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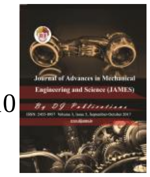

RESEARCH ARTICLE

Capillary Design for Fractional Tonnage Portable Air Conditioner

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ABSTRACT

Refrigeration air conditioning equipment is one of the common household appliances made in large numbers to attain reliable design, quality rich product with cost efficiency. Capillary is the key component, in which the design is empirical based on air flows over heat exchangers of condenser, evaporator, compressor and refrigerant mass flow. Though there are theoretical models, it is very difficult to get an optimum design. Practically, large manufacturers carefully optimize the capillary designs. In this study, the procedure for capillary design and selection is presented to obtain designed pressure drop between condenser and evaporator and to fulfill the role of metering in the air conditioner system.

Keywords: Capillary design, Efficiency improvement, Portable air conditioner, Optimization, Load variation.

1. INTRODUCTION

The basics of capillary function in reducing condenser pressure to evaporator pressure have been mentioned in [1]. The capillary parameters which give rise to the differential resistive pressure are length and internal bore. The thickness of the capillary is not a design parameter. It is determined by the manufacturer for strength purpose and brazing considerations.

As the air conditioning refrigeration cycle is a closed cycle, the refrigerant pumped by the compressor for a given load should necessarily pass through the capillary that matches the flow rate in order to prevent flooding or starving of flow. [2] The efficiency is maximum for a balanced system with uniform continuous flow. As compressor capacity rating is fixed for a selected capacity, only the refrigerant mass and the capillary design are the independent variables. As mass is also grossly known for the capacity, it is the capillary size that controls the refrigeration flow. Hence it is called the metering system of the air conditioner.

Matching the flow through compressor and capillary at the designed capacity is often called normal load. When the load changes to lower (rainy season) or to a higher value (peak summer), the balance of flow shifts from optimum and would have less efficiency.

Table 1. Capillary metering for different loads

Load	Evaporator pressure Pisa	Condenser Pressure Pisa	Pressure drop Pisa	Pressure Ratio
Low	65	265	200	4.08
Normal	90	315	225	3.50
High	105	415	310	3.95

Table 1 provides the condenser and evaporator pressures, pressure drops and pressure ratios for different loads. The capillary is selected for the normal load and adjusted to perform under low and high loads. Flow resistance causes more pressure drop. Resistance is more, if capillary length is more or the bore is less. When resistance is more, for a given condensing pressure, the condensing-evaporating

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pressure increases, hence suction pressure gets lowered than required.

When capillary length is short or bore is large, resistance is less and more refrigeration flows to the evaporator which cannot vaporize. When resistance is more, the phase of the refrigerant may not change totally and more refrigerant gas may be present along with the liquid, thus causing less refrigerant effect. However, a capillary would work effectively for a range of load, though not at optimum level.

The advantage of capillary over shut off expansion valves is that when power and compressor are off, the device is not shut off; but the high and low side refrigerant pressures equalize, so that when power returns and compressor restarts, there will be no load on the motor and the starting torque requirements can be less.

If excess refrigerant is charged during off cycle, the liquid refrigerant might enter the evaporator or compressor and cause failure of valves. Specially, in air conditioner with rotary or scroll compressors, where the refrigerant enters the compressor cylinder directly, a liquid refrigerant accumulator is kept between the outlet of evaporator and inlet of compressor. Accumulator acts as a reservoir to hold excess liquid in the off, equalized condition or to provide required refrigerant for high loads. The function of the accumulator is to prevent the liquid refrigerant from entering the compressor when switched on.

Also, it is better to keep the capillary bore as small as possible, so that liquid refrigerant is retained in the condenser in the compressor off position. Also, a strainer (filter) is connected between the condenser-out and the capillary-in to prevent the moisture, dirt and debris from entering the compressor which has precision mating parts, like suction and discharge valves that may fail. It is a good practice to solder the capillary to the compressor suction tube to keep it cool and make only liquid refrigerant enters the evaporator.

The practical assembly problems are discussed in [3, 4]. There should be no kinks in the capillary bend; it should be smooth around a circular path, which is the smallest circle that can be no less than a finger size. Capillary can be inserted in the evaporator-out which forms the inlet to the compressor for better results. Also, if thermostats are used for sensing for setting temperatures, they will perform well if kept between fins of evaporator. [5-7] have given a detailed compressor performance calculations based on fundamental equations of thermodynamics. More detailed analytical models are available in [8, 9]. Further, researches to provide capillary for alternate refrigerants and capillary design for such models are provided [10-14]. This capillary design procedure for R22 can be extended to other alternate refrigerants replacing R22. R22 has been changed over in many countries, and India needs to totally stop using R22 by 2020 as per Montreal & Kyoto protocols. The possible replacement gases for R22 are R407c, R404a, R232a, R134a and hydrocarbons. Capillary design to these refrigerants has to be established.

All the above advantages make capillary the right choice for large production of air conditioners. As per this procedure, it is necessary to calculate flow rates (φ), for given system capacity and capillary inlet pressures. Also, we can calculate capillary lengths for different bores and flow rates (φ) from the charts provided by ASHRAE. In this study, these charts are used for calculation. Also, for capillary design, many manufacturers use this practical method of calculation and gets data from charts, for example, Tecumseh products [8]. Tecumseh is one of the largest manufacturers of hermetic compressors. This manual is used by Tecumseh for all air conditioners using compressor. In this study capillary design and selection is done for 0.75ton mobile air conditioner with R22 refrigerant. A mixture of British, FPS & SI system of units is used in this report.

2. AIR CONDITIONER REQUIREMENT

At present, air conditioner becomes a basic household requirement. The purpose of air conditioner is to provide better atmosphere throughout the day for better living. ASHRAE document 55 has defined the region of psychrometric space which is a comfort zone. Four parameters to be controlled are:

- Room temperature: The main function of an air conditioner is to quickly bring the ambient temperature to the set value. Generally, the comfort temperature is set about 21 to 26°C. The set temperature, 21°C will be maintained at the evaporator outlet.

- Air humidity: Dehumidification is obtained by setting the evaporator temperature below the dew point temperature. As the air with high specific humidity passes over the evaporator coil, moisture in air condenses. Humidity causes major discomfort in such areas as a person sweats more in such conditions. Air humidity can be controlled by decreasing or increasing the moisture contents of air during summer or winter respectively in order to produce comfortable and healthy conditions. Humidity control is not only necessary for human comfort but it also increases the efficiency of the workers. In general, for summer air conditioning, the relative humidity should be less than 60% whereas for winter air conditioning, it should be more than 40%.
- Air purity: In addition to the above two main parameters of humidity and temperature control, present air conditioners provide filters to clean air and kill bacteria and fungus present in air which is let into the room. Many cities have high pollution and the sulfur and nitride oxides need to be properly filtered. Purification of air is essential both at residential homes and working environments.
- Motion of air: The air flow both over evaporator and condenser is very important for good heat transfer. The distribution of air should be uniform without causing any flow disturbance. In conditioned system, the ducting air can be released at multiple points within the room space.

Domestic air conditioners (AC) are basically

1. Window air conditioner or unitary air conditioner
2. Split air conditioner
3. New types of portable or spot air conditioners are also getting into the market.

The main difference in window and split AC is that high and low pressure side systems are located in one single unit called unitary system in a window AC, whereas in split AC, the high side unit is kept outside and the low side unit is kept inside the room. For a portable unit, both evaporator and condenser are inside the room, and have the same ambient temperatures to heat exchange.

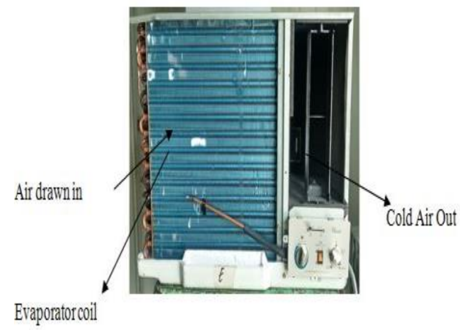

Figure 1.Front view of a room air conditioner

Figure 1 shows the evaporator. The air with ambient temperature is drawn in by the blower as it passes through evaporator coil, and the air temperature drops and flows out at the lowered temperature. Iteratively, the temperature reduces to the set temperature which is monitored by the thermostat. The limit of the set value is the evaporating temperature.

3. AIRCONDITIONING PROCESS

Refrigeration air conditioners use a closed thermodynamic flow of refrigerator, R22. In our study, a difluoromonchloromethane HCFC-22 refrigerant is used. As it has a chlorine molecule, it possesses ozone depleting and high global warming potential. Its use for new air conditioners is allowed only up to 2020 in India, where the alternate refrigerants are in evaluation. The refrigerant goes through a closed Rankin cycle as in figure 2. In figure 2, point 1 is the entry of refrigerant from the evaporator to the compressor, where it gets compressed isentropically from 1-2 to the condenser pressure and at a superheated state point 2. In the constant pressure process in the condenser 2-3, the superheated gas loses heat and then phase change occurs and finally sub cooled state 3 is achieved. Process 3 to 4 occurs in the capillary, an isenthalpic process, and the pressure reduces to evaporator pressure. The sub cooling from saturation point to point 3 provides more refrigeration effect as the length of 4-1 increases. The specific heat per unit mass is considered and heat equations of refrigerant are described.

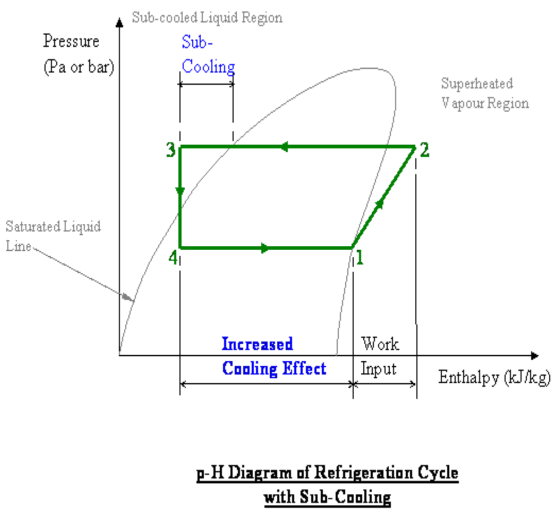

Figure 2.Air conditioning cycle, from net.

Let, h_1, h_2, h_3 and h4 are enthalpies at state points 1, 2, 3 and 4 respectively as shown in figure 2.
The refrigerant effect is $h_4 - h_1 = h_{41}$
The compressor work is $h_2 - h_1 = h_{21}$
Coefficient of performance, COP = net refrigerant effect / net-work input.

$$COP = h_{41} / h_{21} = T_l / (T_2 - T_l)$$

where, T_2 is condenser temperature and T_l is evaporator temperature. Psychrometric method is used to obtain the capacity of air conditioning.

4. CAPACITY CALCULATION OF AIR CONDITIONER

Air conditioner is tested using psychrometric method by measuring the enthalpy of air as per IS 1391 standards. Table 2 gives the normal load test conditions to be maintained in the two rooms. The test air conditioner is kept in a window between the two rooms.

Table 2.AC capacity rating conditions for test rooms

Temp / Room	Dry Bulb Temperature (DBT)	Wet Bulb Temperature (WBT)
Indoor	27	19
Outdoor	35	24

To calculate the exact cooling capacity, it is required to maintain accurate dry and wet bulb temperatures at both indoor and outdoor rooms of testing as per the ISI standards. The test conditions for an hour before taking readings are stabilized. The air out of air conditioner (V_{air} m/s) by anemometer is measured and then the area of the air conditioner outlet air evaporator side (A m^2/s) is calculated.

$$Q_v = A * V_{air}, m^3/s$$

The air volume flow rate (Q_v) is calculated in the room cooling capacity (Q) and can take the readings after continuous running of 1hour period at balanced ambient only.

We can calculate the cooling capacity by using psychrometric chart.
$Q = m (h_1 - h_2)$
h = Enthalpy
m = mass flow rate.

Then h_1=63kJ/kg (from psychrometric chart)
DBT = 16°C
WBT =13.5°C
h_2=32kJ/kg.

Mass flow rate = Density X CFM (cubic feet per minute of air flow)
=0.00612x1231.78Kg/hr
(density from psychrometric chart)
Capacity= 0.00612x1231.78x (63-32) =8414 Btu/hr

The values of capillary selection of mobile air conditioners used indoors are,

- Capacity 9000 Btu / hr
- Suction pressure: 72Psig
- Discharge pressure: 275 Psig
- Sub cooling: 10F
- From chart h1=45 Btu/lb, h3=110Btu/lb, Refrigerant effect= 65 Btu/lb
- Actual mass flow rate = capacity /refrigeration effect=9250/65=142.5lbs/hr.
- Theoretical mass flow from chart: 275Psig, sub cooling 10F is =70lbs/hr
- Flow factor φ = Actual mass flow rate/ Theoretical =1.02
- From graph, for flow factor φ, of 1.0; bore of 0.080"; length is 50"length
- Suitable capillary selected of 0 .080" bore 50" length

- Note, 1 KW, Power = 3412.14 Btu/hr; 9000Btu/hr =2.64 KW

This air conditioner is tested at Tecumseh products limited for assessing performance parameters and gas charge as in table A1. Gas charge of 350g is found to be better than 400g. A 0.75ton rotary compressor of Tecumseh is used, which is a high side compressor with discharge gas in shell; A typical shell top temperature is about 103.4℃. The motor thermal rating should be high to withstand this temperature. The overall sound of the mobile air conditioner is 64dB, which is the acceptable range.

4.1. Compressor work

It can be seen from the above diagram that the compressor compresses refrigerant from 70Psig to 365Psig.

The compressor work can be calculated as follows;

$$W_{comp} = m_{ref}(h_2 - h_1)$$

where,

W_{comp} = Compressor work (kW)

The specific heat work input to the compressor is 315 kJ/kg - 242 kJ/kg = 73 kJ/kg.

If the refrigerant flow rate in the above example is 0.3 kg/s, then the compressor heat capacity is,

m_{ref} = Mass flow rate of refrigerant (Kg /hr)

h_2 = Specific enthalpy at point 2 (KJ/Kg)

h_1 = Specific enthalpy at point 1 (KJ/Kg)

$W_{comp} = m_{ref*}(h_2 - h_1)$

$W_{comp} = 0.00612x\ (73)$, $W_{comp} = 21.9$ kW

4.2. Refrigeration effect

The refrigeration effect can also be determined from the above diagram by using the following formula,

$$RE = m_{ref}(h_1 – h_4)$$

where, RE = Refrigeration or cooling effect (kW)

m_{ref} = Mass flow rate of refrigerant (kg/S)

h_1 = Specific enthalpy at point 1 (kJ/kg)

h_4 = Specific enthalpy at point 4 (kJ/kg)

RE = 0.3 (242 – 68) = 55.2KJ/S =KW

4.3. Coefficient or performance

The coefficient of performance is an indication of how efficient a refrigeration system is.

COP = Refrigeration effect / Work input

or

$COP = RE / W_{comp}$

In this example, COP is

$$COP = 52.2 / 21.9 = 2.38$$

Compressor manufacturer expresses efficiency in calorimeter test in Energy Efficiency Ratio (EER). EER units are BTU/HR W. EER is also used in bureau of energy efficiency star rating that they would also express in Seasonal Energy Efficiency Ratio (SEER), obtained by the ratio of capacity of cooling obtained for the whole year over all seasons divided by the power consumed in this period. Indian refrigeration association has defined, ISEER in a similar way. The conversion is 3.412 EER = 1 COP. Hence the 2.38 COP is 8.12EER.

Capillary is a pressure reducing item in the refrigeration system. For an air conditioner with R22 refrigerant (liquid refrigerant) coming out of the condenser at high pressure 300Psig and temperature 55^{o}C, the evaporating pressure and temperature would be 75Psig and 35^{o}C respectively. Expansion valve is also a possible throttling device. It is mandatory to use expansion valves where the capacity is more than 5tons, as the capillary valve has a limitation of its functional use for high flow rates. The disadvantage of expansion valves lies in setting the position of the valve accurately and maintaining this position undisturbed during its life under adverse conditions of transportation and use.

Good technological advancements take place with thermostatic expansion valves where evaporator out sub-cooling temperature is controlled by the capillary pressure drop. Also, accurate electronic pressure drop control is possible. However these are difficult to use in household refrigerators and air conditioners due to price, space and technology involved.

Capillary tubes are the most important part of an air conditioning system with a small bore and large length of path, as the refrigerant passes through this part, the frictional loss of heat energy lowers the temperature and pressure. At the outlet of the capillary, evaporator inlet temperature and pressure are provided. Generally, it is used for low capacity air conditioners below 5ton capacity. The advantages of capillary tubes over expansion valves are

- They would cause equalizing of pressures when switched off quickly to lower the starting torque requirements of the compressor motor.
- They are easy to install, cost less, take less space and can be wrapped in evaporator-out for better performance.
- Can accommodate about 20% of load variation due to seasonal performance.

Capillary tube is called as metering device as it controls the evaporator and condenser pressures. A correct selection is the vital design parameter along with gas charge to optimize capacity and power performance of the air conditioner. The present work is for a 0.75ton, 9000Btu/hr capacity air conditioner. By deciding the condenser outlet pressure and actual and theoretical mass flow rate, flow factor is calculated. The data for figure 3 is taken from American Society of Heating, Refrigerating and Air-Conditioning Engineer, ASHRAE, Handbook [1] and reformatted. For 0.75ton mobile AC, the bore selected is 0.080". The units used are FPS.

The pressure and temperature vary along the capillary. ASHRAE has given a chart of these changes to use for design aspects. Table 3 shows the capillary effect or throttling that causes pressure drop as the refrigerant flows in a capillary. The 0.80" capillary requires longer length as the requirement of pressure drop increases. This looks favorable for water coolers, display coolers or refrigerators.

The pressure drops initially under constant temperature up to 13feet; then both pressure and temperature drop at accelerated rate. Figure 3 shows the drop in temperature and pressure as the liquid refrigerant from condenser passes through the capillary up to the inlet of the evaporator.

Performance parameter of air conditions is given in table 4. For 0.5ton to 2.0ton range, suction pressure is 87Psia and discharge pressure is 300Psia. For sub-cooling of 10°F, this particular sub-cooling in the condenser is as per figure 4. We can read mass flow rate for given condenser pressure.

Table 3.Capillary effect

Temp °F	Distance from inlet, feet	Pressure Psia
88	0.5	165
88	3	155
88	7	140
88	11	122
88	13	112
86	14	108
82	15	102
76	16	92
68	17	78
49	17.5	60
36	17.8	48
16	18.2	35
-5	19.2	22
-0	19.6	15

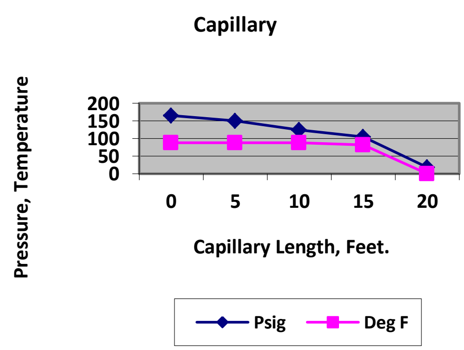

Figure 3.Pressure and temperature along capillary

For superheating to 10°F, the P-h chart of R22 gives h_1 = 45 Btu/lb and h2= 110 Btu/lb, thus results in a refrigerant effect of 65 Btu/lb.

Actual mass flow rate = Cooling Capacity / Refrigerant effect (Lbs/hr).

Table 4.Air conditioning parameters for R22

Sr. No.	Tonnage	Cooling Capacity, (Btu/hr)	Mass flow rate (Lbs/hr)
1	0.5	6000	95
2	0.75	9000	142.5
3	1	12000	190
4	1.5	18000	285
5	2.0	24000	380

Table 4 gives typical mass flow rate and capacity for air conditioners with capacity ranging from 0.5ton to 2.0ton. From figure 4, theoretical mass flow rate 110 Lbs/hr can be obtained for 10°F sub-cooling over condenser, and the outlet condenser pressure, 275Psig. A linear relation of increased mass flow rate with respect to condenser pressure is obtained.

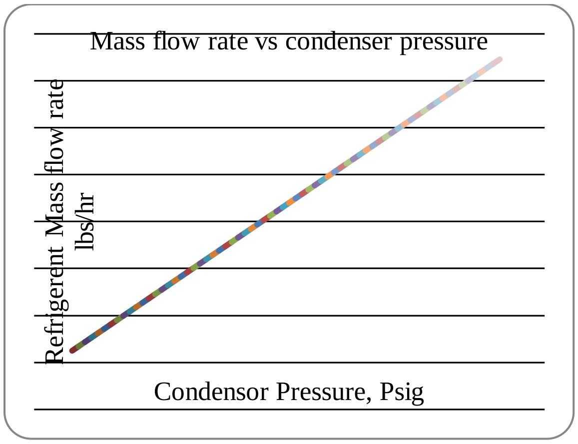

Figure 4.Standard mass flow rate for R22 for 10^{O}F sub cooling

Table 5.Flow factor for different loads

Capacity	Actual mass flow rate	Flow factor, low load	Flow factor, normal load	Flow factor, high load
Tons	Lbs/hr	@250 Psia	@300 Psia	@400 Psia
0.5	95	0.88	0.76	0.63
0.75	142.5	1.32	1.14	0.95
1	190	1.76	1.52	1.27
1.5	285	2.64	2.28	1.90
2	380	3.52	0.03	2.53

A normal air conditioner will experience normal load at 35℃, ambient low load occurs at about 29℃ and high load at 43℃. The corresponding pressures and flow factors are shown in table 5. Flow factor reduces from low load to high load. Similarly, flow factor is increasing with increased load.

$$\text{Flow factor} = \frac{\text{Actual mass flow, 285}}{\text{Theoretical mass flow, 110}} = 2.6$$

5. CAPILLARY DESIGN

For a 0.75ton air conditioner, we take the flow factor of 1.14 for normal load flow factor. Using graph for the flow factors, the length of capillary is determined for a particular bore. Table 6 lists the bores and lengths for different capillary options. Lists of lengths are written for a flow factor of 1.14 from ASHRAE graphs.

Table 6.Capillary design for 0.75ton AC

Sr. No	Bore inches	Length inches
1	0.050	10
2	0.060	35
3	0.70	100
4	0.80	200

Figure 5.Capillaries of different bores

Figure 5 is a picture of capillaries of different bores and lengths. Generally, they come in the coiled forms. The bores can be cross checked with bore gauge pins for verification. The required length can be calculated by the circumference of the coil, and cut or a thread of required length is used as a gauge. In figure 6, additional connectors are fixed; these are useful, if optimization is being done on the system. With shut off valves, these capillaries are connected so that there is no gas leakage and wastage. Capillaries in parallel are connected. Nobody have used capillary in series which can be a new test.

Figure 6.Capillary with end tubes

6. EFFICIENT RUNNING

For efficient running, the evaporator temperature should be as high as possible. This is restricted by the dew-point temperature in an air conditioning application. The condenser temperature should be as low as possible. However, during summer, when maximum cooling is generally required, the condensing pressure is high and the system becomes least efficient. By proper selection of the system metering device (capillary), efficiency can be obtained. This study is done for the mobile spot cooler inside the room and the condenser is not exposed to outside ambient temperature. It runs inside the room and is locally cooled. Hence the temperature of condenser is low and can be set to run at low pressures and temperatures of condenser. 275Psi and 65Psi definitely will give better efficiency than the normal 300Psig and 75Psig. Pressures occur in regular rooms and split air conditioners.

7. CONCLUSIONS

Design and selection of a capillary for a 0.75ton mobile air conditioner is designed using ASHRAE procedure. It is found that for the mobile air conditioner which is inside the room, the pressures are always low. For the flow factor, capillary bore and length selected is 0.070” bore 45” length which is better than 0.060” bore 15” or 0.050” bore 10” length. Though, all three capillaries are theoretically acceptable for the calculated mass flow rate and flow factor, capillary with longer length allows steadier throttling and maintains the desired pressure drops.

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APPENDIX

Table A1.Mobile AC performance test at Tecumseh Lab

TECUMSEH PRODUCTS INDIA Pvt. Ltd., HYDERABAD				
(PRODUCT ENGINEERING DEPARTMENT)				
MOBILE AC TEST REPORT				
-	Gas Charge		Compressor	RKA5513EXC
	350gms	400 gms	Serial No.	04M110941151298X
R.G, °C	34.5	29.5	Capillary	0.080*50
D.G, °C	100.5	97.5	Gas Charge	R-22 400gms
Liquid, °C	52.6	55.5	Condenser Coil	14/14*3 ROW
S.Top, °C	103.4	99.4	Copper Tube	3/8" FPI - 18
S.Bot, °C	86	82.6	Evaporator Coil	12/12*2 ROW
E.In °C	10.1	12.1	Copper Tube	3/8" FPI - 18
E.Out °C	30.7	28.4	Evaporator CFM	355
Volts	230	230	Condenser CFM	322
Amps	4.62	4.89	Fan Motor	COOLON FPH Motor
Watts	1064	1125		230V, 50Hz, 1.41A,
S.P	70PSI	78 PSI		149W, 1/5HP, RPM 930
D.P	350PSI	365 PSI	Sound	64dB