Design of Roll Bond Evaporator for Room Air Conditioner

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***Abstract*—The Evaporator is a heat exchanger which gives the desired refrigeration effect in all refrigeration and air conditioning appliances. The evaporators used in air conditioners are predominantly tube and fin type. Domestic refrigerators use roll bond evaporators. This paper presents design of a roll bond evaporator for a room air conditioner. The design is carried out for a 1.5 TR room air conditioner which uses R-22 (Mono Chloro Di Fluro Methane) as refrigerant. The refrigerant enters evaporator in liquid phase and leaves in vapor phase. The design takes into consideration "Two –phase flow" of the refrigerant.**

Keywords—Evaporator; Roll bond ; Room air conditioner; R-22 ; Two phase heat transfer

I. INTRODUCTION

In modern world use of refrigeration and air conditioning systems is on rise. Room air conditioners are very common in comfort air conditioning system. Room air conditioners may be of window type or of split type. In India, it is estimated that approximately 70% of air conditioners are of window type. Window air conditioners of capacities 0.5 TR to 2 TR are very common in India. These contribute to steadily increasing energy consumption. There is need to develop higher efficiency products, which consume less energy while delivering the desired cooling effect. In this pursuit, it is found that the evaporator made from roll bond process gives more uniform distribution of cooling effect when compared to tube and fin evaporator. Roll bond evaporators can be easily manufactured and cost of manufacturing is also low.

Heat exchangers, including evaporators, are designed and employed according to two criteria: heat transfer and pressure drop.

II. LITERATURE SURVEY

The following literature gives ample evidence that roll bond evaporator can be conveniently used as a heat exchanger in many refrigerating and air conditioning devices. It has been proved experimentally that the roll bond evaporator is an alternative to traditional heat exchangers, if proper care is taken in designing it. P.S. Ravi, Dr Arkanti Krishnaiah et al. [1] have studied the suitability of using roll bond evaporator in room air conditioner. A procedure for finding inside heat transfer coefficient has been discussed. Two phase correlations were used to find the heat transfer coefficient. Using experimental works, Fieramonte, Luigi [2], found out that the refrigerator's performance increases drastically with the use of roll bond evaporator. They experimented with different materials of different thickness for manufacture of roll bond evaporator and found an optimum solution to increase the performance of refrigerator container. Chandrakant patel [3] developed a cooling apparatus for a computer sub system. He used a roll bond panel. He found that maximum cooling occurs when it was configured by a roll bond panel. Validating their experimental data, Christian J.L Hermes et al. [4] have developed a numerical simulation model for plate type roll bond evaporators. Anderson SW et al. [5] have studied the flow of refrigerant R-22 through a horizontal tube and gave a correlation to find the heat transfer coefficient. Bio Pierre [6] in their publication studied the impact of Flow resistances of refrigerants which are in boiling conditions. Chawla J M [7] gave correlations of convective heat transfer coefficient for two- phase liquid-vapour flow. The flow through evaporator is predominantly two-phase; this correlation gives an insight of heat transfer coefficient taking viscosity of refrigerant into consideration. Lavin JG and EH Young [8] studied heat transfer characteristics of evaporating refrigerants in two-phase flow. Dembi NJ et al. [9] in their paper presented the effect of use of wire screens in D-X evaporators. Dhar P L [10], in his PhD Thesis, gave the procedure to Optimise a Refrigerating system. The procedure to design different types of heat exchangers of different geometry and for different conditions has been elaborated by Kern D Q [11]. Piert E L and H S Isbin [12] have given correlations for two phase flow in natural circulation evaporators. Heat transfer data books, Manuals from Heat transfer Research Institute, The Tubular Exchanger Manufacturers Association, Inc. (TEMA) etc have given practical approach to design a heat exchanger depending upon consumer needs.

III. DESIGN PROCEDURE OF ROLL BOND EVAPORATOR

The following procedure is established to design a roll bond evaporator which can be used for a room air conditioner.

- Step 1: Calculate Log Mean Temperature Difference (LMTD) for the evaporator.
- Step 2: Assume suitable Overall heat transfer coefficient for the evaporator. This can be approximated with the use of hand books on heat exchangers.
- Step 3: Take heat duty of the evaporator and convert into consistent system of units.
- Step 4: From the relation Q = U A (LMTD), find Area, A of the evaporator.
- Step 5: Find total length, L of the evaporator tube from the relation $A = \pi d_0 L$. For the further subsequent calculations, this value of length L will be considered.
- Step 6: Depending on the selected gauge of the evaporator material find the inside diameter. Generally for roll bond evaporator, BWG 14 (Birmingham wire gauge) is used.
- Step 7: Find inside heat transfer coefficient h_i and outside heat transfer coefficient h_0 from different correlations.
- Step 8: Find overall heat transfer coefficient for the design using the correlation

$$\frac{1}{U_0 A_0} = \frac{1}{A_i h_i} + \frac{1}{A_i h_{fi}} + \frac{\Delta x}{K A_{HT}} + \left\{\frac{\Delta x}{K A_{Frost}}\right\}_{\text{frost}} + \frac{1}{A_0 h_0}$$

here U represents Overall Heat transfer coefficient, A is Area, h is convective heat transfer coefficient, Δx is thickness of plate (length of heat transfer), K is thermal conductivity, subscripts 'o' and ' i' represents outside and inside geometries. As contact resistance is very small, it is neglected. The value of U calculated from above equation is termed as U_{design}.

- Step 9: If $\frac{U_{DESIGN} \sim U}{U} \leq 30$ %, go to step 10. If the above condition is not met, use the value of U obtained in step 8 and repeat the calculations from step 4. Repeat the iterations till the criteria are met.

- Step 10: If the above criteria are met then the Area A obtained in step 4 will be the design Area and hence it is actual area of evaporator. In practice, the required area is taken more (at the maximum of extra 10 %) to compensate for fouling.

IV. DESIGN PARAMETERS

For the present design, a room air conditioner with a capacity of 1 ½ TR (heat load of 18000 BUTH) is considered. The refrigerant which is used in this air conditioner is R-22 ($CHClF_2$ - mono chloro di fluro methane) A high ambient outside conditions for air is considered. Hence a temperature of 50° C is taken as condensing temperature. Air enters evaporator at 28 °C and after cooling, leaves at temperature of 18°C . From the manufacturers catalogue, outside diameter of evaporator tubes is taken as 1/2′′. The roll bond evaporator the plate is made of BWG 14.

V. DESIGN CALCULATIONS

- Step 1; LMTD Calculation :- With R 22 as refrigerant, surface temperature of evaporator is 5°C for a air conditioner. From LMTD calculations, LMTD = 17.527 ° C.
- Step 2:From Chemical Engineering hand book, assumed value of Overall heat transfer coefficient is 100 W/m2K, for refrigerant – air , as heat transfer fluids.
- Step 3: Heat load , Q = 1.5 TR = 5250 W
- Step 4: From the relation Q = U A (LMTD), the area of evaporator is A = 2.995 m2. This is assumed value of Area
- Step 5: From the relation of Area, with the given outside diameter of the evaporator tube, the Length of evaporator tube is 75 m.
- Step 6. The inside diameter is calculated to be d_i= 8.484 mm.
- Step 7:

CALCULATION OF INSIDE HEAT TRANSFER COEFFICIENT

Basic calculations are done with reference to figure 1

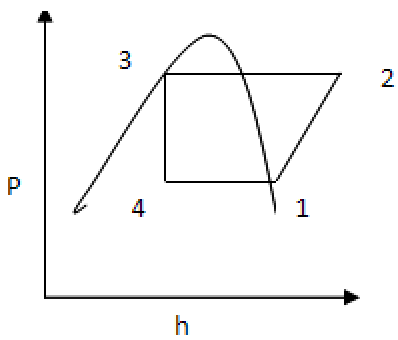

Figure 1: Basic Pressure- Enthalpy diagram

From Refrigerant R-22 properties, enthalpies at state1 and state 4 are 407.45 kJ/kg and 262.27 kJ/kg respectively.

The mass flow rate is calculated from the relation $m (h_1 - h_4)$ = heat load. The estimated mass flow rate of refrigerant is m = 0.03616 kg s^{-1}

Initially, inside heat transfer coefficient of refrigerant is calculated by considering the flow to be in single phase. The following correlations are used

(i) Butterworth correlation
Stanton number, $St = E\, Re^{-0.205}\, Pr^{-0.505}$
Where $E = 0.0225 \exp \{ -0.0225 (\ln Pr)^2\}$
Stanton number $= h/(\rho\, u\, C_p)$
Reynolds number $Re = (4m)/(\pi\, d_i\, \mu)$
Prandtl number, $Pr = (\mu C_p)/k$

ρ is density of refrigerant, u is velocity of refrigerant, C_p is specific heat at constant pressure, k is thermal conductivity of refrigerant, μ is dynamic viscosity of refrigerant.

The heat transfer coefficient so calculated for R-22 is 1244.38 W/m2K

(ii) Dittus Boelter equation:

Nusselt's number $Nu = 0.023\ Re^{0.8}\ Pr^{0.4}$
Nuseelt's number is given by $Nu = (h\ d)/k$

The heat transfer coefficient so calculated for R-22 is 1236.46 W/m2K
(ii) Correlation from heat transfer data book

Nusselt's number $Nu = 0.026\ Re^{0.8}\ Pr^{(1/3)}$
The heat transfer coefficient so calculated for R-22 is 1299.31 W/m2K

(iv) Gnielinski equation:

$$Nu_d = \{ (f/8) \times (Re - 1000)\ Pr \}/\{ 1 + 12.7\ (f/8)^{0.5}\ (Pr^{2/3} - 1)\}$$

friction factor, $f = (0.79 \ln Re - 1.164)^{-2}$

The heat transfer coefficient so calculated for R-22 is 1175.25 W/m2K

In all the above calculations, the length of evaporator is not considered. In roll bond evaporator, the refrigerant is in two phase. So two phase correlations are considered for further calculations. The following calculations show the estimation of inside heat transfer coefficient of refrigerant in two phase.

(i) Spitter, Parker, Quinston Correlation.

$$(h\ D/k) = C_1\{ [GD/\mu_L]^2 [J\ \Delta x\ h_{fg}\ g_c/(L\ g)] \}^{0.4}$$

where D is inside diameter of the tube, $C_1 = 8.2 \times 10^{-3}$, G = m/A , Δx = difference in quality of refrigerant, h_{fg} is enthalpy of evaporation, L is length of evaporator, g_c for SI system is 1 and g is acceleration due to gravity

The heat transfer coefficient so calculated for R-22, in two-phase flow is 2322.123 W/m2K

(ii) Bio-Pierre correlation for complete evaporation:

This correlation considers complete evaporation of refrigerant with 5 to 7K of super heat.

$$Nu_m = 0.0082\ (Re_f^{\ 2}\ k_f)^{0.4}$$

k_f is load factor = $(\Delta x\ h_{fg})/L$

The heat transfer coefficient so calculated for R-22, in two-phase flow is 5788.198 W/m2K

(iii) Two phase Chato- Wattelet correlation

$$h_{tp} = h_1[4.3 + 0.4\ (Bo.\ 10^4)^{1.3}]$$

h_1 is from single phase correlation, Dittus Boelter correlation is considered.

$$Bo = q^{//}/(G\ h_{fg})\ ,\ q^{//} = q/A$$

The heat transfer coefficient so calculated for R-22, in two-phase flow is 5325.116 W/m2K

(iv) Chaddock correlation

$$h_{tp} = 1.85\ h\ [Bo \times 10^4 + (1/ H_{tt})^{0.67}]^{0.6}$$

Where, $H_{tt} = [(1-x)/x]^{0.9} \times (\rho_g/\rho_f)^{0.5}\ (\mu_f/\mu_g)^{0.1}$
here the subscripts g and f refers to gaseous phase and liquid phase respectively.

The heat transfer coefficient so calculated for R-22, in two-phase flow is 3383.92 W/m2K

(v) Bogdanov correlation

$$h = [Z^2\ G^{0.4}\ \Delta T]/d$$

The value of Z is given from the data book and is 1.46.

The heat transfer coefficient so calculated for R-22, in two-phase flow is 4995.465 W/m2K.

(vi) Chato/Dobson correlation

$$h_{tp} = f(\chi_{tt})\ \{ [\rho_L\ (\rho_L - \rho_v) g\ h_{fg}\ k_l^3]/[d\ \Delta T\ \mu_L] \}^{0.25}$$

where $f(\chi_{tt}) = 3.75 /(\chi_{tt})^{0.23}$

$$\chi_{tt} = [(1-x)/x]^{0.9} \times (\rho_g/\rho_f)^{0.5}\ (\mu_f/\mu_g)^{0.1}$$

The heat transfer coefficient so calculated for R-22, in two-phase flow is 3998.98 W/m2K

(vii) Chaddock Brunemann's correlation

$$h_{tp} = 1.91\ h\ [Bo\ 10^4 + 1.5\ (1/ \chi_{tt})^{0.67}]^{0.6}$$

The heat transfer coefficient so calculated for R-22, in two-phase flow is 4362.16 W/m2K

To consider the effects of all the parameters in two- phase flow the average value of all the above heat transfer coefficients is taken for further calculations. The average inside heat transfer coefficient for the refrigerant R-22 is found to be 3796.566 W /2 K

CALCULATION OF OUTSIDE HEAT TRANSFER COEFFICIENT

The following correlations were used to find outside heat transfer confident

(i) Mc Quiston, Spitter & Parker - First correlation

$$St\ Pr^{2/3} = J\ factor$$

Where St is Stanton number, J factor is obtained from the graph given by Spitter. It is a function of J_p, where J_p is given by $J_p = Re_D^{-0.4}(A/A_t)^{-0.15}$, QA is Total heat transfer area (outside area of roll bond evaporator), A_t is Bare tube area of roll bond evaporator (without fins).
For this geometry $(A/A_t) = 2.927$, hence J_p is calculated to be 0.0056.
The outside heat transfer coefficient (air side) so calculated is 25.1 W/m2K

(ii) Mc Quiston, Spitter & Parker -Second correlation

$$J\ factor = 0.0014 + 0.2618\ Re^{-0.4}(A/A_t)^{-0.15}$$

J factor, from the above relation is 5.472×10^{-3}.

The outside heat transfer coefficient (air side) so calculated is 24.52 W/m2K

(iii) Correlation given in heat transfer data book

$$Nu = 0.117\ Re^{0.65}\ Pr^{(1/3)}$$

Nusselt's number is based on hydraulic diameter, $D_h = (4A/P)$
For the geometry of roll bond evaporator, $D_h = 0.1167$.

The outside heat transfer coefficient (air side) so calculated is 15.82 W/m^2K

(iv) Correlation given in Engineering science data unit

$$Nu = a\ Re^m\ Pr^{0.34}$$

a= 0.211 and m = 0.651

The outside heat transfer coefficient (air side) so calculated is 28.74 W/m2K

(v) Briggs & Young correlation

$$Nu = 0.134\ Re^{0.681}\ Pr^{(1/3)}$$

The outside heat transfer coefficient (air side) so calculated is 24.73 W/m2K

(vi)Correlation given in heat transfer data book, based on film temperature and hydraulic diameter

$$Nu = 0.25\ Re^{0.6}\ Pr^{0.38}$$

The outside heat transfer coefficient (air side) so calculated is 20.29 W/m2K

(vii) Correlation from heat transfer data book
This correlation takes into consideration convection, diffusion and radiation phenomenon.
$h_{total} = h_{convection} + h_{diffusion} + h_{radiation}$

Calculation of $h_{convection}$ is based on
$Nu = 0.193\ Re^{0.618}\ Pr^{1/3}$
The convective heat transfer coefficient (air side) so obtained is 19.09 W/m2K

calculation of $h_{diffusion}$: $h_{diffusion}/h_{convection} = 0.1$,
so $h_{diffusion} = 1.909$ W/m2K

$h_{radiation}$ is fixed as 2.5 W/m2K

So $h_{total} = 23.499$ W/m2K

To consider the effects of all the parameters, the average value of all the above heat transfer coefficients is taken for further calculations. The average outside heat transfer coefficient (air side) is found to be 22.61 W /m2 K

- Step 8: Overall heat transfer coefficient for the design using the correlation

$$\frac{1}{U_0 A_0} = \frac{1}{A_i h_i} + \frac{1}{A_i h_{fi}} + \frac{\Delta x}{K A_{HT}} + \left\{\frac{\Delta x}{K A_{Frost}}\right\}_{frost} + \frac{1}{A_0 h_0}$$

In this expression
$A_0 = 8.76$ m2, $A_i = 1.998$ m2, $h_i = 3796.566$ W /m2 K,
$1/h_{fi} = 0.00009$, $\Delta x = 2.1332 \times 10^{-3}$ m, k = 202 W/m K
Δx of frost $= 3 \times 10^{-3}$ m , k of frost = 0.25 W/m K, $A_{frost} = A_0$

Calculated value of overall heat transfer coefficient is U_0 = 21.86 W/m2K. This is $U_{design.}$, So U_{design} = 22 W/m2K

- Step 9:

$\frac{U_{DESIGN} \sim U}{U}$ = 78 %. This is greater than 30 %. So the calculation should be repeated from step 4. Now the value of U should be taken as 22 W/m2 K in further calculations.

II iteration:

The steps are repeated for second iteration and at the end the value of overall heat transfer coefficient U was found to be 17.768 W/m2 K and if the design criteria is checked $\frac{U_{DESIGN} \sim U}{U}$ = 19.23 %.is less than 30 %. The criteria are met.

To have more closeness, the iteration is repeated.

III iteration:
The value of overall heat transfer coefficient was found to be 17.3 W/ m2 K.

Check of design criteria

$\frac{U_{DESIGN} \sim U}{U}$ = 2.63%. This is very much less than 30 %.
Hence this value of overall heat transfer coefficient is accepted.

- Step 10. The area of heat transfer i.e. the area of roll bond evaporator is found to be 17.3 m2.

The total length of evaporator tube is found to be 148 m. The number of passes (bends) of roll bond evaporator depends on the geometry of the room at customer end.

Conclusion: For high ambient conditions i.e. Condenser temperature of 50 °C and moderate evaporator temperature 5 °C, The overall heat transfer coefficient is found out to be 17.78 W/ m2 K, Area of roll bond evaporator is 17.3 m2 and length of roll bond evaporator is 148 m.

The design has been performed for other parameters and the results are tabulated as shown below in Table 1.

Table 1: All design parameters, for fixed condenser temperature and varying evaporator temperature

Temp of refrigerant in condenser, 50 °C						
Sl.No	Temp of refrigerant in Evaporator	Log mean Temp Difference	Quality of Refrigerant entering evaporator	Overall Heat transfer Coefficient based on outside area	Area of Evaporator	Total Length of Evaporator tube
	°C	°C		W/m2 K	m2	m
1	0	22.63	0.308	17.315	13.398	114.61
2	5	17.527	0.285	17.3	17.3	148
3	10	12.33	0.261	17.29	24.63	210.7
4	15	6.82	0.235	17.273	44.56	381

VI . GRAPHS AND CONCLUSIONS

The results obtained from the design of the roll bond evaporator are tabulated in Table 1. These values are plotted in a graph for comparison.

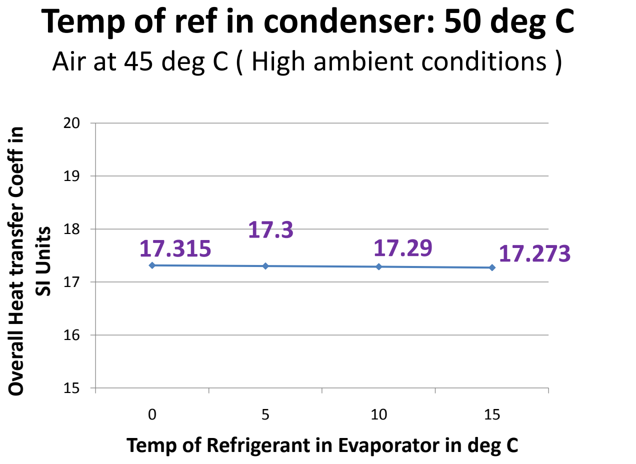

Fig 2: Variation of Overall heat transfer coefficient with temp of refrigerant in evaporator

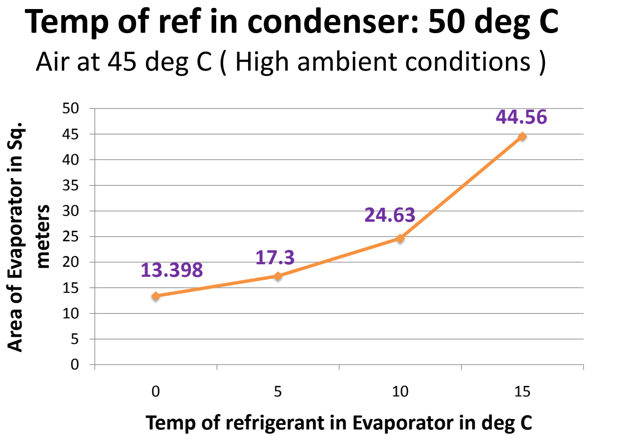

Fig 3: Variation of Area of evaporator with temp of refrigerant in evaporator

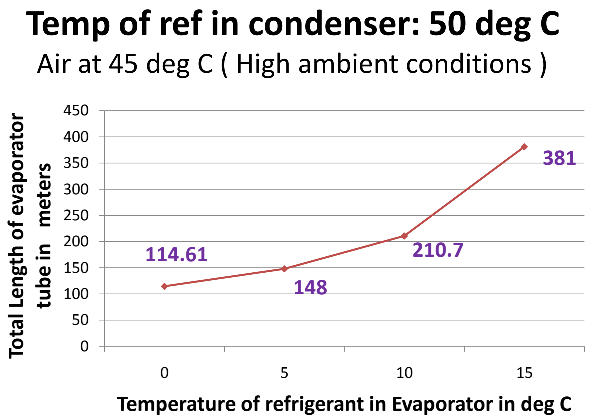

Fig 4: Variation of total length of evaporator with temp of refrigerant in evaporator

Conclusions from the graphs:

Fig 2 shows variation of overall heat transfer coefficient, when the temperature of refrigerant in evaporator is varying, for a fixed temperature of refrigerant in condenser. It can be concluded from graphs that the overall heat transfer coefficient is almost constant, even if the inside temperature changes.

Fig 3 & Fig 4 variation of area and length of roll bond evaporator, when the temperature of refrigerant in evaporator is varying, for a fixed temperature of refrigerant in condenser. It can be concluded that if the temperature of refrigerant in evaporator increases, then the area hence the length of roll bond evaporator increases. To have a optimum value, the

Temperature of refrigerant in evaporator is generally maintained at around 5°C. So for this design the area of evaporator will be 17.3 m2

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