heat load acting on the cabinet is calculated for the selection of system evaporator. Starting from the given load on the refrigeration system the mass flow rate through the system is calculated. This mass flow rate is constant throughout the system. Pressure drop and required length of the condenser and evaporator is calculated by using section by section method and by considering the isentropic efficiency of the compressor the discharge temperature of compressor is calculated. The COP of the system is calculated. For isentropic compression COP is found to be 1.65 and by considering 90% efficiency of the compressor actual COP of the system is 1.48. Stoecker's method is used to calculate the required length of the capillary tube. Mass flow rate vs. length graph of the capillary tube is plotted assuming different test load condition. The length of capillary tube decreases with decreasing the diameter of the tube. Suction line heat exchangers are used for subcooling and superheating of refrigerant

Keywords— **Refrigerator, Heat load calculation, Modelling of basic Components, simulation of refrigerator.**

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I. INTRODUCTION

Domestic Refrigerator and freezer are in the list of maximum energy consumption devices. It works on the principle of VCRS. It has four basic components, i.e. Compressor, condenser, Evaporator, and Expansion valve. Also, some accessories like drier, accumulator, heat loop for proper working of closed circuit. CFCs and HCFCs have excellent thermodynamic and thermo physical properties, but are not environmentally safe. These kinds of refrigerants seriously deplete the Ozone layer in the stratosphere and contribute to the Greenhouse effect. According to Montreal protocol the production of CFC-11 and CFC-12 was completely stopped after 1996.

Halogenated refrigerants cause greenhouse gas emission and in turns contribute significantly to global warming. According to Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) emission of HFCs should be reduced. The advantages of R600a are low critical pressure and high enthalpy difference in two phase zone. Higher the enthalpy difference reduces the mass flow rate per unit cooling capacity. The amount of charge required for R600a is 66% lower than that of R134a[2], which has not only brought the economic advantages but also significantly reduces flammability of hydrocarbon refrigerant.

Evaporator is selected based on the total heat load on the system. Heat load such as thermal wall load, Air change load, Heater load, Water load, Commodity load, infiltration load, fan load etc.H. Karatas, et.al [11] studied air-side heat transfer and pressure drop characteristics of finned-tube refrigerator-freezer evaporators operating under dry surface conditions. Four different evaporator coil were tested for both uniform and nonuniform velocity and temperature inlet conditions of the air flow. Correlations were developed for j and f factor. They observed that a strong dependence of the heat transfer coefficients on the finning factor. Convective heat transfer coefficient increases as the finning factor decreases. They also noticed that the friction factor increases for higher fin spacing values.

Compressor maintain low pressure and temperature at evaporator so that refrigerant can boil init and on the other side of it, which is discharged side, it increases pressure so that refrigerant can condense in the condenser by rejecting heat to the surrounding.Open type compressor gives more efficiency than hermetically sealed type compressor [3].With the open type compressors there is always a possibility of refrigerant leakage since leakages cannot be eliminated completely it require regular maintenance. Regular servicing and maintenance is difficult at small system. Refrigerant leakage problem is not found in hermetic compressor; due to this the hermetic compressors are exclusively used in small capacity systems, these compressors are available for refrigerating capacities ranging from a few watts to kilowatts..

Condensers are the heat exchanger it rejects heat to the surrounding air, which is absorbed by the refrigerant during boiling in the evaporator and due to compressor work. The Condenser should be designed in such a way that it should be capable to reject heat to the surrounding air.P.K. Bansal and Chin[14] developed a simulation model using finite element and variable conductance approach.Nowadays, hot wall condensers are used. P.K. Bansal and T.C.Chin [6] developed a simulation model for hot wall condenser using R134a as refrigerant but did not consider the effect of heat transfer due to Aluminum tape whereas, J.K. Guptaand M. Ram Gopal [7] presented a mathematical model of hot wall condenser In their study, they found that Aluminum tape which is used to stick the condenser tube to outer metal sheet plays important role in heat transfer.

There are different types of expansion devices used in refrigeration system. But selection is based on Application. Capillary tubes are used as an expansion device in most of the small refrigeration system Because of their simplicity and low cost, Capillary tube is a small bore and big length tube. Diameter of Capillary tube varies from 0.4 mm to 2 mm, whereas Length varies from 2 m to 6 m. Another advantage of Capillary tubes are they allowed High and low side pressure equalize during the off cycle. The Capillary tube looks simple in construction, but design and heat transfer characteristic inside the tube are complex. The main concern is to select the appropriate diameter and its length at given capacity and inlet and outlet condition.W.F. Stoecker and J.W. Jones [1] explain the operation of common types of expansion devices. With special emphasis on balanced and unbalanced flow condition occurring between expansion device and compressor. Analytical technique based on fundamental laws is also described. P. K. Bansal and A.S. Rupasinge [12], developed a numerical homogeneous two phase model CAPIL, to investigate performance and design criteria (to compute the length)of an adiabatic straight capillary tube using finite difference methods.The model is validated with earlier simulation model and experimental data, and it is found to be ±10%.C. Yang and P.K. Bansal [13] studied the effects of different geometric and operation conditions on the capillary tube performance.They found that Heat transfer rate and Evaporator capacity of R134a is good as compare to R600a. Heat transfer rate from the capillary tube to the suction line decreases by about 8–10% for non-adiabatic arrangement.

II. TOTAL HEAT LOAD CALCULATION

The first step in equipment selection is to calculate the total heat load on the system. The total heat load on the system is nothing but the Capacity of the evaporator.The Heat load on the system is the contribution due to following loads,

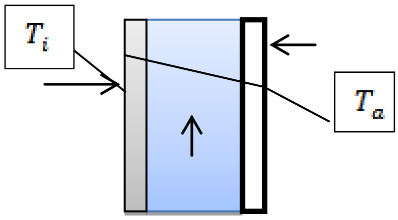
2.1 Thermal wall load:

It is added to the Cabinet due to temperature gradients. This can be calculated as following,

$$Q = \frac{\Delta T}{R_{th}} \tag{1}$$

Liner

Wrapper



Insulation foam

Fig. 1 Element of composite wall of Refrigerator

$$Q = \frac{T_a - T_i}{\frac{1}{h_o * A_0} + \left(\frac{L}{KA}\right)_{wrapper} + \left(\frac{L}{KA}\right)_{insulation} + \left(\frac{L}{KA}\right)_{liner} + \frac{1}{h_i * A_i}} \tag{2}$$

2.2 Air change load:

The Air change load is due to the sensible heat and latent heat. Most of the products are at a higher temperature than storage temperature, when they are first placed in Refrigerator comparment, Heat to be removed from the product to lower its temperature to a point above freezing is called as sensible heat.

$$\text{Sensible Heat} = m * Cp * \Delta T = \rho * Q * Cp * \Delta T \tag{3}$$

Heat to be removed from the product to lower its temperature than freezing is called as Latent heat.

$$\text{Latent Heat} = m * Cp * \Delta W = \rho * Q * Cp * \Delta W \tag{4}$$

2.3 Heater load:

The heater is used in a refrigeration system to defrost the ice crystal formed on the surface of the evaporator. The accumulation of frost over the evaporator surface reduces the cooling capacity and consequently the overall performance of the refrigerator

$$Q_{defrost} = P_{heater} \frac{t_{defrost}}{60} \left(\frac{24}{16}\right. \tag{5}$$

2.4 Commodity load:

These are the food products which are stored in the refrigerator at lower temperature to avoid from spoilage. Refrigerator consist of Freezer compartment (FC)and Refrigerator compartment(RC).

Refrigerator compartment:

$$Q = \frac{[\text{Weight Of Commodity} * \Delta T * \text{SpecificHe}}{24} \tag{6}$$

Freezer compartment:

$$Q = \frac{[\text{Weight of Commodity} * \Delta T * \text{Sp.Heat} + \text{Wt. Of Water} * \text{Lat.He}}{24} \tag{7}$$

2.5 Water load:

$$Q = \frac{[\text{Weight Of Water} * \Delta T * \text{Sp.Heat} + \text{Wt. Of Water} * \text{Lat. Heat}]}{24}$$

(8)

2.6 Fan load:

$$Q_{fan} = P_{fan} * \left(\frac{1}{2}\right)(24h) \quad (9)$$

TABLE I.
Heat load on Refrigerator

Heat Load	FC	RC	Total(W)
Thermal Wall Load	23.36	38.36	61.72
Air Change Load	24.84	18.46	48.30
Heater Load	0.75	0.00	0.75
Commodity Load	9.14	8.43	17.57
Water Load	15.38	4.56	19.94
Total Load	58.09	65,25	143.28

III. EVAPORATOR DESIGN

Evaporators are the heat exchanger. The fluid flowing inside the Evaporator called as Refrigerant. It undergoes phase change during Evaporation. Produces cooling effect by absorbing surrounding heat.heat transfer rate in Evaporator is given as,

$$Q = U * A * \Delta T \quad (10)$$

MTD and LMTD are the methods for Evaporator Selection

$$\text{MTD} = \left(\frac{T1+T2}{2}\right) - Te \quad (11)$$

$$\text{LMTD} = \frac{\Delta T1 - \Delta T2}{\ln\left(\frac{\Delta T1}{\Delta T2}\right)} \quad (12)$$

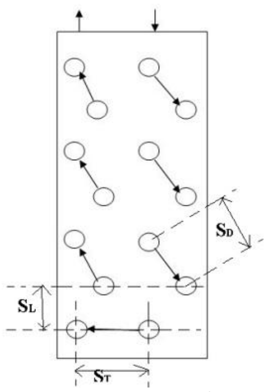


Fig. 2 Cross sectional view of evaporator

Fig. 3 shows the flow chart used to develop simulation technique for evaporator. In this method section by section approach is used to calculate the total length required for evaporator.

IV. COMPRESSOR DESIGN

Generally compressors are called as the Heart of the refrigeration system. The function of the compressor in the vapor compression refrigeration cycle is to draw vapor refrigerant through evaporator so that low temperature and pressure can be maintained in Evaporator. And on the discharged side, it raises its pressure and temperature up to Condenser pressure so that it can be condensed in a condenser. And reject heat to external fluid. Fig. 4 and Fig. 5 shows the processes on P-h and T-S diagram.

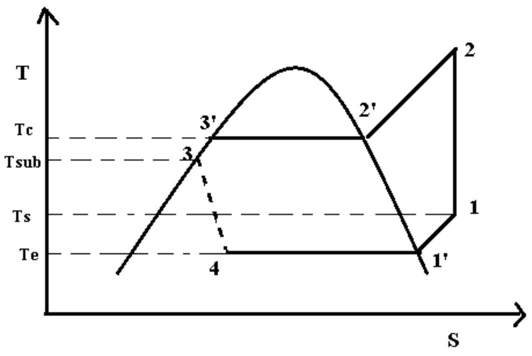


Fig. 4 Process on t-s Chart

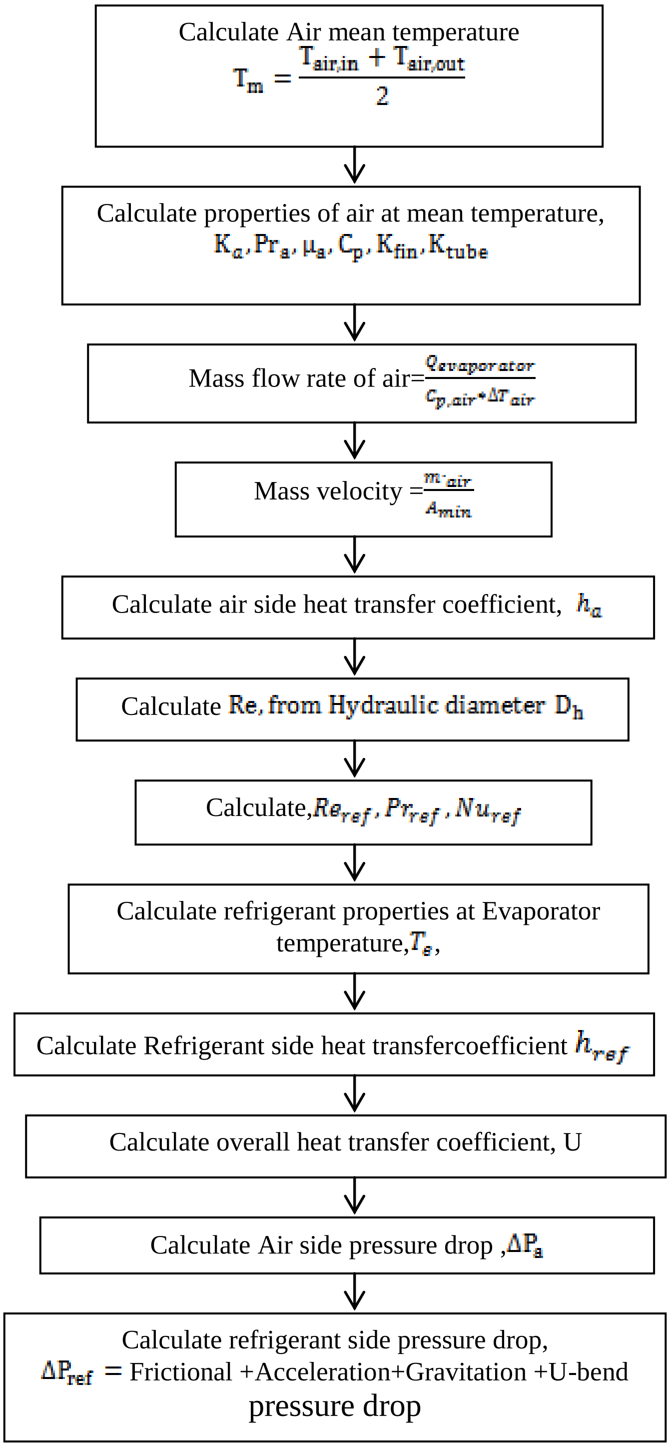


Fig. 3.Flow chart for design of Fin-and tube Evaporator.

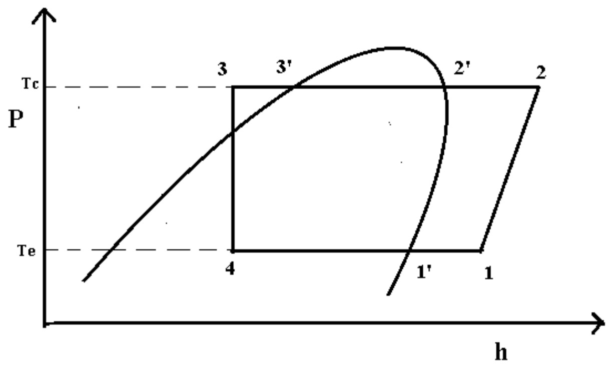


Fig. 5Process on p-h chart.

The entropy and enthalpy at point 1 in the superheated region can be calculated as,

$$S_1 = S_1' + 2.3 * C_{pv}\log\left(\frac{T_1}{T_1'}\right) (13)$$

$$h_1 = h_1' + C_{pv}(T_1 - T_1') \quad (14)$$

Similarly Entropy and Enthalpy at point 2 is calculated using temperature T_2 and T_2'.
Considering isentropic compression, discharged temperature of compressor is calculated.
Enthalpy in the liquid region at point 3 is,

$$h_3 = h_3' - C_{pl}(T_3 - T_3') (15)$$

$$\text{Compressor Efficiency} = \frac{\text{Isentropic Work}}{\text{Actual Work}} = \frac{(h_2 - h_1)}{(x - h_1)}$$

From the above equation, Actual enthalpy at exit to compressor can be calculated.
Piston displacement= Mass flow rate * Specific volume
Using the above equation Diameter of piston and Length can be calculated, these parameters will help us to select Compressor model. As system is critically ,hermetically sealed compressor are mostly used in small capacity refrigeration system.

V. CONDENSER DESIGN

Conventional refrigerator uses wire-on-tube condenser, which is attached to the back of the refrigerator. However, these condensers may damage or dirt may accumulate and form a scale on the hot surfaces. This increases the fouling resistance and reduces the heat transfer coefficient significantly from the condenser, due to these factor hot wall condenser are introduced to replace existing wire-on-tube condenser. Total heat rejected by condenser equals to,

Q_condenser = Q_evaporator + W_compressor,

$$Q = m * (h_2 - h_3) (16)$$

The required condenser area is given by the equation,

$$Q = U * A * \Delta T_m (17)$$

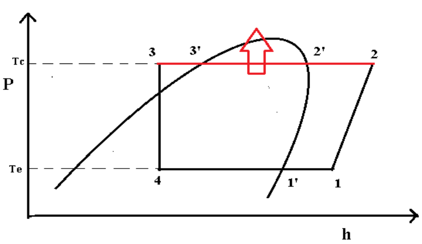


Fig. 6 Condenser heat rejection on p-h chart

$$\text{LMTD} = \frac{(T_{ait,out} - T_{air,in})}{\ln\left(\frac{T_c - T_{air,in}}{T_c - T_{air,out}}\right)} (18)$$

Copper coated steel tubes are generally used for hot wall condenser. These refrigerant carrying tubes are attached to the inner wall of wrapper.An aluminium tape holds these tubes in contact with outer metal sheet.Mathematical modellingof hot wall condenser is presented below. MATLAB is used as simulation tool.First small elemental unit of condenser consist of tube,Aluminium tape and outer sheet is selected as shown in Fig.7.

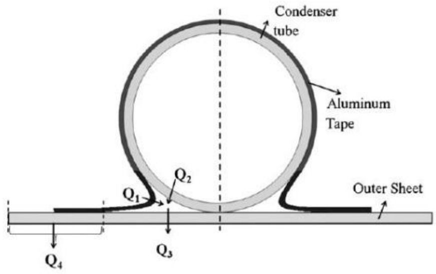


Fig.7Heat transfer in the cavity and through outer wall[7]

Mean surface temperature of the plate portion $T_m$is given by,

$$T_m = T_a + \frac{Q_{out}}{hc_a A_{ele}} (19)$$

Properties of air are calculated at $\frac{(T_m + T_a)}{2}$

Computation of Outer heat transfer coefficient

$$hc_{a,c} = \frac{Nu_a K_a}{L_{cha}} (20)$$

$$hc_{a,r} = \frac{\varepsilon * \sigma * (T_m^4 - T_a^4)}{(T_m - T_a)} (21)$$

$$hc_a = hc_{a,c} + hc_{a,r} (22)$$

Computation of inner heat transfer coefficient

- Single-phase region

$$Nu_{rf} = 0.023 * Re_{rf}^{\ 0.8} Pr_{rf}^{\ 0.33} \text{ for turbulent flow} (23)$$

$$Nu_{rf} = 3.66 \text{ for laminar Flow} (24)$$

$$hc_{c,rf} = \frac{Nu_{rf} K_{rf}}{d_i} (25)$$

- Two Phase region

In this region convective heat transfer is depend on flow type and tube orientation. Different types of flow regimes are determined by using Wallis dimensionless gas velocity and Martinelli parameter.
Pressure Drop Calculations:

- single-phase region

In this phase , pressure drop occur is due to the friction between wall and fluid.

$$\left(\frac{dp}{dz}\right)_f = \frac{8 * f * m_{rf}^2}{\pi^2 * \rho_{rf} * d_i^5} (26)$$

- Two-phase region

Pressure drop in two phase region is composed of Acceleration,frictional and gravitational pressure drop.

VI. DESIGN OF CAPILLARY TUBE

To design the new refrigerator units the diameter and the length of the capillary tube need to be selected such that the compressor and the capillary tube achieve the balanced point at the desired evaporator temperature. The solution procedure for design of capillary tube suggested by Hopkins and Copper and Brisken is as follows,

Assumptions made in the flow of Refrigerant inside the capillary tube are, Flow is steady and incompressible.Capillary tube is adiabatic and gravitational effects are not considered. Consider the small elemental control volume as shown in Fig. 8Stoecker model of capillary tube:

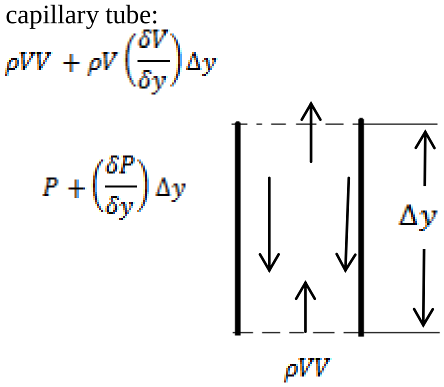


Fig. 8 Elemental control volume of capillary tube[3]

- Applying conservation of mass to control volume

$$\rho VA + \frac{\delta(\rho V)}{\delta y}\Delta y A - \rho VA = 0 \quad (27)$$

- Applying conservation of momentum to elemental control volume

$[\mathrm{Momentum}]_{out} - [\mathrm{Momentum}]_{in}$=Net force on C.V.

$$\pi R^2\left[\rho VV + \rho V\frac{\delta V}{\delta y}\Delta y\right] - \pi R^2[\rho VV] = -\pi R^2\frac{\delta p}{\delta y}\Delta y - \rho_{avg} g\pi R^2\Delta y - 2\pi R\Delta y\tau_w \quad (28)$$

Neglect gravity term,

$$\rho V\frac{\delta V}{\delta y} = -\frac{\delta p}{\delta y} - 2\frac{\tau_w}{R} \quad (29)$$

G=ρV=Constant

Integrating momentum equation, we get,

$$\Delta P = G \cdot \Delta V + \left[\frac{G}{2D}\right][FV]_{mean}\Delta L \quad (30)$$

$$\Delta P = \Delta P_{acceleration} + \Delta P_f \quad (31)$$

The incremental length of capillary tube is given by the formula,

$$\Delta L_1 = \frac{-\Delta P - G\Delta V}{\left(\frac{G}{2D}\right)[FV]_{mean}} \quad (32)$$

Known parameters, Mass flow rate($\dot{m}$) capillary inlet temperature(T_{sub})&Select suitable diameter d_{ci}

↓

Calculate mass Velocity G=$\frac{\dot{m}}{A}$

↓

Calculate Velocity V=$\frac{G}{\rho}$,Reynolds number,$R_e = \frac{4\dot{m}}{\pi D\mu}$

↓

Calculate friction factor $f = \frac{0.32}{R_e^{0.25}}$

↓

Let us assume suitable temperature drop of 1°C

↓

Find refrigerant properties at point i=0 (on saturation line)

$V_0 = V_f$,$h_0 = h_f$,$\mu_0 = \mu_f$

↓

Consider isenthalpic expansion, calculate dryness fraction at point i=1,using

$h_0 = h_1 = x_1 h_{1g} + (1 - x_1)h_{1f}$

↓

Calculate at point i=1,

$h_1, V_1, \mu_1,$

↓

Calculate $\Delta V = V_1 - V_0$, $\Delta P = P_1 - P_0$&

$[FV]_{mean} = \frac{[F_0V_0 + F_1V_1]}{2}$

↓

Calculate ΔL_1, for 1°C temperature drop,

$\Delta L_1 = \frac{-\Delta P - G\Delta V}{\left(\frac{G}{2D}\right)[FV]_{mean}}$

↓

Calculate $\Delta L_2, \Delta L_3, \Delta L_4, \Delta L_5 \ldots\ldots\ldots \Delta L < 0$

Choke flow condition

↓

$L = \Delta L_1 + \Delta L_2 + \Delta L_3$……….up to Evaporating Temperature.

Fig. 9.Flow chart for the design of the capillary tube

VII. SUCTION LINE HEAT EXCHANGER

Following are the advantages of using suction line heat exchanger in refrigeration system

- It increases the degree of subcooling,which directly affect in increasing the Refrigeration effect. Which in tern increases the COP of the system.
- The Compressors are generally made for compression of vapor refrigerant. Entry of liquid refrigerant may damage the compressor. To prevent this slightly superheating is required which is provided by the SLHX

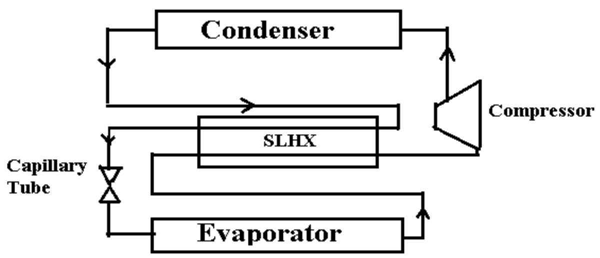
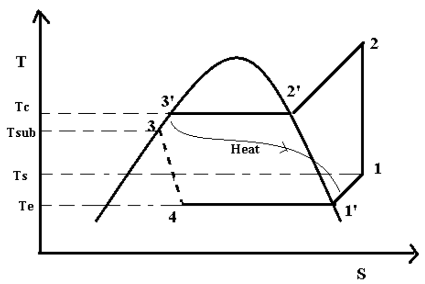
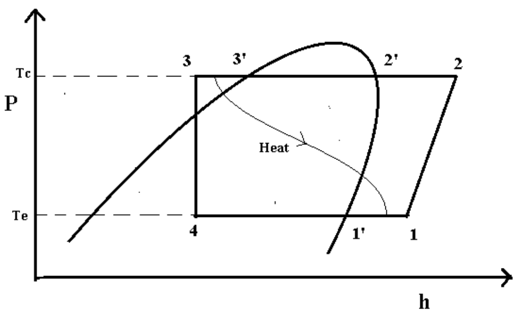


Fig. 10The Suction line Heat Exchanger.



(a)



(b)

Fig. 11Superheating and subcooling on (a) T-S and(b) P-h chart

The mass flow rate required for R600a can be calculated as,

Evaporator Load= $\dot{m}_c h_{fg}$ (33)

The mass flow rate will be constant as it is flowing through sealed system therefore

$\dot{m}_c = \dot{m}_s$

The amount of Heat dissipated by capillary tube = Heat gained by suction tube

$$\dot{m}_c C_{pc}(T_{ci} - T_{co}) = \dot{m}_s C_{ps}(T_{so} - T_{si}) \quad (34)$$

Heat Capacity ratio, $c = \frac{C_{min}}{C_{max}}$ (35)

Calculate heat transfer coefficient of refrigerant inside Capillary tube and suction tube, using Mc Adams equation

$$Nu = 0.023 R_e^{0.8} P_r^{\,n} \quad (36)$$

Here,n=0.3 for cooling and 0.4 for heating.

Calculate Overall heat transfer coefficient (U),

$$Q = UA\Delta T = \frac{\Delta T}{R_{th}} \quad (37)$$

For externally brazed Capillary tube U is,

$$\frac{1}{U} = \frac{1}{h_c} + \frac{t_c}{K_c} + \frac{t_w}{K_w} + \frac{t_s}{K_s} + \frac{1}{h_s} \quad (38)$$

For concentric tube heat exchanger U is ,

$$\frac{1}{UAi} = \frac{1}{h_c Ai} + \frac{\ln(r_o/r_i)}{2\pi KL} + \frac{1}{h_s Ao} \quad (39)$$

Number of transfer units (NTU),

$$NTU = \frac{U.A}{C_{min}} \quad (40)$$

For externally brazed SLHX,

$A = l \times w$

Effectiveness of Counterflow heat exchanger,

$$\epsilon = \frac{1 - e^{-NTU(1-c)}}{1 - ce^{-NTU(1-c)}} \quad (41)$$

VIII. RESULTS AND DISCUSSION

Input parameters are listed in the Table II according to Indian usages condition.

Table II

Design input parameters

Input parameter	Values
Total heat load(Loading condition)(W)	143.28
Evaporator temperature(°C)	-27
Suction Temperature(°C)	43
Condenser Temperature(°C)	51
Degree of subcooling(°C)	3
Capillary inlet temperature(°C)	48
Compressor Efficiency	90%

Using the input parametersvalues in Table II, results obtained are shown in Table III.A compressor discharged temperature for a given input parameter are found as 110°C.that is ainlet temperature to the condenser. That will be first desuperheated followed by isobaric condensation and then subcooled by 3°C.

Table III

Output Parameters

Output Parameters	Values
Mass flow rate (Kg/s)	0.000711
Discharged temperature °C	109.84
Compressor work done (isentropic)W	86.66
Compressor work done(Actual)W	96.29
Isentropic COP	1.65
Actual COP	1.48

Mass flow rate vs. Length graph is plotted by considering various energy test load condition. 0.71mm, 0.65mm, 0.60mm, 0.55mm diameters of capillary tube are assumed shown in fig.12.

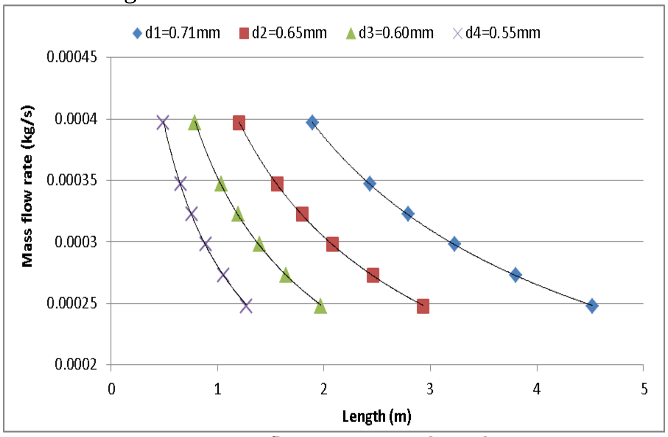


Fig.12Mass flow rate vs. Length graph

IX. CONCLUSION

1. Complete vapor compression refrigeration system is studied for the application of domestic refrigerator.
2. The total heat load acting on the system is calculated considering all kinds of load. It is found to be 143.28W. that is nothing but the Evaporator capacity.
3. Considering the isentropic compression process, Compressor discharged temperature is calculated. It is found to be 110 ..
4. Assuming some values of Evaporating temperature, suction temperature, discharged temperature, and condensing temperature according to the Indian usages condition mentioned above. The COP of the system is calculated. For isentropic compression, the COP of the system is 1.65 and considering 90% efficiency of the compressor, Actual COP is found to be 1.48.
5. For capillary tube selection, mass flow rate vs. length graphs is plotted considering 0.71mm, 0.65mm, 0.60mm, 0.55mm diameters. graph shows that decrease in diameter Length decreases.
6. Mathematical modeling and simulation technique of Suction line heat exchangers are presented. MATLAB is used as simulation tool to calculate the Effectiveness of SLHX using effectiveness NTU methods.

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