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Development of Simulation Technique for Performance Estimation of Water Cooler

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ABSTRACT

a The temperature of earth is increasing drastically in the past few years due to which water temperature is also increasing. Water cooler is a device used to cool the temperature of water so that it is suitable for drinking purpose. This system works on the principle of vapour compression refrigeration system. CFC 22 is currently used in the system, but because of its high GWP and ODP value it is to be phase out by R290, but different refrigerant have different thermodynamic properties so the same components can not be used for different refrigerants. Mathematical modeling and simulation technique has been widely used for performance prediction and optimum design of refrigeration systems. Simulating a model is an easy and fast method to show how the model responds to the input. If the predicted performance does not meet the requirement, the configuration parameters should be adjusted, and simulation with the adjusted structural parameters will be done again. In this work medium size water coolers 80ltrs and 120ltrs are considered. Required length of the condenser and evaporator is calculated by using section by section method. For simulation of capillary tube Stroker and Jones method is used. Mass flow rate vs. length graph of the capillary tube is plotted assuming different test load condition for both the refrigerants and the results shows that R290 requires almost same length of capillary tube than CFC 22 and the length of capillary tube decreases with decreasing the diameter of the tube. Modeling results of capillary length is compared with DanCap software it shows 10-15% deviation. Length of condenser is heighest for R290.

Keywords— **a** Capillary tube ,Modelling of basic Components, Simulation of water cooler ,Water Cooler

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I. INTRODUCTION

The use of water cooler application has been increasing rapidly in recent years and it has become more important for people's daily life. The water cooler is one of the most electricity consuming product in the world. It has four basic components, i.e. Compressor, condenser, Evaporator, and Expansion valve. CFCs and HCFCs currently used as refrigerants in this application have excellent thermodynamic and thermo physical properties, but due to their high tendency towards ozone depletion potential and global worming potential these refrigerants are banned according to Montreal and Kyoto protocol.

Halogenated refrigerant CFC 22 due to its good thermophysical properties is most commonly used in the water cooler application. But this refrigerant consists of chlorine atom which is more prone to the depletion of ozone layer and it also consist of fluorine atom which has the potential to cause global warming. The hydrocarbon refrigerant R290 has low values of ozone depletion and global warming potentialas given by both the protocols. It also have high enthalpy difference in two phase zone. Higher the enthalpy difference reduces the mass flow rate per unit cooling capacity. The amount of charge required for R290 is nearly 50% lower than that of R22[2]. The hydrocarbon refrigerants has high flammability than CFCs, but due to their low charge the flammability concern is very less.

When certain refrigerant used in existing systems is to be changed the various parameters tests needs to be performed to check whether the alternative refrigerant is suitable for the system. It is important to make the design process of refrigeration systems more efficient and the product performance better. For this purpose numerical simulation techiques has been widely used for design and optimization of new products in refrigeration and air conditioning industries. With the help of these simulation tools researchers can predict the performance of the new product with the help of computers which helps to reduce the time and money to develop the real system in labs.

Vapour compression refrigeration system simulation mainly falls into two categories: steady state and transient state.Steady state in which simulation technique is used for performance prediction and product evaluation and transient state in which simulation technique is used for control design and seasonal performance evaluation. These simulation techniques are performed on four components of vapour compression system compressor, condenser, evaporator and expansion valve.

Compressor draws vapor refrigerant at low pressure through the evaporator and raises its pressure up to condenser pressure for continuous operation of the cycle. Condensers are the heat exchangers those rejects heat to the surrounding fluid. The Condenser should be designed in such a way that it should be capable to reject heat to the surrounding fluid. In the water cooler application fin and tube condensers are used as condensers. Capillary tubes are used as an expansion device in most of the small refrigeration system. When Capacity is less than 10KW generally capillary tube is used as a Expansion Device and that hence they are used in water coolers. Capillary tube is a device with small diameter and large length . The diameter of capillary tube can vary from 0.5mm to 2mm whereas length can vary from 2m to 6m[1].

Simulation techiques help in predicting the performance of each component independently and after steady state is reached these components are integrated in a single program to the predict the performance of entire system.

Nomenclature:

h	Enthalpy kJ/kg
h_{fg}	Latent heat of vaporization kJ/kg
T	Temperature,℃ $or\ K$
S	Entropy, kJ/kgK
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
RE	Refrigerating effect, kJ/kg
COP	Coefficient of performance
W	Isentropic compressor work
P	Pressure, MPa
Q	Total heat load(W)
HCFCs	hydro chlorofluorocarbon
HCs	hydrocarbons
CFCs	chlorofluorocarbons
HFCs	Hydro fluorocarbons
C_p	Specific heat , kJ/kg K
$\dot{m}$	Mass flow rate
dc	Diameter of capillary tube
Ds	Diameter of suction tube
C_{pl}	Specific Heat of liquid.
NTU	Number of transfer unit
ϵ	Effectiveness of heat exchanger
X	Dryness fraction
Re	Reynold number
Nu	Nusselt number
U	Overall heat transfer coefficient
Pr	Prandtl number
L	Length of capillary tube

II. MODELLING OF COMPONENTS

2.1 Compressor modeling:

Compressor is also known as the heart of the vapour compression system. It determines the system capacity and also thecapacity of the expansion valve. Predicting the performance of this component is very important because if there is error in the circulation of mass flow rate it will affect the system capacity.

There are number of compressor models developed so far. According to Zhao et al. these models falls into there categories:

1) Map-based models: these models are based on the extensive experimental data taken from the compressor and it has accurate performance prediction for mass flow rate, power consumption and discharge temperature.
2) Effeciency-based model: these models use isentropic and volumetric efficiency with the help of some empirical or semiemperical formulae and are based on ideal compression process.
3) Detailed compressor model: these models take into each and every process of the compressor such as compression process, heat transfer between refrigerants and compression parts and refrigerant leakage. These models are mainly useful for design of compressor but not useful for system level simulation because of its complexity and high computational time.

2.2 Heat Excahnger Modeling:

Heat Exchangers are used for transfer of heat from one fluid to another. They vary significantly from each other according to its geometry and configuration but from the modeling point of view they are mainly classified in four categories.

1) Lumped parameter model:
This parametric models takes into account whole heat exchanger as one control volume for performance prediction and for calculation the overall heat transfer coefficient UA. This model is mostly used for the cycle analysis of VCR system.
2) Zone or moving boundry model:

In this model the heat exchanger is modeled according to the various phases occurring inside and outside the tube. This model is maily introduced to keep the track of two phase flow in the heat exchangers. Idealy, this model should be capable of handling four region: supercritical region, superheated region, two phase and superheated region.This model is more accurate than lumped parameter model.

3) Finite Volume or distributed parameter model:
In this model the heat exchanger is divided in several segments. Each segment uses the inlet refrigerant state to evaluate the thermophysical properties with the help of coreelations to calculate heat transfer correlation and friction factor. Each segment outlet is considered as the inlet of the next segment. For phase transition region the present segment an be further divided into number of segments.

4) Tube by tube model:
With the help of rigorous and detailed scheme this model simulate the influence of arrangement of refrigerant circuit and tubes on the performance of heat exchanger. In this model each tube can be considered as single control volume or the tubes can be divided into several segments and further analysis can be done by distributed parameter approach.

2.3. Expansion Valve:
In vapour compression refrigeration system capillary tube, valves and orifices are used as an expansion device. Function of expansion device is to expand the fluid coming from the condenser and convert it into liquid form before entry to the evaporator. Based on the modeling approach, expansion devices has two models.

1) Correlation based model:
In this model the correlations are used for predicting the performance of expansion device. Mass flow rate is calculated given the inlet condition and outlet pressure.this model has good accuracy in the range of regression. Correlation based model can work for specific refrigerant but it can fail for other refrigerants.

2) Distributed parameter model:
Compared to correlation based model distributed parameter model have greater accuracy in terms of performance prediction. Depending upon whether the two phase flow is homogeneous or not this model is divided into two groups: homogeneous model in which the slip ration between vapor and liquid is one and separated flow model in which void fraction needs to be evaluated with some semi empirical formulae.

Basically while modeling the capillary tube , the tube is considered as adiabatic. Hence no heat flows through the tube and the enthalpy is equal to the stagnation enthalpy of fluid. But in some application like household refrigerator the process is not adiabatic because it is in thermal contact with the suction line heat exchanger. This inceases the complexicity.

III.DATA REDUCTION

When simulation of any vapour compression system is to be done, mathematical modeling of the compeonents is important. Once the mathematical modeling is done it is easy to simulate the entire system by combining all the components in a single program.

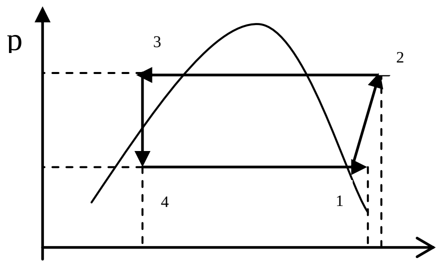

Figure 1: Theoritical Cycle

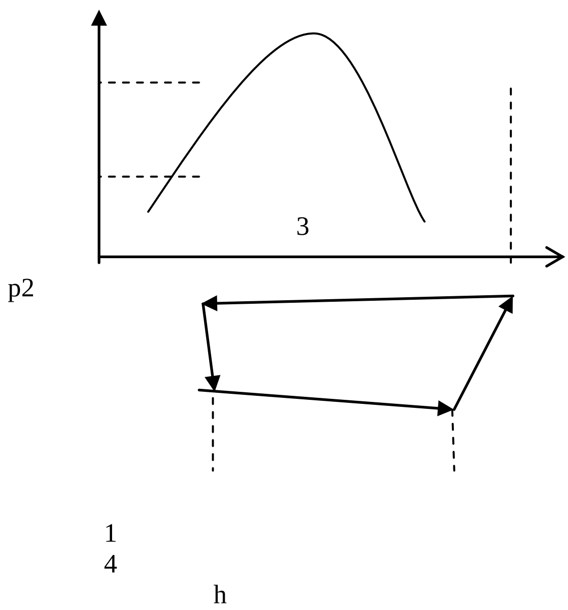

Figure 2: Actual Cycle

Figure shows the therotical cycle in which there is no preesure drop but in ideal case there is some preesure drop occurring in the condenser and evaporator due to friction and momentum in the tubes of heat exchanger. This preesure drop can be seen in the actual cycle figure .
Following are the mathematical equations used for the mathematical modeling of components.

1) Compressor

Generally the process in the compressor is considered to be isentropic theoretically. But due to the inefficiency of the compressor the actual process inside the compressor is never isentropic. The outlet temperature of the compressor depends upon this inefficiency of compressor.

- Theoretical work done by the compressor
- Enthalpy at outlet:

By using the outlet temperature the isentropic outlet enthalpy is calculated.

$$_t = h_{gout} + C_{pg}(T_{sup} - T_{gout}) \quad (1)$$

- Isentropic work done by the compressor:

$$W = \dot{m} \times (h_{out} - h_{in}) (2)$$

- Actual work done by the compressor

Efficiency of compressor is given by

$$\eta = \frac{actual\ work\ done}{isentropic\ work\ done} \quad (3)$$

$$= \frac{(T_{out,actual} - T_{in,actual})}{(T_{out,isentropic} - T_{in,isentropic})}$$

From the above equation actual outlet temperature is calculated.

- Actual COP of the system

$$COP = \frac{Refrigerating\ effect}{Actual\ Work\ done\ by\ the\ compressor}$$

$$= \frac{(h_4 - h_1)}{(h_2 - h_1)} \quad (4)$$

Calculation of the bore and stroke of the cylinder

$$Piston\ displacement\ of\ the\ compressor = \dot{V}_p = \dot{m}v_1 (5)$$

- Piston displacement is also given by

$$\dot{V}_p = \frac{\Pi \times D^2}{4} \times L \times N \quad (6)$$

Where

N= rpm of compressor

Now, from the given rpm and bore to stroke ratio we can calculate the diameterof the compressor in order to select the compressor.

2)Heat Exchanger

Since the condenser is finned tube for each element, the heat transfer capacity is calculated using the ε -NTU method. Air is flowing outside the tube and refrigerant is flowing inside the tube.

$$Q = \varepsilon C_{min}(T_{ref,in} - T_{air,in}) \quad (7)$$

where

$$C_{min} = MIN(C_{ref}, C_{air}) (8)$$

$$C_{air} = m_{air}c_{p,air} \text{and } C_{ref} = m_{ref}c_{p,ref}$$

If C_{min}= unmixed (9)

$$\varepsilon = \frac{1}{C_r}(1 - \exp(-(1 - \exp(-NTU))\, C_{min}/C_{max})) (10)$$

If C_{min}= mixed

$$\varepsilon = 1 - \exp(-\frac{1}{C_r}(1 - \exp(-NTU\, C_{min}/C_{max})))$$
(11)

$$NTU = \frac{UA}{C_{min}} \text{and} c_{r=} \frac{C_{min}}{C_{max}} \quad (12)$$

$$UA = \frac{1}{\frac{1}{h_{ref}A_{t,in}} + \frac{\ln\frac{D_{out}}{D_{in}}}{2*3.14*L*K} + \frac{R_c}{A_{t,out}} + \frac{R_f}{A_{t,out}} + \frac{1}{h_{air}A_{total}\eta_s}} (13)$$

$$\eta_s = 1 - \frac{A_{fin}}{A_{out}}(1 - \eta_{fin}) \quad (14)$$

$$\eta_{fin} = \frac{tnh\ mL}{mL} \text{and} m = \sqrt{\frac{2\, h_{air}}{k\, \delta}} (15)$$

Each heat exchanger element is calculated one by one along the refrigerant flow path from the coil inlet to outlet. The inlet condition of each element is equal to the outlet condition of the previous element.

3)Capillary Tube

As the refrigerant flows through the capillary tube, its pressure and saturation temperature progressively drop and the fraction of vapor x continuously increases. Thus at any point

$$h = (x \times h_g) + (1 - x)\, h_f \quad (16)$$ $$v = (x \times v_g) + (1 - x)\, v_f (17)$$

Now the total drop in the pressure is calculated as follows

$$\Delta p_t = p_{in} - p_{out} \quad (18)$$

Acceleration pressure drop is calculated as

$$\Delta p_a = G \times \Delta V \quad (19)$$

Frictional pressure drop is calculated by

$$\Delta p_f = \Delta p_t - \Delta p_a \quad (20)$$

Incremental length is calculated by the formula

$$\Delta L = \left(\frac{\Delta p_f}{\left(\frac{G}{2d}\right) \times f_{mean} \times V_{mean}}\right) (21)$$

Where

$$f_{mean} = \left(\frac{f_{in} + f_{out}}{2}\right) \text{and } V_{mean} = \left(\frac{V_{in} + V_{out}}{2}\right) \quad (22)$$

$$f = \frac{0.32}{Re^{\ 0.25}} \quad (23)$$

$$V = v \times G \quad (24)$$

IV. SIMULATION & METHODOLOGY

Component models are very important for the performance of system level simulation. The function of system level simulation technique is to combine all the component models toghether according to the relation between component parameter for calculating the system performance provided with some constraints and boundry condition. Steady state simulation tools are most commolnly used for system design . So these simulation tools needs to be efficient , robust and accurate.

While solving the equations the unknown variable are generally thermophysical properties of the fluid. The properties such as capacity and power consumption can be calculated once all the fluid related properties are found out. There are two basic numerical in which this unknown varaibles are solved.

1) Succesive approach
2) Simultaneous approach

In successive approach the unknown variables are solved before moving to the next variables.

This approach is suitable for simple system but it is not suitable as the system gets complicated, mostly in the multistage system.another disadvantage of this system is that if only one parameter is changed entire simulation method needs to be revised again. But this approach has less number of unknown variables are is robust and efficient.

In simultaneous approach the unknown variables are solved simulateneous considering each variable independent of each other when constructing system level equations. This approach is very time consuming and also not economic. Newton raphson method or quasi newton equation solvers are used.

In this study successive approach is used to calculate the system performance. The detail approach is explained with the help of flow chart below.

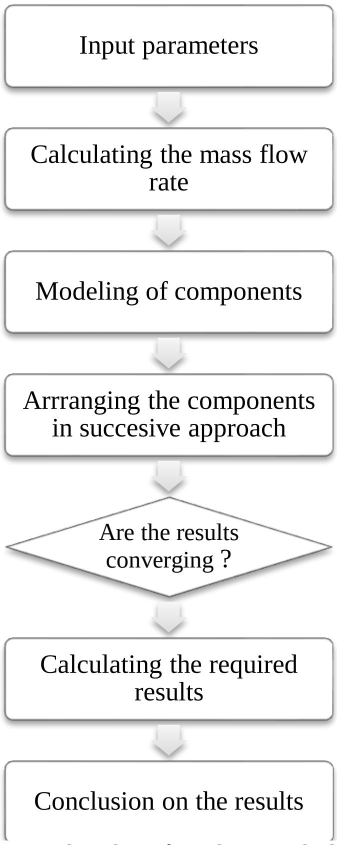

Figure 3: Flow chart of simulation methodology

V. RESULT & DISCUSSION

1) aCapillary tube length calculation:

Storker and Jones model used mathematical equations form 16 to 24 to calculate the incremental length of capillary. The lengths are calculated for different diameters of 1mm, 1.1mm and 1.2mm. Then this results are compared standard software to calculate the required length of capillary tube.

The input parameters given are listed in the following table

Table 1: Input parameters for capillary valve

Parameters	**Value**
Capacity	80ltrs(625watt) 60ltrs(525watt) 60ltrs(500watt)
Condensing temperature	50^0 C
Degree of subcooling	6^0 C
Dryness fraction at inlet of capillary tube	0
Diameter	1mm,1.1mm,1.2mm

The graph of mass flow rate vs length is calculated. Three graphs are plotted for three diameters and length of capillary tube is compared for refrigerants.

From the figures 4a to c and 5 we can see that

a) As the mass flow rate is increased the required length of capillary tube decreases because as the mass flow increases the amount of rate in the evaporator increases which is required for cooling.

b) From figure 6 we can see that the length of capillary tube increases with the increase in the diameter of tube as the friction factor decreases which is responsible for preeure drop.

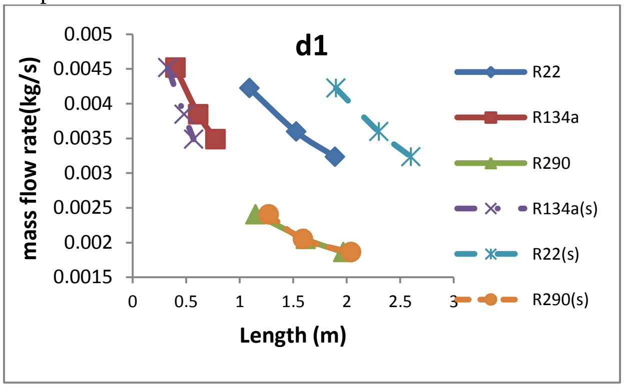

Figure 4a: $\dot{m}$vs length for d1=1mm

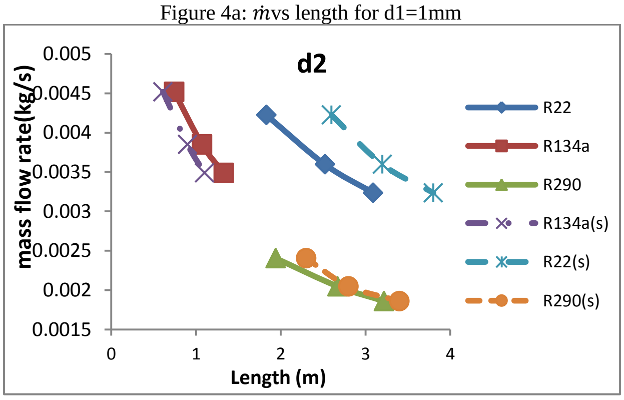

Figure 4b: $\dot{m}$vs length for d2=1.1mm

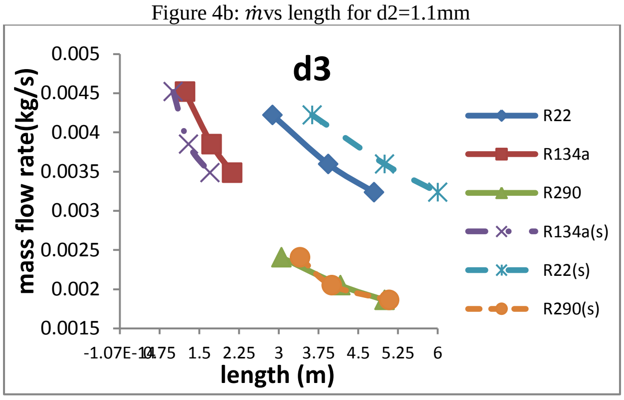

Figure 4c: $\dot{m}$vs length for d3=1.2mm

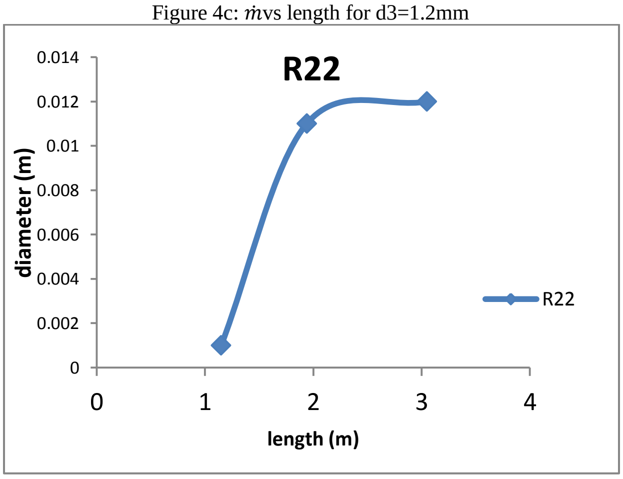

Figure 5: Diameter vs length

From these figures 3a,3b,3c we can see that modeling lengths and software results desnoted by dotted lines vary be 10-15% which is acceptable limit. So, the Stroker and Jones method can be used for required length of capillary tube.

2) Condeser :

By using the equation 7 to 15 and simulation methodlogy proposed by reseachers required length of condenser is calculated. Different equations are used for superheated, subcooled and two phase region. Same mass flow rate is used as it is calculated while capillary tube. Input parameters taken are:

Table 2: Input parameters of condenser

Parameters	**Value**
Capacity	80ltrs(625watt) 60ltrs(525watt) 60ltrs(500watt)
Condensing temperature	50^0 C
Degree of subcooling	6^0 C
Degree of superheating	5^0 C
Temperature of air	35^0 C
Diameter of tube	9.525 mm outside and 9.225 mm inside
Number of fins per meter	500
Fin spacing	3.9mm
Tube transverse and longitudinal spacing	40mm and 22mm
Number of tubes	12

The length is calculated for R22 , R134a and R290. For R22 it is 4.5m, R134a it is 4.34m and for R290 it is found ti be heighest 5.12m because of reduced mass flow rate.

VI.CONCLUSION

Mathematical modeling and simulation technique for water cooler has been studied. Also various approaches are given. From the capillary tube model it was found that the length of the tube decreses with the increases in mass flow rate and the model was also tested against software and the results vary only 15-20%. Conndenser length was also calculated and the length of R290 was heighest i.e. 5.12 as its mass flow rate was lowest.

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