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# Design and Manufacturing of Water Chiller for Process Industry

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**Abstract:** Refrigeration can be costly in terms of equipment and energy, if not done correctly will fail to achieve its objectives and lower the quality and safety of the product. To ensure that refrigeration is effective, we need to be able to calculate, heat load, fluid temperatures, over all dimensions of the system. The aim of this project is to design a water chiller which chills water from a temperature of 20°C to a temperature of 15°C. The refrigerant used is R-407C, which is ozone friendly. Incorporated in this report is the literature study, which discusses the components of the chiller and the detail design of the chiller, including the specifications of the standard components and the designs of the heat exchangers is mentioned. The standard components specified for this chiller are the compressor, condenser, expansion valve, evaporator, fan and water pump. The housing of the entire system was also designed. Initially we have calculated the value of heat load then depending on capacity entire system is divided into two sub systems, out of which one is working & one is stand by unit. In evaporator we have calculated temperatures of water, shell diameter, number of tubes by taking standard tube diameter. Similarly we have calculated temperatures of refrigerant in condenser. Now from safety point of view various safety instruments like flow switches, purge valve, thermostat, pressure switches, solenoid valve, etc. are installed wherever required. Also for easy control of the equipment various display devices and control switches are provided.

## I. INTRODUCTION

### A. Chiller

A chiller is a system which functions to chill or cool water to desired temperatures which is usually a temperature of about 15°C. This is a thermodynamic vapour compression system which can be used for air-conditioning, industrial and aerospace applications. A water chiller has four main parts: evaporator, condenser, compressor and expansion valve. The main purpose of a water chiller is to remove the heat from water and replace the heat with cold. Not only does a water chiller remove heat from water, it removes heat from the air surrounding the water. An inlet of water at a temperature of about 20 to 30°C flows through a heat exchanger which works as an evaporator. This is to remove the heat and thus cools the water. A cold refrigerant is generally used to boil the gas, and the pressure is increased using a compressor. This vapor is then at a temperature higher than that of the ambient. The heat absorbed from the water, and the work of the compressor is then released to the environment, and as a result, the refrigerant is condensed. The refrigerant then flows through an expansion valve which decreases the temperature, before it once again flows through the evaporator and the cycle begins again.

### B. Vapour Compression Refrigeration(VCR)

Heat flows naturally from hot to cold body. In refrigeration system the opposite must occur, i.e. heat flows from a cold to hot body. This is achieved by using a substance called refrigerant, which absorbs heat and hence boils or evaporates at low pressure to form a gas. This gas is then compressed to higher pressure, such that it transfers the heat it has gained to ambient air or water and turns back (condenses) into liquid. In this way heat is absorbed or removed from a low temperature source and transferred to a higher temperature source.

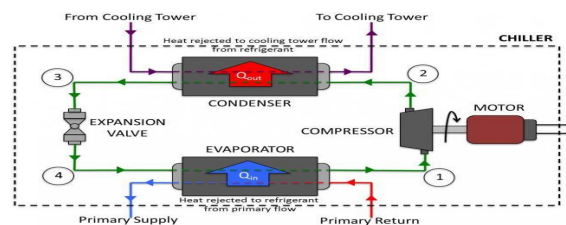


Fig. 1 -Experimental Setup



FIG.2



FIG.3

## II. PROBLEM STATEMENT

**Design and manufacturing of customized water chiller for industrial application (food process industry).**

Design parameters:

Inlet condition of water = 20 °c

Outlet condition of water = 15 °C

Capacity= 16TR

## III. OBJECTIVES

To design and manufacture an effective, user friendly and environmental safe water chiller which will meet the industrial requirements and industrial and environmental norms.

To make the system energy efficient and reduce the environmental impact.

## IV. CALCULATIONS

For this design, it is assumed that steady-state processes exist. Therefore, time-varying effects are not considered, other than when considering the reliability. Slight pressure drops which do not have a significant effect will be considered as negligible for this design.

Selection Parameters of Refrigerants:

*A. Physical Properties*

1) *Vapor Density* : To enable use of smaller compressors and other equipment the refrigerant should have smaller vapor density.

2) *Enthalpy Of Vaporization*: To ensure maximum heat absorption during refrigeration, a refrigerant should have high enthalpy of vaporization.

3) *Thermal Conductivity*: Thermal conductivity of the refrigerant should be high for faster heat transfer during condensation and evaporation.

4) *Critical Temperature* : In order to have large range of isothermal energy transfer, the refrigerant should have critical temperature above the condensing temperature.

5) *Critical Pressure*: Critical pressure of the refrigerant should be higher than the condenser pressures. Otherwise the zone of condensation decreases and the heat rejection occurs.

6) *Evaporative Pressure*: This is the most important property of refrigerant. In a negative pressure evaporator Atmospheric air or Moisture will Leak into the system. The moisture inside the system will starts freezing at low temperature zones and clogs and chokes the system.



7) *Condensing Pressure*: The lower the condenser pressures the power required for compression will be lower. Higher condenser pressure will result in high operating costs. Refrigerants with low boiling points will have high condenser pressure and high vapor density. The condenser tubes have to be designed for higher pressures which also give raise to capital cost of the equipment.

8) *Heat Transfer Coefficient* : Higher heat transfer coefficient requires smaller area and lower pressure drop. This makes the equipment compact and reduced the operating cost.

#### B. Chemical Properties

1) *Oil Solubility* : The lubricating oils must be soluble in Refrigerants. If the oil is not miscible in the refrigerant used and it is heavier it will settle down in the evaporator and reduces the heat transfer. Therefore, oil separators are to be employed. If the oil density is less than the refrigerant used and it if it is immiscible, the oil will float on the surface of the refrigerant. Therefore, overflow drain is to be provided to remove oil. If the refrigerant velocity is not sufficient, then it cannot carry all oil back into the compressor. It may accumulate in evaporator. This phenomenon is called Oil logging.

2) *Water Solubility*: Most of the refrigerants form acids or bases in the presence of water. This will cause corrosion and deteriorates valves, Seals and Metallic parts. Insulation of windings in hermetic compressors will also get damaged. The free water apart from the dissolved water in refrigerant freezes below 0°C and chokes the narrow orifice of expansion valve. This may also cause bursting of the tubes.

3) *Reactivity*: The refrigerants should not react with the materials used in refrigeration cycle like evaporators, condenser tubes, compressors, control valves etc. Ammonia reacts with Copper and Cuprous alloys and forms copper complexes. CH<sub>3</sub>Cl reacts with Aluminium. Most of the refrigerants form acids with water. CCl<sub>2</sub>F<sub>2</sub>, CH<sub>4</sub>Cl can form HCL with water which dissolves the copper from condenser tubes and deposits them on compressor pistons and deteriorates the life of the machinery.

#### C. Safety:

1) *Toxicity*: The refrigerant used in air conditioning, food preservation etc. should not be toxic Refrigerants will affect human health if they are toxic.

2) *Flammability*: The refrigerant should not make combustion mixture in Air. Freon, Carbon Dioxide, SO<sub>2</sub> are nonflammable. Methane, butane and other hydrocarbons are flammable. Ammonia will form explosive mixture when the concentration in air is between 16 to 25 %.

3) *Leak Tendency*: The refrigerant may leak out of the system. The problems with leakage are wearing out of joint or the material used for the fabrication of the system. A denser refrigerant will have fewer tendencies to leak as compared to higher density refrigerant. The detection of leaks should be easy to loss of refrigerant. Leakage can be identified quickly if the refrigerant has distinct color or odor.

#### D. Effect on Environment

1) *ODP(Ozone Depletion Potential)*: According to the Montreal protocol, the ODP of refrigerants should be zero, i.e., they should be non-ozone depleting substances. Refrigerants having non-zero ODP have either already been phasedout (e.g. R 11, R 12) or will be phased-out in near-future (e.g. R22). Since ODP depends mainly on the presence of chlorine or bromine in the molecules, refrigerants having either chlorine (i.e., CFCs and HCFCs) or bromine cannot be used under the new regulations .

2) *GWP(Global Warming Potential)*: Refrigerants should have as low a GWP value as possible to minimize the problem of global warming. Refrigerants with zero ODP but a high value of GWP (e.g. R134a) are likely to be regulated in future.

#### E. Cost of Refrigerants

The quantity of refrigerant used in industries is very less. The cost of the refrigerants is generally high when compared to other chemicals in the industry. Very low industry professional will not take necessary action to control the leaks.

#### F. Availability:

Refrigerants should be readily available near the usage point. It must be sourced and procured within a short span of time to enable the user in case of leaks, maintenance schedules etc.

### V. SELECTION OF REFRIGERANT

R-407C

*A. Composition*

(R-32 / 125 / 134a) • (23 / 25 / 52 wt%)

*B. Replaces*

R-22

*C. Application*

Medium temperature commercial and industrial refrigeration and residential and commercial air conditioning

*D. Performance*

Lower discharge temperature

Closest capacity match to R-22

Similar P/T and flow properties = no component changes

*E. Lubricant*

Polyolester lubricant

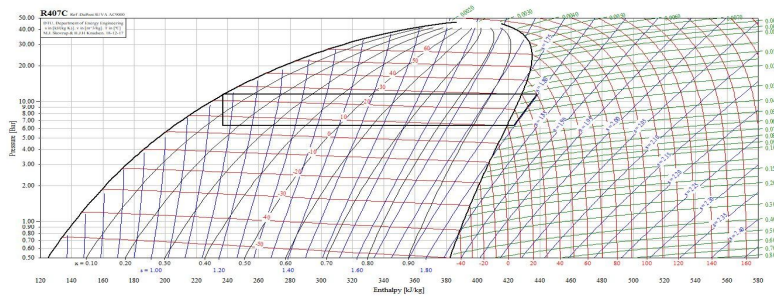


FIG.4 -P-h Chart of R407C- Cycle plot

Table 1: Comparison chart of refrigerant (values from Coolpack software)

Sr. No.	Refrigerants	COP	W (KW/kg)	Qe (KW/kg)	Ps- Pc (bar)
1	R407A	6.6	23	153	7-20
2	R404	6.2	18.4	115	8-20
3	R22	6.88	23.7	162	7-18
4	R134A	6.9	21	140.5	4-12
5	R410A	8.8	24	215.9	10-28
<b>6</b>	<b>R407C</b>	<b>6.8</b>	<b>25.1</b>	<b>159.8</b>	<b>6.5-18</b>
7	R409A	5.6	28.5	160.17	4-12

### VI. THERMODYNAMIC CALCULATIONS

Table 2. Given conditions

Specification	Symbol	Value
Cooling capacity	Qc	8TR
Inlet temperature (water)	T <sub>wi</sub>	20°C
Outlet temperature (water)	T <sub>wo</sub>	15°C

**A. Compressor Selection**

Condensing Temperature: 30

Evaporating Temperature: 10

Condensing Pressure: 11.55.7 bar

Suction Pressure: 6.327 bar

The specific enthalpy of superheated steam can be found out from coolpack software:

$$h_1 = 423.67 \text{ kJ/kg}$$

1

$$h_2 = 438.7 \text{ kJ/kg}$$

2

$$h_3 = h_4 = 236.8 \text{ kJ/kg}$$

3 4

$$R.E = h_1 - h_4$$

1 4

$$= 423.67 - 236.8$$

$$= 186.87 \text{ kJ/kg}$$

Flow rate of refrigerant =

$$= 0.2 \text{ kg/sec}$$

Power required for compressor

$$P = m \times (h_2 - h_1)$$

2 1

$$= 0.2 \times (438.7 - 423.67)$$

$$= 3 \text{ KW}$$

Compressor Emerson Copeland ZR81KCE-TFD-522 is selected it is Scroll Compressor. Reciprocating Compressor for the given requirements are also satisfying the criteria but to have quieter operation Scroll Compressor is selected.

ZR81KCE-TFD

HFC, R-407C, Dew Point, 50 Hz, 3 - Phase, 380/420 V



**FIG.5 : Emerson Copeland Scroll Compressor**

### ZR81KC, KCE

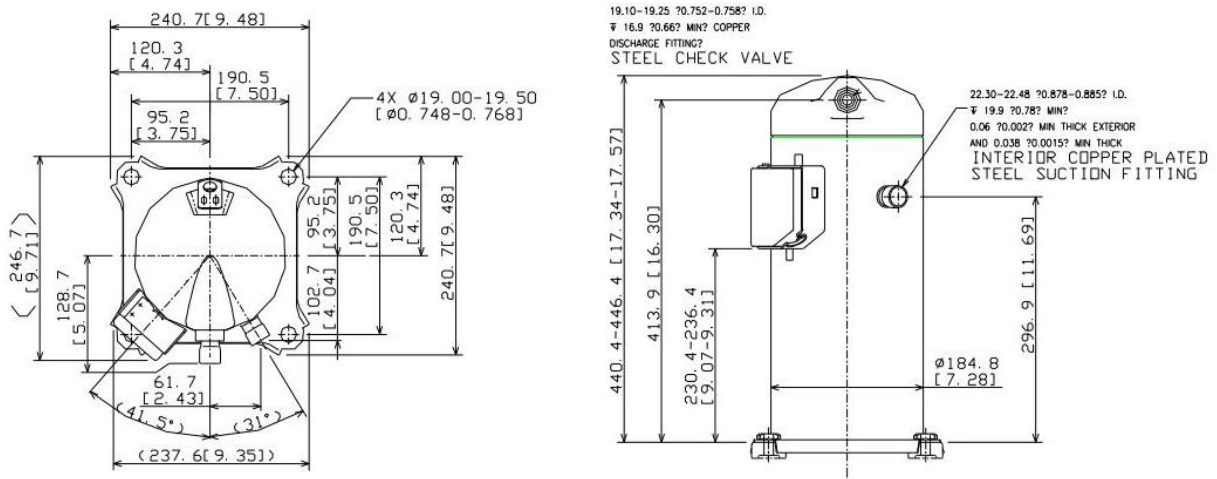


Fig:6: Emerson Copeland Scroll Compressor

### VII. EVAPORATOR DESIGN

#### A. Customer Requirement

Cooling Load – 16 TR

R407C inlet temperature - 10

Temperature Reduction-20 to 15

Energy balance equation is given by,

$$Q = m \cdot w \cdot (h_1 - h_2)$$

Flow rate of refrigerant  $M_c =$

$$= 0.2 \text{ kg/sec}$$

$$Q = m \cdot c_{pc} \cdot (T_{co} - T_{ci})$$

$$16 \times 3.517 = (T_{co} - 3)$$

$$T_{co} = 13.706$$

Logarithmic mean temperature difference (LMTD),

Inner diameter of tube ( $d_i$ ) = 16mm

Outer diameter of tube ( $d_o$ ) = 19mm

(from table 8.1 pg no 289. BWG Gauge 18, od of tubing: Heat exchanger selection, rating & thermal design-KAKAC)

Properties of tube side fluid (R407C) at 4

$$C_p = 0.8610 \text{ J/kgK}$$

$$K = 0.0129 \text{ W/m K}$$

$$= 1272 \text{ kg/m}^3$$

$$= 1.2610 \text{ N-sec/m}^2$$

Properties of shell side fluid (water) at avg. temperature 283K.

$$C_p = 4.184 \text{ J/kgK}$$



$$K = 0.583 \text{ W/m}^2 \text{ K}$$

$$Pr = 8.61$$

$$= 1000 \text{ kg/m}^3$$

$$= 10.14910^{-4} \text{ N-sec/m}^2$$

First estimate the no. of tubes(STR)

$$A_0 =$$

(Consider Value of U from table 9.5, HEAT EXCHANGERS Selection, Rating, and Thermal Design, 3rs edition by kakaSadik)

$$= 2.678 \text{ m}^2$$

Assume length of evaporator as 6 feet= 180 m long

$$N_t = 21 \text{ tubes}$$

(as per table no. 8.3 , page no.294 ,Heat exchanger design by kakac)

Inner shell diameter

Where,

CL=tube layout constant

$$CL = 0.87 \text{ for } 30 \text{ \& } 60$$

CTP= tube count calculation constant....(Page no. 303)

$$CTP = 0.5 \text{ .... for 8 tube passes}$$

$$D_s = \{ [42 \cdot 0.87 \cdot (0.0254/0.0190)^2 \cdot (0.019)^2] / (0.7850.5) \}^{1/2}$$

$$= 0.202 \text{ m}$$

$$= 202 \text{ mm}$$

$$8 \text{ inch}$$

Baffle spacing:-

$$B = (1/5) \text{ (Shell I.D.)}$$

$$= (1/5) \cdot (0.202)$$

$$= 0.4 \text{ m}$$

Equivalent diameter:-

$$D_e = 0.0202 \text{ m}$$

Reynold's no. can be calculated as

$$= 36228.6$$

Assuming constant properties,the heat transfer coefficient can be estimated from

$$= 5723.96 \text{ W/m}^2 \text{ K}$$

Tube side heat transfer coefficient:-

$$= 190195.33$$

$$= 717.81 \times (0.099/0.016)$$

$$= 4107.69 \text{ W/m}^2 \text{ K}$$

The overall heat transfer coefficient for clean surface is

$$=$$

$$\text{W/m}^2 \text{ K}$$

(U cal- Uassumed / U assumed) is less than 0.3 hence calculations as permissible.

**For individual evaporator,**



Shell diameter

No. of tubes

Length L=1.8m

Outertube diameter

Inner tube diameter

Square tube pitch PR= pitch ratio= 1.25

Baffle spacing B= 0.04m

### VIII. CONDENSER DESIGN

Refrigerant R407C

Evaporating temperature: 10

Condensing temperature: 30

Inlet temperature of water: 23

Outlet temperature of water:28

No. of passes –4

Assuming length of tube as 4 feet.

Taking BWG gauge factor 18 and OD of tubing ¾ inch.

(Ref: data from 3D labs Ebook)

I.D. of copper tube -16mm

O.D. Of copper tube- 19mm

Heat rejected to single condenser

$$\begin{aligned} \text{heat rejected in the condenser} &= (\text{refrigerant flow rate}) (h_2 - h_3) \\ &= 0.2 \times (438.7 - 236.8) \\ &= 40.33 \text{ KW} \end{aligned}$$

Heat rejected by dual condenser = 80.66 KW

Logarithmic mean temperature difference:-

LMTD =

$$= 5.14$$

Outside Tube surface area:-

$$\begin{aligned} A_0 &= \\ &= 3.712 \text{ m}^2 \end{aligned}$$

(Consider Value of U from table 9.5, HEAT EXCHANGERS Selection, Rating, and Thermal Design, 3rs edition by kakaSadik)

Number of tubes

Nt= 51 tubes

The flow rate of water =

$$\begin{aligned} &= \\ &= 1.93 \text{ kg/s} \end{aligned}$$

Volume flow rate is

$$\begin{aligned} &= \\ &= 1.93 \times 10^{-3} \text{ m}^3/\text{sec} \end{aligned}$$

Velocity of water through tubes

$$\begin{aligned} V &= \\ &= 1.89 \text{ m/s} \end{aligned}$$

Condensing coefficient:-



$$h_{cond} = 0.725$$

the density and latent heat of vaporization  $h_{fg}$  at 30

$$= 1.109 \text{ kg/l}$$

$$= 1109 \text{ kg/m}^3$$

$$h_{fg} = 191 \text{ kJ/kg} \quad (\text{Coolpack software})$$

$$K = 0.0155 \text{ W/mK}$$

$$= 0.000142 \text{ pa-s}$$

The average no. of vertical tubes in a vertical row N is

$$\text{Assuming } 5 \text{ k}$$

$$h_{cond} = 0.725$$

$$= 504 \text{ W/m}^2 \text{ k}$$

Conductivity of copper is 390 W/mK and resistance of tube is

$$= 0.000002735 \text{ m}^2 \text{ K/W}$$

Fouling factor

$$0.000176 \text{ m}^2 \text{ K/W}$$

Water side coefficient:

Properties of water at 32

$$= 0.000773 \text{ pa-s}$$

$$C_p = 4190 \text{ J/kg.k}$$

$$K = 0.617 \text{ w/mk}$$

Water side heat transfer coefficient:-

$$h_w = 5548.69 \text{ W/m}^2 \text{ K}$$

Overall heat transfer coefficient:-

$$= 0.000176$$

$$= 0.0004269$$

$$= 2342.2 \text{ W/m}^2 \text{ K}$$

(U cal- U assumed / U assumed) is less than 0.3 hence calculations as permissible.

Diameter of shell Ds

$$D_s = \times$$

CTP is the tube count calculation constant: For 4 tube passes CTP= 0.8

CL is the tube layout constant: CL=0.87 for 30 and 60





**Table 3: Piping and Instrumentation Diagram Description**

SR. NO.	COMPONENT NAME	Description	QTNV
1	Evaporator	Shell and tube type-Bundle type- Insulated	1
2	Condenser	Shell and Tube type	2
3	Compressor	Scroll	2
4	Expansion Valve	Thermostatic	2
5	Solenoid Valve	-	2
6	Sight Glass Ball Valve	-	2
7	Dryer	-	2
8	Ball Valve	-	16
9	Pump	Centrifugal	6
10	Strainer		6
11	Cooling tower		1
12	Tank	-	1
13	Pressure Gauge	-	4
14	Flow control valve		1
15	Pressure Relief Valve		2
16	Purge Valve		2

## XII. CONCLUSION

The project covers the design of a chiller, which is both efficient and environmentally friendly. The requirement of the chiller is to deliver chilled water at 15°C from a temperature of 20°C, at a flow rate of 1000 l/hr. The total system capacity is 16TR for which two systems of 8 TR each is designed for varying cooling load. The literature study allowed for knowledge gained in terms of the workings of the system components, and the types of materials and heat exchangers that should be used. A functional analysis is been done to specify which each main component is required to do in the system. Concept generation and concept selection was then done to determine the best heat exchangers for the system as well as the best layout for the system Two. separate cycles of the system with a common single shell evaporator with a vertical separator throughout in the center of the shell is selected in order to make the system compact and also reduce the cost of the system. Detail design and selection of components was then done for the



standard components. And detailed drawing was made for the components which needed to be manufactured. Piping and instrumentation diagram and cad model of the system was made in order to facilitate proper assembly of components. In conclusion, this chiller is energy efficient and environmentally friendly. The chiller meeting the customer requirements is been manufactured which fulfills the industrial and environmental norms.

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