EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE OF BUNDY TUBE TYPE EVAPORATOR COIL IN CHEST FREEZER

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ABSTRACT

Refrigeration is an enabling technology in a wide range of applications mainly required in food preservation and it always needs an improvement in performance and low manufacturing cost. Chest freezers are used for this purpose. Emerging experimental studies are focused on the optimization in terms of the design and development of evaporator coils under various operating conditions. Evaporators are manufactured in different shapes, types and designs to suit diverse nature of cooling requirements. Bundy tube, a double wall copper brazed tube which is a material may be a promising innovation in the development of evaporator coils and the present investigation is to be carried out using R-134a as a refrigerant. The experimental investigation on bundy evaporator coil used in chest freezer of 425 Lts. capacity is done. Through the experiments, the length of the evaporator coil is optimized with increase in performance and reduced cost.

KEYWORDS: *Optimization; Evaporator coil; Performance; Chest freezer; Bundy tube evaporator*

1.0 INTRODUCTION

CFC12 is the most commonly used refrigerant in small hermetically sealed systems. This is because of its high stability, excellent thermodynamic properties, low index of compression making it suitable for use at extreme pressure ratio's and good motor winding cooling characteristics (Lee and Su, 2002; Akash and Said, 2003). HFC134a (tetra flouro ethane) is considered to be the most preferred substitute for R12.

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HFC134a has a 6% higher capacity at 50°F evaporating temperature and 6% higher at 0°F evaporating temperature. For the same amount of subcooling, R134a produces a greater refrigerating effect. The use of oil in R134a system requires a very stringent quality control. It is not soluble in mineral oil. So for R134a the POE (ester based) oils are used. This refrigerant contains no chlorine atoms at all and, therefore has negligible ozone depletion potential (Avinash et al., 2005).

Xuan and Chen (2005) experimented with ternary mixture R161/R125/R143a (10:45:45 percentage by weight) and reported that physical properties of R161 mixture are similar to R502 with environmental properties are lesser than R502 and R404A. The COP of R161 mixture and R404A are equal at low evaporator temperatures and its discharge temperature is slightly higher than R404A. The COP of the ternary mixture was greater than R404A at higher evaporator temperatures while its discharge temperature was lower. Binary mixture composed of R744 and R290 at 71:29 mole fraction was used as alternative to R13 in cascade refrigeration system. It has been reported that COP and capacity of the mixture are greater than R13 (Baolian and Zhang, 2006). The performance of 280l R134a based domestic refrigerator with liquefied petroleum gas (LPG) composed of R290, R600a and R600 (60:20:20 by mass fraction) as an alternative (Fatouh and El Kafafy, 2006). Experimental investigation with R407C with 10% and 20% HC blend composed of 45% of R290 and 55% of R600a (by weight) as an alternative in window air conditioners without changing the mineral oil (Jabaraj et al., 2006). It has been reported that 19% increase in condenser tube length is required to suit the mixtures as compared to R22. The experimental results reported that R407C with 20% HC blend was found to be the promising alternative to R22 in window air conditioners without changing the mineral oil. Calm (2006) has investigated 28 different pure refrigerants for chiller applications. The results reported that R123 remains the best current option to reduce the substantial global warming contributions from chiller and air conditioning applications. R123 has low ODP and very low GWP, very short atmospheric lifetime and the highest energy efficiency of all the current options. Experiments were conducted with two pure HC refrigerants (R1270 and R290) and three binary mixtures of R1270, R290 and R152a as alternatives to R502 in low temperature refrigeration applications having 9.6–18.7% higher capacity with 17.1–27.3% higher COP. The compressor discharge temperatures were similar, while those of all the other refrigerants were 23.7–27.9ºC lower than that of R502.

The charge requirement was reduced by 60%. The above alternatives offer better performance than R502 and can be used as long-term substitutes for R502 having excellent environmental properties (Park and Jung, 2007).

Refrigerators manufactured before 2000 were still running on R12. To full fill the objectives of the Montreal protocol, R12 has to be replaced by either hydrocarbon mixtures or R134a/hydrocarbon mixtures without modification in the exiting system (Mohanraj, 2009). A review work done by Poggi et al. (2008) shows the relation among the system architecture, the cooling capacity and the refrigerant charge of the system. It is pointed out that the ratio of the cooling capacity versus the refrigerant charge depends on the size of the components; these works are related mainly to the heat pump and air conditioning systems but much of the work is not available for chest freezers.

Kim (1998), a high-efficiency compact evaporator for household auto-defrost refrigerator- freezers has been developed and a series of tests was performed to investigate the thermal performance of the system and concluded that the thermal performance was better with improved cooling speeds by 2% for the refrigerator compartment and by 3% for freezer compartment. Energy efficiency was improved by 7% and compressor on-time ratio was decreased by 5 to 20%; the size and material of the evaporator can be reduced by 7% and 40%, respectively. Barbosa (2010) developed a refrigerator simulation model comprised of sub-models for each component was used in a COP-based geometric optimization of the AFE (accelerated flow evaporator). If on the one hand, the PEC (performance evaluation criteria) defined as the normalized ratio of the COP to the evaporator mass yielded a reduction of the evaporator cost by as much as 70% with a 7.8% decrease in the COP, on the other hand, when the system COP was the objective function, the COP increase by approximately 1%, whereas the amount of material decreased by 5.1% when compared to the baseline.

Radha et al. (2012) performed the experimental investigations on the design and development of chest freezers using R134a as refrigerant and obtained the 8.42 COP maintaining recommended inside conditions of -23°C at 43°C ambient using copper as evaporator coil. The developments made are both cost effective and at the same time energy efficient with an increase in storage periods.

On low temperature applications like freezers, until now copper tube is used in evaporator, as it has excellent heat transfer properties, but as the length increases the cost of the copper tube also increases. Thereby the cost of refrigeration system also increases. Before sizing an evaporator, careful evaluation should include consideration of initial cost, operating cost service life and type of load. If evaporator size is too large, it is expensive and create operating problems in lower ambient conditions, an undersized evaporator can also cause operating problems in higher ambient conditions.

Bundy's steel refrigeration tubing is manufactured to meet the internal residue and moisture standards required for today's high reliability refrigeration systems. The experimental investigation on Bundy evaporator coil for a chest freezer of 425 Lts. capacity is done. Through the experiments, the length of the evaporator coil is optimized by using R–134a as refrigerant. The system design is in such a way that it has optimum efficiency with moderate costs. Hence, a bundy tube type may be a promising innovation in the development of evaporator coil.

1.1 Chest-Type Freezer with Bundy tube coil

A chest freezer is nothing but a storage unit for frozen food such as meat, poultry, fish, prawns, vegetables and some fruits. The cold air is heavier than warm air; the very cold air in a chest-type freezer does not spill out each time the lid is opened. This stops a considerable amount of moisture from entering the cabinet as shown in Figure 1 and Figure 2.

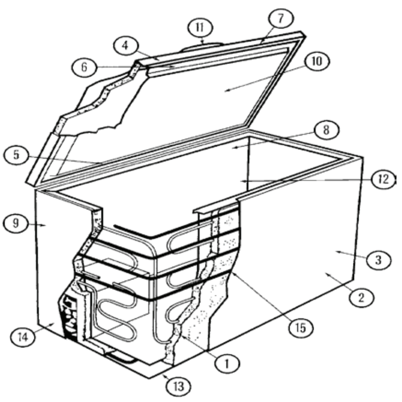

Figure 1. Chest Type Freezer

Figure 2. Double walled bundy tube

The parts of a chest-type freezer as shown in Figure 1: 1-polyurethane foam insulation, 2-wrap-around steel cabinet, 3-baked-on enamel finish, 4-self-adjusting lid, 5-spring-loaded hinges, 6-vinyl lid gasket, 7-safety lock and self-ejecting key, 8-lift-out wire baskets, 9-temperature-control knob, 10-automatic interior light, 11-power-on light, 12-vertical cabinet divider, 13-defrost water drain, 14-sealed compressor and 15-wrap-around condenser.

Bundy tube is a type of double-walled low-carbon steel tube manufactured by rolling a copper-coated steel strip through 720 degrees and resistance brazing the overlapped seam in a process called bundy welding. It may be zinc or terne-coated for corrosion protection. Fine inside cleanness, high strength, nice elongation, good foundation for late process, anti leakage, anti high pressure explosion, excellent anti corrosion power after surface treatment are the properties of bundy material possessing higher withstanding pressure and higher vibration fatigue strength. Furthermore, the tube is also equipped with superior properties such as solderability, brazeability, bendability, and workability in end terminal preparation, Available in sizes of 4.76 mm × 0.7 mm, 6.35 mm × 0.7 mm, 8 mm × 0.7 mm, etc. which are approved as ISO9001.

2.0 OPTIMIZATION OF LENGTH OF EVAPORATOR COIL

The capacity of an evaporator is the rate at which heat will pass through the evaporator tubes from the refrigerated space or product to the vaporizing liquid inside. Evaporator must always have sufficient capacity to produce the required load when operating at the design conditions. The evaporating unit capacity depends on air velocity and minimum dehydration of the product. This is mainly due to natural convection, which is a function of the temperature differential between the evaporator and the space. The greater the difference, the higher the air circulation. The circulation of air by natural convection is greatly influenced by the shape, size, and location of the evaporator, and the placement of the stored product in the refrigerated space. Earlier 80 m of copper coil is used for evaporator in chest freezer whose COP is 5.8. Hence first replacing bundy evaporator of same length we perform experimental test and then we are theoretically optimizing the evaporator length. The surface area, the value of U, and the capacity of the evaporator depends on the mean effective temperature difference between the cooling coil and the refrigerated space.

3.0 CALCULATIONS

Outside heat transfer coefficient, $h_o = 20$ W/m²K
Inside heat transfer coefficient, $h_i = 9$ W/m²K

Coil thickness, $x_1 = x_2 = x_3 = (0.7/3) \times 10^{-3}$ m
Insulation thickness, x_{insul} =0.04 m
Coil thermal conductivity for copper coating, $K_1 = K_3 = 386$ W/mK
Coil thermal conductivity for low carbon steel, $K_2 = 36.3$ W/mK
Thermal conductivity of insulation, $K_{insul} = 0.025$ W/mK
Overall heat transfer coefficient,

$$U = [1/(1/h_o) + (1/h_i) + (x_1/K_1) + (x_2/K_2) + (x_3/K_3) + (x_{insul}/K_{insul})] = 8.189 \text{ W/m}^2\text{K} \quad (1)$$

Ambient temperature, T_1= 43°C =316 K
Evaporator outlet temperature, T_2 = -22.1°C =250.9 K
Evaporator temperature, T_e = -23.7°C = 249.3 K
Diameter of coil, d = 5/16" = 0.007937 m
From the load calculation, Q = 197 W
We have,

$$\text{LMTD} = (td_1 - td_2)/\log(td_1/td_2) \quad (2)$$

where

$$td_1 = T_1 - T_e = 69 \text{ K} \quad (3)$$
$$td_2 = T_2 - T_e = 3 \text{ K} \quad (4)$$

LMTD =17.452 K
From the heat transfer equation for evaporator,

$$Q = U \times \text{A} \times \text{LMTD} \quad (5)$$

Area, A = Q/(U × LMTD) = 1.37 m²
Area of coil = (3.14 × d × L) =1.37 m²
Optimised length of evaporator coil, L = A/(3.14 × d) = 55.28 m

4.0 RESULTS AND DISCUSSIONS

4.1 Refrigerant Charge Quantity

It is one of the tests to specify the minimum amount of refrigerant that a freezer can work at a specified temperature range, so that the system runs with optimum performance. In this test, a 400 gm of refrigerant is charged into the system as per compressor specifications. Then the system is run for 2 hrs and then the temperature is noted to check for steady state then the performance test is carried out. Every time 10 gm of refrigerant is purged out through displacement of water (1 gm is equivalent to 100 ml of water) from the system. The test is continued until the system reaches a steady state, continued up to a slight warmer temperature is reached. 'U' shaped curve is obtained. Then the amount of refrigerant can be known from the steep point of the curve which is 310 gm.

4.2 No Load Test

In this test, the compressor will be running continuously bypassing the thermostat. For every half an hour the temperatures are noted till steady state is reached. Significance of this test is to find out how much time is required to attain specified temperature at the air center. This test helps us to know how the system is running. In no load cycling test, the system is run for 4 hours keeping the thermostat in cycling mode in the refrigeration system. As the temperature reaches specified highest set freezing temperature, the compressor stops which is called the cut-off time, and as the temperature inside the cabinet reaches lowest set freezing temperature, the compressor starts which is called the cut-in time, taking the power and maintaining the temperature inside the cabinet at stabilized condition. The compressor on/off can be noted down directly from the digital temperature control unit, which records the temperatures. Significance made through this is to find the time required to attain the specified temperature near the air center when freezer is in unloaded condition.

4.3 Load Test

In this test, the freezer is fully loaded, and the thermostat is by-passed. The thermocouples are placed at different locations except at the air center and temperatures are noted till steady state is reached. Significance of this test is to find out how much time is required by the loaded product to attain the specified temperature. The system performance is tested according to center temperature of cabinet and time, which shows how the system runs at full load condition and how much time is required to pull down the load. In load cycling test, the thermostat is connected to the circuit at full load condition. As the temperature reaches highest set freezing temperature the compressor stops which is called the cut-off time, and as the temperature inside the cabinet reaches the lowest set freezing temperature, the compressor starts which is called the cut-in- time, taking the power, maintaining the temperature inside the cabinet at stabilized condition. The compressor on/off can be noted down directly from the digital temperature control unit, which records the temperatures. Significance of this test is to find out how much time is required by the loaded product to attain the specified temperature at full load condition also shows how power is required by the compressor at cut-in and cut-off positions. The system is made to run for 24 hrs at full load condition; from Figure 3, we could say that the system comes to steady state condition in 18 to 20 hrs time.

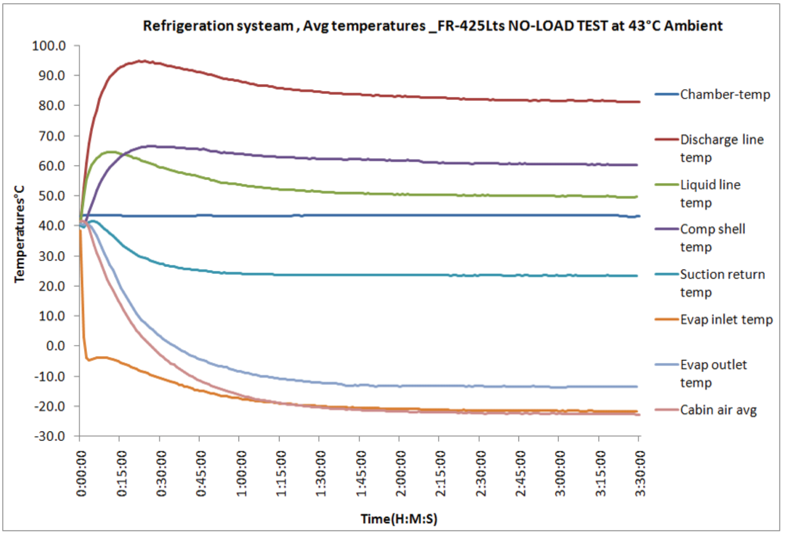

Figure 3. Temperature vs time for no-load test

From the Figure 4, it is observed that the discharge line temperature increased with time till 25 minutes then decreased slightly and thereafter the variation is zigzag sloping slightly downwards, this maybe the system has reached the steady state. The temperature is maintained 82.2°C till the end of the test. The suction line temperature increased initially up to 10 minutes and decreased slightly with time till 45 minutes and thereafter the variation is zigzag sloping slightly downwards. The temperature is maintained 23°C till the end of the test.

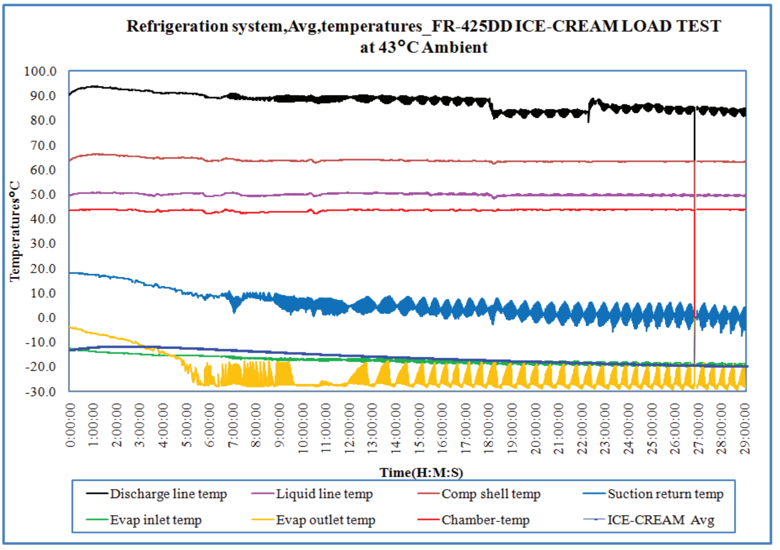

Figure 4. Temperature vs time for load test

From the Figure 5, it is observed that the evaporator inlet temperature initially decreased suddenly as the system is just switched on to running mode, then the variation is curvy till 1 hour 30 minutes so as to reach the cabinet temperatures and thereafter the variation is constant. The temperature is maintained -19°C till the end of the test. Evaporator outlet temperature decreased initially till 1 hour 15 minutes, thereafter the variation is constant with slight change in temperature. Temperature is maintained at 5°C till the end.

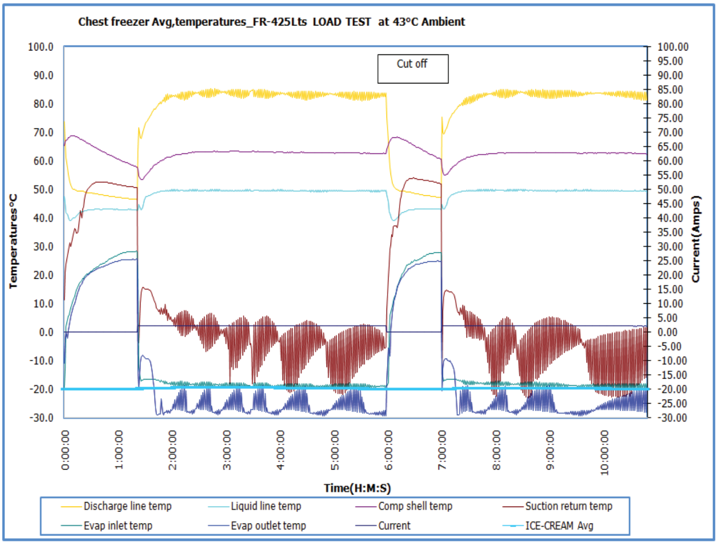

Figure 5. Load test results for a 425 Lts. chest freezer with cut-off time

From Figure 6, it is observed that the evaporator inlet temperature increased in first one hour, decreased suddenly so as to reach the steady state temperature and then remained constant with time thereafter the variation is repeatable maintaining -17°C due to cyclic ON/OFF of temperature. The cut-off time is for 1 hour after reaching the steady state temperatures. The evaporator outlet temperature increased initially till 1 hour, decreased upto 2 hours and thereafter the variation is wavy and the cycle is repeatable maintaining -23°C temperatures. It has cyclic and noncyclic condition i.e. power ON and OFF.

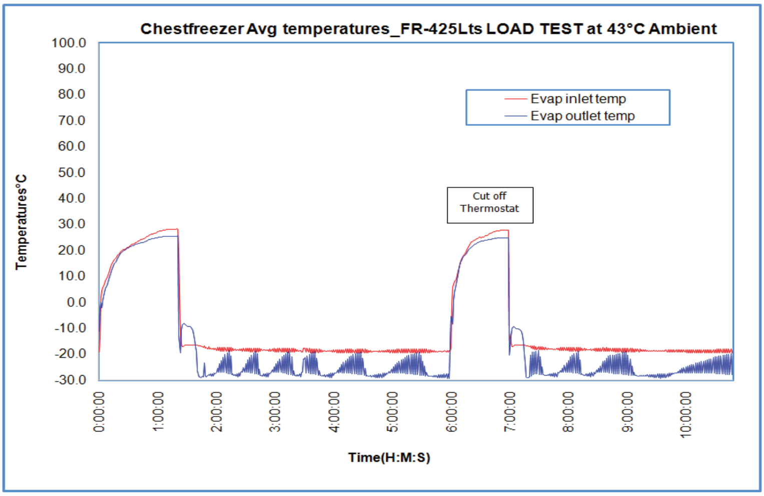

Figure 6. Evaporator inlet and outlet Temperatures for Load Test

4.4 Calculation of COP

Optimised evaporator Length = 55.28 m
Ambient temperature = 43°C
Compressor suction temperature, T_1 = 23.6°C
Compressor discharge temperature, T_2 = 83°C
Condensing temperature, T_3 = 48°C
Suction pressure, P_1 =1.5 bar
Discharge pressure, P_2 =12.5 bar

From P-h chart for R-134a, the calculation of performance parameters:

1. Net Refrigerating Effect (NRE) =162 kJ/kg
2. Heat of Compression = 30 kJ/kg
3. Coefficient of Performance (COP) = NRE/Heat of Compression = 5.4

When compared with the COP obtained by Radha. et al (2012), the net refrigerating effect increased by 0.372% but the work done also increased by 1.14%, and reducing the COP by 0.55%. COP is not effective when compared to the chest freezer without bundy evaporator coil, so inorder to reduce the cost of the material used in evaporator coil, bundy type of material may be used without any effect on the performance of the freezer.

4.5 Cost Analysis

For low temperature applications like freezers, until now copper is used in as an evaporator coil in the design of evaporator, as it has excellent heat transfer properties, but as the length increases the cost of the copper material also increases, in turn the total equipment cost also increases.

Cost analysis for optimized length of 55.28 m evaporator coil:
Cost of bundy tube per one feet = 0.325 USD
Cost of copper tube per one feet = 0.41 USD
Cost of total 181.36 feet bundy tube = 58.86 USD
Cost of total 181.36 feet copper tube = 73.57 USD

Total amount of cost saved by using bundy tube = 73.57 - 58.86 = 14.71 USD

Total percent of cost reduced = (14.71/73.57) × 100 = 20%

Hence 20% cost reduction is assured by using bundy tube instead of copper.

5.0 CONCLUSIONS

In the design of the refrigeration system for a freezer, rigid standards are maintained so as not to have any compromise with the quality and flexibility of the system. The system design is in such a way that it has optimum efficiency with moderate costs. Hence, efficient equipment design will result in conservation of energy, which reduces the running cost. Placement of the freezer also plays a major role in reducing the load on the system. As freon is the blowing agent in the insulation material, only in order to reduce ODP, the insulation is change to polyol isocyanate and cyclopentane as the blowing agent which have zero ODP. By changing the insulation the freezer model is still developed with optimum efficiency. For low temperature applications like freezers, until now copper is used in as a evaporator coil in the design of evaporator, as it has excellent heat transfer properties, but as the length increases the cost of the copper tube also increases. Thereby, the refrigeration system cost also increases. The experimental investigation on bundy evaporator coil for a chest freezer of 425 Lts capacity is conducted. Through the experiments, the length of the evaporator coil is optimized. The results infer that the COP obtained is 5.4. 20% cost reduction is assured by using bundy tube. Hence, the proposed chest freezer with bundy evaporator is economical and efficient.

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APPENDIX

Mechanical properties:

- Tensile strength = 290 MPa-296 MPa.
- Yield strength = 180 MPa - 190 MPa.
- Elongation = 20%- 30%.
- Wall thickness = 0.70 to 0.1 mm.
- Flaring = 25%- 30%.
- No leakage when charged with 34.3 MPa nitrogen gas for 1 min.