PARAMETRIC OPTIMIZATION OF HEAT PIPE BY COMPONENT AND SYSTEM ANALYSIS

[1]JAMAL SAEED, [2]A. SHAHID, [3]E. UDDIN, [4]A MUBASHAR

[1,2,3,4]Computational Mechanics Group, Department of Mechanical Engineering, SMME, NUST, Pakistan
E-mail: 1saeid.jamal@smme.nust.edu.pk

Abstract - Heat pipes are thermal exchangers equipped for exchanging heat energy hundreds of times faster than traditional techniques. The energy consumption has increased significantly during the recent decade. The impact on the energy consumption of an air conditioning system is simulated with 8-row heat pipe installed in the HVAC system. It was also compared to the HVAC system without heat pipe. Optimal configuration, angle and cost analysis was done using the results of thermal analysis of the components. The thermal analysis was done on the component level using finite element method and transient system analysis on the system level by empirical representation of all components and simulating the modular components. The efficiency of the air conditioning was increased by 15%. The heat pipe added the advantage of free precool and reheat, no heat is added to conditioned space, as well as it increases system efficiency.

Keywords - Heat Pipes, HVAC, Dehumidifier, Heat Rate, Simulation

I. INTRODUCTION

Heat pipes are thermal exchangers equipped for exchanging heat energy hundreds of times faster than traditional techniques. Dehumidification heat pipes fold around the cooling coil to drastically increase the moisture evacuation without the necessity of extra energy making them ideal for supermarkets, libraries, theaters, labs and different applications requiring exact humidity control. With the improvement in living standards of ordinary people of Pakistan, the use of air-conditioning equipment has significantly increased during the recent years. The ever increasing energy requirement is creating a great burden on the already depleting energy resources. Reduction in the energy consumption by saving the energy from HVAC system is the need of time. A heat pipe dehumidifier consists of a heat exchanger filled with the refrigerant. The condensed refrigerant is returned to the evaporator section with the help of capillary action and gravity as well. Heat pipe have a number of advantages over conventional heat exchanger devices [1]. The main advantage is it is operated on gravity and capillary action and does not require external power to operate. Heat pipe is an efficient heat transfer device that can be used in AC systems for energy efficient system via energy recovery. It can be coupled with the AC systems operating in both hot and cold climates. Application of heat pipe enhances the performance of AC systems [2-4].

Various studies have been performed by using analytically and experimentally [5-12]. The one of the most important parameter in the heat pipe is its design and heat transfer. Several analytical studies were performed optimizing various parameters. Rajesh et al. [5] minimize the weight of heat pipe using a non-linear programming approach for the optimal design of a heat pipe. Interior Penalty Function Method is used in order to convert the constrained problem into an unconstrained problem. Maziuk et al [7] calculated maximum heat flow, heat pipe thermal resistance, and the heat transfer coefficients of condenser and evaporator and developed a software for flat miniature heat pipe. Suman et al. [9] utilized a macroscopic approach for formulating an analytical model for heat transfer in a micro-heat pipe. The model formulated provides expressions for critical heat input, dry-out length and capillary head. The model also calculated the performance factor, which is useful for designing heat pipe.

Several modifications were made to the heat pipe. Tong et al [6] conducted flow visualization for closed-loop pulsating heat pipe (PHP). Fluid oscillations had large amplitude during the initial period while circulation starts occurring in steady operation. The fluid circulation is due to the bends, uneven slug and non-concurrent boiling at the evaporator. Closed-end oscillating heat pipe was analyzed by Sakulchangsatjatai et al [8] using explicit finite element method. The heat flux decreases by increasing evaporator length and increases by increasing inner diameter. Kyu Huyung Do et al [10] developed a model (mathematical model) for thermal analysis of a micro heat pipe with rectangular grooved-wick. Yongping Chen et al [11] developed a transient model to predict the thermal response characteristics of a heat pipe with axially "Ω" – shaped microgrooves. With the increase/decrease in input power the temperature of the evaporator starts to rise/drop quickly. The study also indicated that the thermal conductivity and time constant are large in the startup process as compared to the shutdown process. Effect of nanofluid on on thermal performance inclined screen mesh heat pipe was studies by Ghanbarpour et al [12] They reported an optimum inclination angle of 60° for the thermal performance enhancement.

In this research, the effect on energy consumption of an air conditioning system is simulated with 8-row heat pipe installed in the HVAC system and compared to the existing HVAC system without the heat pipe. Optimal configuration, angle and cost analysis was calculated using modular and system analysis. The study enables us to calculate the yearly impact on energy consumption to be predicted realistically as a possible justification for retrofitting the heat pipe into the space's conditioning system.

II. EMPIRICAL STUDY OF HEAT PIPE DEHUMIDIFIER

The thermal load on the room under consideration was calculated for both the heating and the cooling for winter and summer season respectively. This enabled us to calculate the appropriate dimensions of heat pipe. The dimensions of the room are **38.5ft * 12ft.**

The winter and summer load are as follows

Winter load

When outside temperature = -4°C and occupants=25 (average)

Total Heating Load = 9990.69 W

Summer load

When outside temperature = 47°C and occupants=25 (average)

Total Cooling Load = -18342.2 W

2.1. Material Selection:

Three materials are widely used for the fabrication of heat pipes namely Copper, Aluminum and Steel [13]. A comparison of thermal properties of these materials is given in Table 1. Based on the thermal conductivity and thermal expansion data comparison of these materials copper was selected for the current study.

2.2. Empirical analysis

The total prevailing load in space ($\dot{q}_T$) was found out by using the following equation, provided that it is a constant air volume system:[14]

$$\dot{q}_T = \dot{q}_{sen} + \dot{q}_{lat} = m_a(h_r - h_s) \quad (1)$$

Where $\dot{q}_{sen}$ the sensible space load in watts is, $\dot{q}_{lat}$ is the latent space load in watts, m_a is the supply air mass flow rate in kg/s, h_r is the room air enthalpy in J/kg and h_s is the supply air enthalpy in J/kg.

The general heat equation for a function T (x,y,z,t) for spatial and temporal variables is given as [14]

$$\frac{\partial T}{\partial t} - \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = 0 \quad (2)$$

whereT(x,y,z,t) is the temperature while α is the thermal diffusivity. This equation is used in describing the distribution of heat spatially and temporally. The change in internal energy per unit volume of the material ΔQ in J/m^3, can be found out by using the equation (3):

$$\Delta Q = c_p \rho \Delta u \quad (3)$$

Where c_p the specific heat capacity in J/kg.K is, ρ is the mass density of the material in kg/m^3 and Δu is the change in temperature in K.

The thermal diffusivity α in m^2/s, which is also being used in the general heat equation, can be found out by: $\alpha = \frac{k}{c_p \rho}$ (4)

Where k is the thermal conductivity in W/m.K, c_p is the specific heat capacity in J/kg.K and ρ is the mass density in m^3/kg.

Time required cooling (or heating) the object t, can be found out by using Newton's Law of Cooling which is mathematically given as:

$$t = \frac{m \times c_p \times (T_s - T_f)}{Q} \quad (5)$$

$$Q = \frac{m \times c_p \times (T_s - T_f)}{t} \quad (6)$$

Where Q is the heat added (or rejected) in watts, m is the mass of object in kg, c_p is the specific heat capacity of the object in J/kg.K and T_s and T_f are the initial and final temperatures in K, respectively.

The basic parameters which deal with regenerative cooling are gas side heat transfer coefficient $h_{gc,}$ coolant side heat transfer coefficient h_c and heat flux q. To prevent a sufficient amount of heat being transferred to the walls, the gas side heat transfer coefficient is kept as low as possible. Then the coolant side heat transfer coefficient is kept as high as possible so that all the heat can be absorbed, which is then transferred to the walls. In this case, the basic governing equations of heat transfer are as follows:

$$h_{gc}(T_{aw} - T_{wg}) = q = \left(\frac{\kappa}{t}\right)(T_{wg} - T_{wc})$$

$$H(T_{aw} - T_{co}) \quad (7)$$

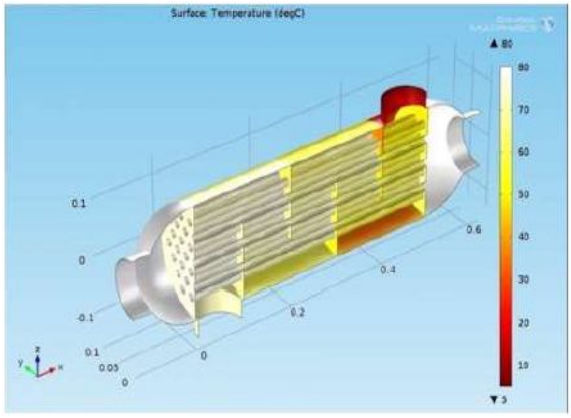

Figure 1: Heat Exchanger

where q is heat flux with units of Btu/in^2-s , h_{gc} is over-all gas side thermal conductance in Btu/in^2-s-°F, h_c is coolant side heat transfer coefficient in Btu/in^2-s-°F, k is thermal conductivity in Btu/in^2-s-°F/in, t is the chamber wall thickness in inches, H is overall heat transfer coefficient in Btu/in^2-s-°F, T_{co} is coolant bulk temperature in °R while T_{aw}, T_{wg} and T_{wc} are adiabatic, gas side and coolant side wall temperatures in °R, respectively [15, 16].

III. RESULTS AND DISCUSSION

3.1. Results

The first step in the analysis of heat pipe is the designing and validation of the heat exchanger. The shell tube heat exchanger was modelled in the commercial software COMSOL CFD Module by COMSOL Co. Ltd., USA with Tubular (heating or cooling). The gases pressure inside the tube was atmospheric pressure and heat flux boundary condition was used on the outside tubes where **5.37W/ (m².K)** for specific dimensions [17]. The tabular comparison is shown in Table 2.

	Proposed model	**J. Primo [6]**
Temperature water	80°C	80°C
Temperature air	5°C	5°C
Wall thickness	5mm	5mm
U	5.37**W/ (m².K)**	5.3689 **W/ (m².K)**

Table 1: Validation of Heat Exchange

Figure 1 shows the temperature contours of the heat exchanger modelled for the validation with the J. Primo [17].

After the validation of the heat exchanger, phase change material was introduced in the heat exchanger. Below are the advantages of using phase change material as a working fluid.

[1] Heat absorbed from system is used as latent heat of working fluid.
[2] Average temperature of the system is nearly constant.
[3] No external force is required to move the working fluid.

The temperature contours for the heat exchanger with phase change material is shown in Figure 2.

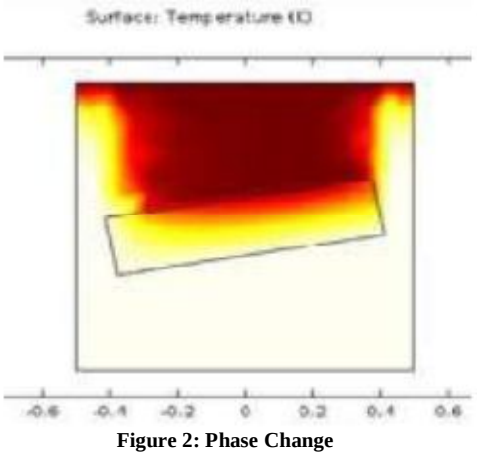

Figure 2: Phase Change

Material selection for heat pipe depends on following factors.

1. Thermal expansion
2. Mechanical properties
3. Conductivity

Considering the thermal conductivity, stress endurance and conductivity copperis selected material for heat pipe [18]. The working Fluid for heat pipe depends on following factors.

1. Reactivity
2. Boiling Point
3. Vapor Pressure

Considering the compatibility with copper, methanol isselected as the working fluid for heat pipe [16].

After selecting the material and the refrigerant, the optimal angle of the heat pipe was calculated. As the refrigerant flows down the tube under the action of the gravity and the capillary action, the heat pipe is needed to be placed at an angle. The change in the angle of the heat pipe has following effects:

1. Easy motion due to gravity
2. Avoids bubble formation in working fluid
3. Increase in Heat transfer
4. Rapid separation of liquid and gas phase

Several cases were simulated for different angles of attack.The temperature at the exit of the heat pipe is plotted as function of the angle of attack in Figure 3.45^o is selected based on the best heat transferred, the temperature contours corresponding to 5°, 45°, 55°, 90° is the figure 4. Figure 4(b) shows the optimal angle of the heat pipe.

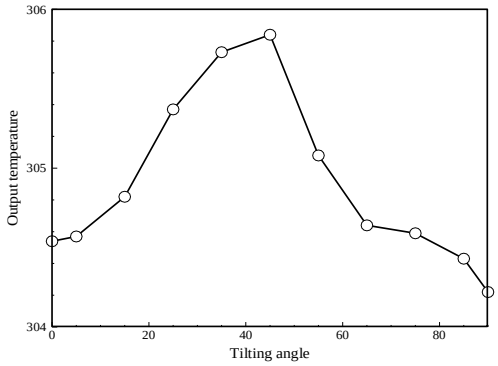

Fig. 3: Tilting Angle vs Output Temperature

The parameter other than angle of heat pipe is the capillary. The change in diameter of capillaries in heat pipe affects the

1. Increase in heat transfer
2. Increase in cost
3. Increase difficulties in manufacturing
4. Increase heat loss

Table 5 shows the heat transfer for different diameter of the capillary tube. Linear relation was found between the capillary size and the outlet temperature.

Capillary size (inches)	Outlet temperature (K)
0.4	308.18
0.5	310.38
0.6	311.65

Table 5: Temperature for different capillary sizes

Figure 5 shows the temperature contours of the diameter of the capillary tube for 0.4 mm, 0.5 mm, 0.6 mm diameter.

By looking on the linear relationship between the capillary size and heat transfer, 0.5 was selected based on the availability in the market.

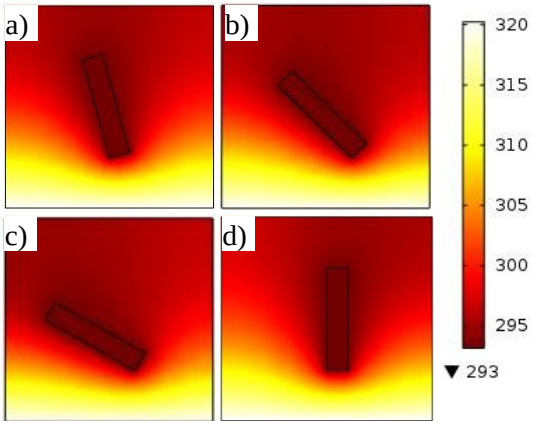

Figure 4: Tilting angle of the heat pipe

The comparison of the heat pipe with the already available heat pipe with comparison of working fluid, advantages, disadvantages and the coefficient of performance is shown in A1.

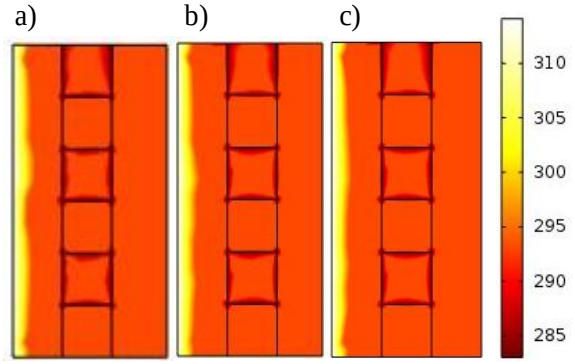

Figure 5: Temperature contours for heat pipe with 0.4, 0.5 and 0.6 mm capillary sizes

3.2. System level modelling of the heat pipe

After designing the heat pipe for the room, system level modelling is completed in the the commercial software TRNSYS by Thermal Energy System Specialists, USA. TRNSYS is transient systems simulation software, applied in the present study for the HVAC system modeling for the building installed. The modular nature has allowed empirical representations of all components to be added into the program. The schematic of the system modelled is given in figure 6 below.

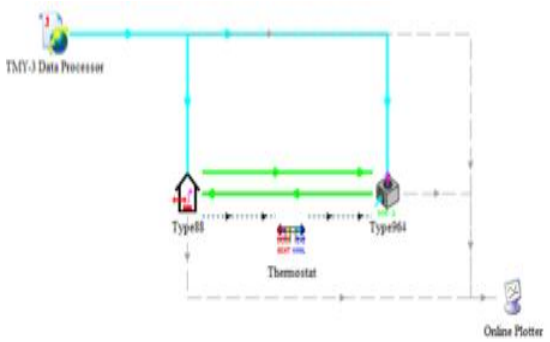

Figure 6: Schematic diagram in TRNSYS

Figure 7 to 10 shows the ambient, zone and supply temperature with red, purple and blue respectively for a day. The red lines shows the ambient air temperature supplied to the room after going through the air conditioner, blue line shows the average temperature of the room and purple line shows the air temperature supplied to the air conditioner. The supply air temperature (purple line) is for a day of July so it remainsthe same for Figures 7 to 10. A2, Figure 7 and Figure 10 shows that the 5 ton air conditioner can give same output as 6 ton air conditioner with the help of heat pipe. Also heat pipe also increase the efficiency of the system current system.

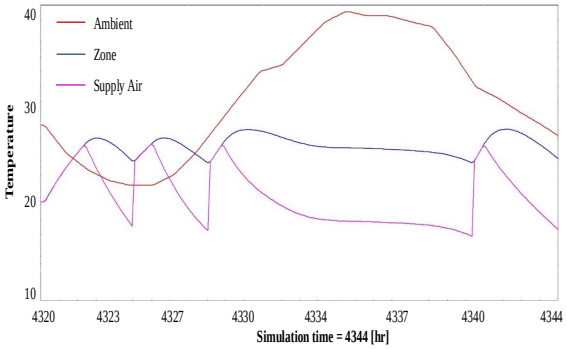

Figure 7:6 ton air conditioner (without heat pipe)

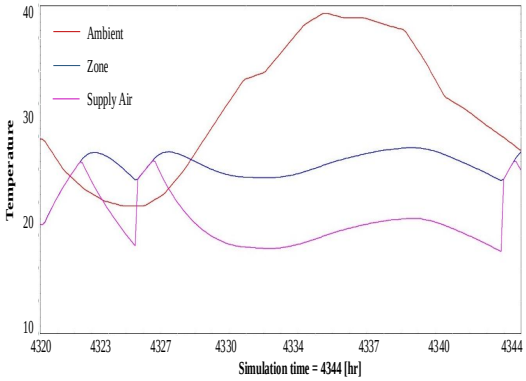

Figure 8: 6 Ton Air Conditioner (With Heat Pipe)

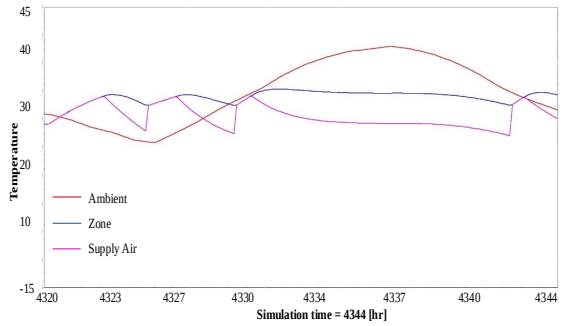

Figure 9: 5 Ton Air Conditioner (Without Heat Pipe)

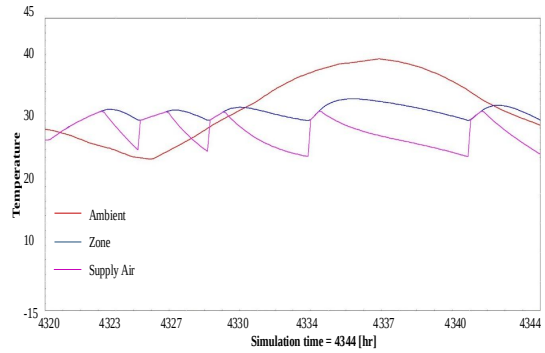

Figure 10: 5 ton air conditioner (with heat pipe)

3.3. Comparison of the electricity (units) used by a 1.5 ton air conditioner (AC) with and without heat pipe

The rating for a1.5-ton AC is approximately 1.2kW, measured in Kilowatt-hour (KWh). The compressor consumes most of the power, with a rating of 1kW. Therefore, the total is approx. 1.2 kW.To calculate the units consumed by the AC, we need to distribute the power consumed from the compressor and the evaporator and auxiliary parts. The indoor unit is running constantly, however, the compressor switches on and off as required. On average for the indoor temperature set at 26°C, in an hour, the compressor is switched on for about half an hour.

$$[(1kW \times 0.5hrs) + (0.2kW \times 1\ hr)] = 0.7\ kWh$$

A 1 shows the running time and rating for the compressor and evaporator. For 6 hours of running every day, then the total units consumed would **126 units per month.** For the 4 ACs each of 1.5 ton wattage, total units consumed are**126x 4 = 504 units per month (1008 unit per month for 12 hours operation).** At current rates of around 15 Pakistan Rupees per unit energy in Pakistan, the price of running the AC for a month will be **504 x 15 = 7560 Rs.**

The Heat Pipe Dehumidifier is 15 % more efficient than the AC without the heat pipe, so the electricity bill would be reduced by 15 % i.e. for 504 units per month, the new electricity bill would be 6,426 Rs, saving 1,134 Rs/per month and 13,608 Rs/per year by using Heat Pipe Dehumidifier.

A 1: Input and Output from TRNSYS

	Ambient Air Temperature (temperature of atmosphere)	Zone Temperature (Average temperature of the room)	Supply air Temperature (Air supplied to room)
6 Ton without heat pipe	Average temperature for the room is 22°C	Average temperature for the room is 27°C	Supply air is taken for the day of month of July
6 Ton with heat pipe	Average temperature for the room is 19°C	Average temperature for the room is 25°C	Supply air is taken for the day of month of July
5 Ton without heat pipe	Average temperature for the room is 25°C	Average temperature for the room is 31°C	Supply air is taken for the day of month of July
5 Ton with heat pipe	Average temperature for the room is 22.7°C	Average temperature for the room is 28°C	Supply air is taken for the day of month of July

CONCLUSIONS

The study conducted focuses on the use of heat pipe dehumidifier for the CADCAM Lab. Heating load for the CADCAM lab was calculated and heat pipe was designed and component and system level modelling was undertaken in COMSOL and TRNSYS respectively. The efficiency of the air conditioning was increased by 15%.Cost analysis show a saving of 55,000 Rs. (550 USD) per year by its use for a 24 hour operation of lab. The addition of heat pipe gave the advantages of free precool and reheat, zero heat addition to the conditioned space and allows entire system to work more efficiently. It increases latent capacity without additional energy consumption and dehumidifies air entering the ductwork also helps in better compliance with ASHRAE 62-1999 Standard. An increase in the wind intake can have a negative effect on working and proper handling. The simple principle of operation of the heat pipe results in no moving parts to break down or wear out. The heat flow varies from material to material. Future studies can be done on different combination of the heat pipe material and the working fluid.

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