International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 3 Issue 6, October 2019 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Design Calculation of Main Components for Lab Based Refrigeration System

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ABSTRACT
The purpose of this paper is for the students to know the basic function of main components of refrigeration system. Theoretical and experimental of design calculation of main components and their results are reported in this paper. During the performance of testing, the length of expansion device is varied and the result data are also described. In this system, R134a refrigerant is used as working substance. Because it is now being used for a replacement of R-12 CFC refrigerant. It can be handled safely because it is not toxic, corrosive and flammable. Moreover, it has no damage effect to ozone layer and greenhouse.

KEYWORDS: *main components, refrigeration system, expansion device, refrigerant, toxic, corrosive, flammable*

How to cite this paper: Ko Ko | Aye Aye San | Khin Maung Than "Design Calculation of Main Components for Lab Based Refrigeration System" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-3 | Issue-6, October 2019, pp.688-692, URL: https://www.ijtsrd.com/papers/ijtsrd29212.pdf

IJTSRD29212

1. INTRODUCTION

Refrigeration is the process of removing heat from a site where it is not necessary to transfer the heat to a place where it makes little or no difference. Refrigeration relates to the cooling of air or liquids and thus provides lower temperatures to preserve food processing, cool beverages, make ice, and for many other applications [1]. Nowadays, refrigeration system is widely used in residences, offices, buildings, air ports, hospitals and in mobile applications such as industrial freezers, electricity production, pharmaceutical, technical equipment, automobiles, aircrafts etc.

2. FUNCTION OF MAIN COMPONENTS

A refrigeration system has mainly five essential components:

1. Evaporator
2. Compressor
3. Condenser
4. Expansion valve
5. Refrigerant

2.1. Compressor

The main function of the compressor is to suck the low pressure vapour from the evaporator and force it into the condenser. The refrigerant is continuously circulated by the compressor through the refrigeration system. to reduce the volume and increase the pressure of refrigerant. The capacity of refrigeration system depends on the capacity of compressor. This system is used hermetic type compressor to reduce noisy and leakage. And it is a portable type and can be replaced with another.

Figure.1. Compressor

2.2. Evaporator

The function of the evaporator is to receive liquid refrigerant from the expansion device and to bring it in close thermal contact with the load. The refrigerant takes up its latent heat from the load and leaves the evaporator as a dry gas. Evaporators are classified according to their refrigerant flow pattern and their function [1]. It is used in the low pressure side of the refrigeration system.

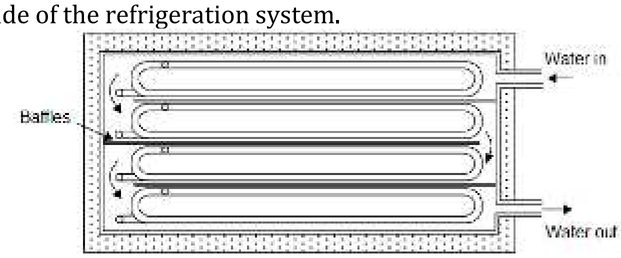

Figure.2. Evaporator

2.3. Condenser

The purpose of the condenser is to remove the hot, high-pressure gas or vapor refrigerant from the compressor and cool it to remove first the superheat and then the latent heat, so that the refrigerant will condense back to a liquid. In nearly all cases, the cooling medium will be air or water or combination of the two[1]. As condenser is one of an important device for the refrigeration system, it is used in the high pressure side of the refrigeration system.

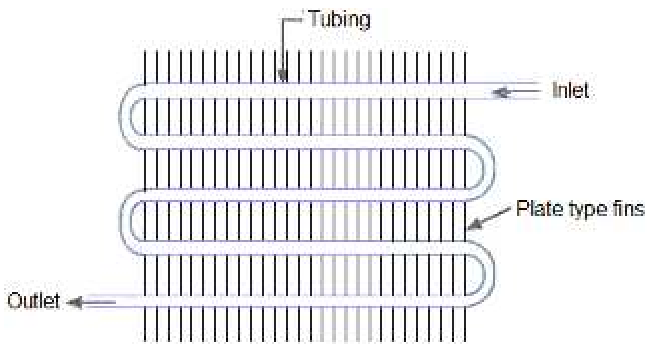

Figure.3. Condenser

2.4. Expansion Device

It is also known as a metering device. The main performance of the expansion device is to control the flow of sufficient pressure differential between the high and low pressure sides of the system. It is used for metering the correct amount of refrigerant to the load on the evaporator [2].

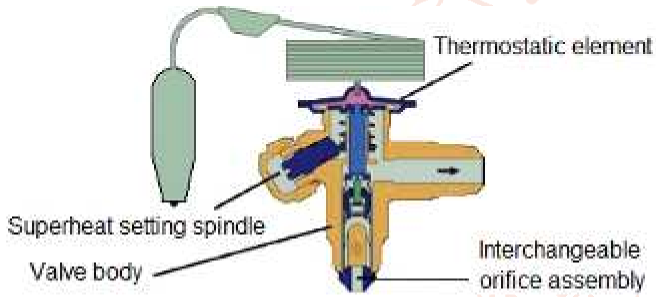

Figure.4. Expansion device

2.5 Refrigerant

The refrigerant is usually a liquid or gaseous compound. It easily absorbs heat from the fluid medium and can provide cooling or air conditioning in combination with other components such as compressors and evaporators. Without refrigerant, there would be no air conditioning and refrigeration technology.

Figure.5. Refrigerant

3. LAYOUT OF LAB BASED REFRIGERATION SYSTEM

Figure.5. Lab based refrigeration system

The design and construction of all components for lab based refrigeration system is as shown in Figure 5. It is a kind of domestic refrigerator. All components are fixed firmly on the stand board. The testing results are based on different lengths of capillary tube. The lengths of capillary tube were 0.9144 m, 1.524 m and 2.135 m. Because this lab based refrigeration system was only the project.

We observed that during the testing, suction pressure, discharge pressure and others are changed. Running time is 15 minutes. The components of this system are;

A. Compressor
B. Condenser
C. Evaporator
D. Expansion device
E. High pressure gauge
F. Low pressure gauge
G. Filter drier
H. Sight glass
I. Shutoff valves

4. DESIGN SPECIFICATIONS OF MAIN COMPONENTS

4.1. Detail Designs of Compressor

For the volumetric efficiency of compressor,

$$\eta_v = 1 + c - c\left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \quad (1)$$

Where,

η_v = volumetric efficiency

P_1 = suction pressure, Pa

P_2 = delivery pressure, Pa

c = clearance (between 2% and 5%)

γ = Isentropic index

For piston diameter and stroke length,

$$P_D = \frac{\pi D^2}{4} \times L \times N \times n \quad (2)$$

Where,

N = compressor speed, rpm

n = no. of piston

P_D = Piston displacement, cm^3/rev

L = 0.8D (Hermetic type compressor)

For required work done of compressor,

$$W_c = \frac{\gamma}{\gamma - 1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (3)$$

Where,
W_c = work done of compressor, kJ/cycle

For the required actual power of compressor,

$$P = \frac{W_c \times N}{60} \quad (4)$$

Where,
P = actual input power, kW

For input power of compressor,

$$\text{Input power} = \frac{W_c}{\eta_{mech}} \quad (5)$$

Where,
η_{mech} = mechanical efficiency
W_{input} = input power of compressor, W

4.2. Heat Transfer in Condenser

For heat transfer in condenser,

$$Q_{con} = U_{copper} \times A_{con} \times \Delta T_m \quad (6)$$

Where,
Q_{con} = heat rejected in condenser, W
U_{copper} = overall heat transfer coefficient of air velocity, (60-65 W/m²K)
A_{con} = area of condenser, m²

Foe mean temperature of the condenser,

$$\Delta T_m = \frac{(T_r - T_{a,in}) - (T_r - T_{a,out})}{\ln\left(\frac{(T_r - T_{a,in})}{(T_r - T_{a,out})}\right)} \quad (7)$$

Where,
T_r = condensing temperature, °C
$T_{a,in}$ = air inlet temperature, °C
$T_{a,out}$ = air outlet temperature, °C

For heat transfer area of the condenser,

$$A_{con} = \pi d_t \times L_{con} \quad (8)$$

Where,
d_t = outside diameter of condenser, m
L_{con} = length of the condenser, m

4.3. Detail Designs of Evaporator

T_a = ambient temperature = 306 K
T_1 = evaporator outlet temperature = 263 K
T_e = evaporator temperature = 245 K

For Log mean temperature difference,

$$\Delta T_m = \frac{T_{d1} - T_{d2}}{\ln\left(\frac{T_{d1}}{T_{d2}}\right)} \quad (9)$$

Where,
T_{d1} = maximum temperature difference, °C
T_{d2} = minimum temperature difference, °C
ΔT_m = log mean temperature difference, °C

For the capacity of evaporator,

$$Q_{eva} = U_{eva} \times A_{eva} \times \Delta T_m \quad (10)$$

Where,
Q_{eva} = capacity of evaporator, W
U_{eva} = overall heat transfer coefficient, W/m²K
A_{eva} = area of the evaporator, m²

For the length of evaporator tube,

$$A_{eva} = \pi D_{eva} \times L_{eva} \quad (11)$$

Where,
L_{eva} = length of the evaporator tube, m
D_{eva} = outside diameter of evaporator, m

For overall heat transfer coefficient of evaporator,

$$U_{eva} = \frac{1}{\frac{1}{h_r} + \frac{x_a}{k_a} + \frac{1}{h_i}} \quad (12)$$

Where,
h_r = heat transfer coefficient of refrigerant, W/m²
h_i = heat transfer coefficient of air side, W/m²K
x_a = thickness of evaporator, °C
k_a = thermal conductivity of aluminum, W/mK

Air side heat transfer coefficient can be calculated the following equation,

$$h_i = 1.24 \left[\frac{\Delta T_i}{D} \right]^{\frac{1}{3}} \quad (13)$$

Where,
ΔT_i = sub cooling temperature difference, °C

For modified latent heat transfer coefficient,

$$h_{fg1} = h_{fg} + \frac{3}{8} c_f \Delta T \quad (14)$$

Where,
h_{fg} = latent heat, kJ/kg
h_{fg1} = modified latent heat, kJ/kg
c_f = correction factor

For heat transfer coefficient of refrigerant,

$$h_r = 0.555\left[\frac{g\times\rho_r\left(\rho_r-\rho_g\right)\times k_r^3\times h_{fg1}}{\mu\div\Delta T_i\times D_i}\right]^{\frac{1}{4}} \quad (15)$$

Where,

k_f = thermal conductivity of refrigerant, W/mK

ρ_r = density of refrigerant, kg/m³

ρ_g = density of gas, kg/m³

g = gravitational force, m/s

μ = viscosity of refrigerant, kg/ms

4.4. Expansion Device

Inside diameter = 0.5 mm to 2.25 mm

Length = 0.5 mm to 5 m

5. RESULTS AND DISCUSSIONS

5.1. Design Calculation for Compressor

P_1 = 96.5 kPa

P_2 = 2413 kPa

c = 2%

γ = 1.14

By using Equation (1),

Volumetric efficiency of compressor is

η_v = 68 %

By using Equation (2),

No. of piston, n = 1

Compressor speed, N = 3000 rpm (2 poles compressor motor)

L = 0.8D (Hermetic compressors)

Piston displacement is

P_D = 9.2 cm³/rev

Piston diameter, D = 24 mm

Piston stroke length, L = 19 mm

By using Equation (3),

V_1 = 9.2 cm³/rev

γ = 1.14 (isentropic compression)

Required work done of compressor is

$W_c = 3.5047\times10^{-3}$ kJ/cycle

By using Equation (4),

Actual power to drive the compressor,

P = 0.1752 kW

By using Equation (5),

η_{mech} = 0.92

Input power of compressor,

$W_{input} = 3.809\times10^{-3}$kW

5.2. Design Calculation of Condenser

d_t = 0.004 m

T_r = 65°C

$T_{a,in}$ = 32°C

U_{copper} = 60 W/m²K

By using Equation (7),

Mean temperature difference is

ΔT_m = 27.6°C

By using Equation (6),

Q_{con} = 323 W

Area of condenser is

A_{con} = 0.195 m²

By using Equation (8),

Length of condenser is

L_{con} = 15.5 m

5.3. Design Calculation of Evaporator

$T_{d1} = T_a - T_e$ = 61 K

$T_{d2} = T_a - T_o$ = 43 K

By using Equation (9),

Log mean temperature difference, ΔT_m = 51.47 K

By using Equation (13),

Inside diameter of evaporator,

$D_i = D_{eva} - 2t_{eva}$

$D_i = 0.00635 - (2\times0.00068) = 0.005$ m

Heat transfer coefficient of air side is

h_i = 26.36 W/m²

By using Equation (14),

c_f = 0.065

h_{fg} = 215 kJ/kg (P_r = 0.9 MPa)

Heat transfer coefficient for refrigerant side is

h_{fg1} = 216.49 kJ/kg

By using Equation (15),

ρ_r = 1379.8 kg/m³

ρ_g = 4.833 kg/m³

$k_r = 104.5\times10^{-3}$ W/mK

$\mu = 0.0392\times10^{-4}$ N/m²

Heat transfer coefficient of refrigerant is

h_r = 44.324 W/m²

By using Equation (12),

Q_{eva} = 323 W

Overall heat transfer coefficient of evaporator is

U_{eva} = 23.95 W/m²K

By using Equation (10),

Area of evaporator is

A_{eva} = 0.2996 m²

By using Equation (11)

Length of the evaporator tube is

L_{eva} = 15.02 m

5.4. Selection of Expansion Device

Capillary tube is one of the important types of used in expansion device. The selection of capillary depends on the compressor work done. Due to the testing results, capillary tube length is inversely proportional to the refrigerant flows. And then, condenser pressure and evaporator pressure are increased. According to the experiment, the suitable length of the capillary tube is between 1.524 m and 4.877 m.

Table1. Refrigeration Preference Chart for Capillary Tubing (Fan Cooled Units Only and add 10 % length for Static Cooled)

R-134a/R-401a/R-401b						
H.P	Low		Medium		High	
	°C	m	°C	m	°C	m
1/8	26	3.073	26	2.337	26	1.346
1/6	26	1.198	26	2.692	26	2.007
1/5	31	1.499	31	0.991	31	0.660
¼	31	1.194	31	2.515	31	1.676
1/3	42	2.591	42	2	42	0.991

According to above table, the selection for capillary tube length is 1.524 m.

Table2. Results for Main Components of Lab Based Refrigeration System

No.	Main Components	Value	Unit
1	Compressor	3000	rpm
2	Compressor	0.175	kW
3	Piston diameter	0.024	m
4	Stroke length	0.019	m
5	Condenser length	15.5	m
6	Condensing pressure	2413	MPa
7	Condensing temperature	42	°C
8	Evaporator length	15.02	m
9	Evaporating pressure	0.0965	MPa
10	Evaporating temperature	-28	°C
11	Capillary tube length	1.524	m
12	Capillary tube diameter	0.0008 ID 0.0002 OD	m

Table3. Performance Testing and Results for Capillary Tube Length of 0.9144 m

Time (min)	Pressure (psi)		Evaporator Temp. (°C)		Condenser Temp. (°C)	
	Suction	Discharge	Inlet	Outlet	Inlet	Outlet
0-5	18	365	8.3	18	41.2	31.2
5-10	20	365	1	13	42.7	32.7
10-15	20	365	0	10	44.7	34.7

Table4. Performance Testing and Results for Capillary Tube Length of 1.524 m

Time (min)	Pressure (psi)		Evaporator Temp. (°C)		Condenser Temp. (°C)	
	Suction	Discharge	Inlet	Outlet	Inlet	Outlet
0-5	12	345	17	26	38.5	28.5
5-10	12	345	8.1	25	35.9	25.9
10-15	14	350	5	23	25.9	15.9

Table5. Performance Testing and Results for Capillary Tube Length of 2.134 m

Time (min)	Pressure (psi)		Evaporator Temp. (°C)		Condenser Temp. (°C)	
	Suction	Discharge	Inlet	Outlet	Inlet	Outlet
0-5	13	360	15	26	32.9	22.9
5-10	15	370	7.9	23	37.5	27.5
10-15	16	375	5	21	42	32

6. CONCLUSION

This lab based refrigeration system analyzed the detail designs of compressor, condenser, evaporator and coefficient of performance by varying the capillary tube length.

This system is simple in structure and easy to maintain. It can be used for laboratory experiments of basic refrigeration processes and principles of each component. It is fairly inexpensive and therefore much suitable for mechanical engineering students. It can also be used as teaching aids. The design calculations and results will help for other new designs.

7. RRFERENCES

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