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## Experimental Studies on Porous Wick Flat Plate Heat Pipe

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### ABSTRACT

In recent years, the use of heat pipe for electronic equipments thermal management has been growing faster to meet the future requirements. The flat plate heat pipes (FPHP) are promising heat transporting devices capable of transmitting high heat fluxes rejected by modern electronic equipments. In the present study, the experimental analysis of the thermal performance of flat plate heat pipe is carried out for various heat input rates with different working fluids. Quantity of working fluid charged into the heat pipe is varied and its influence on performance is obtained. Different working fluids have been tested with heat pipe and their performance has been compared. At lower heat flux the fluids such as acetone, ethanol, and methanol are better than water, whereas at higher heat flux water is best candidature among these fluids considered.

Keywords: flat plate heat pipe (FPHP), working fluid, wick structure, heat input

### 1. INTRODUCTION

The flat plate heat pipe (FPHP) will have great potential for electronic cooling because of its unique performance of high response, efficiency, temperature flattening and lightweight feature. The flat plate heat pipe is able to transport high heat fluxes liberated by electrical and electronic equipments. Many research workers have done studies on pressure, velocity, temperature distributions of heat pipe experimentally and analytically. A lot of work has been reported on performance of heat pipe with or without wick materials for different working fluids, orientations, heater position. Amir Faghri (1995), Chi (1976) and David Reay and Peter Kew (2006) presented the working principle, fabrication, heat transfer limitation and applications of heat pipes. Chen and Faghri (1990) conducted a numerical analysis for the overall performance of heat pipe with single or multiple heat sources. Pruzan *et al.* (1991) studied a 1-D, two-phase model for predicting dry out heat fluxes in sintered-wick heat pipes. The influence of wick thickness, effective capillary radius of curvature, porosity and heated diameter on heat pipe performance was studied parametrically. Kim and Peterson (1995) investigated experimental phenomena in capillary driven heat pipes and both analytical and experimental approaches were utilized to identify and better understanding of the parameters that govern the entrainment the liquid. Sun *et al.* (1995) presented an approximate method for calculating the effective length of a flat plate heat pipe when a strip heater is partially covering the evaporator section. Huang and Liu (1996) developed an analytical model to calculate the liquid flow field with localized heating condition and also examined the effect of the location and the geometry of the heater on the heat pipe performance. Leong *et al.* (1997) compared rectangular porous wicks made of copper powder at two different sintering temperatures and the effect of sintering time. Wang and Vafai (2000a) performed an experimental investigation of the transient characteristics of a flat heat pipe during start-up and shutdown operations. Effects of input power and the heat transfer coefficient on the thermal performance of the heat pipe are investigated. Wang and Vafai (2000b) developed analytical models for predicting the transient performance of a flat plate heat pipe during startup and shutdown operations. Transient temperature distributions in the heat pipe walls and wicks are presented. Xuan *et al.* (2004) studied the performance and mechanism of a flat plate heat pipe under different heat fluxes, orientations and amount of the working fluid by means of both experimental and theoretical approaches. Savino *et al.* (2008) compared the performances of different composite wick or wickless heat pipes filled with pure water and water/alcohol binary mixtures under normal gravity and low-gravity conditions. The heat pipes filled with the binary mixtures perform better when compared to the same heat pipes filled with pure water. Xiao and Faghri (2008) developed a detailed 3-D model to analyze the thermal hydrodynamic behaviors of flat heat pipes without empirical correlations. The model takes into account for the heat conduction in the wall, fluid flow in the vapor chambers and porous wicks. Cao *et al.* (1996) tested heat pipes under different heat inputs, cooling temperatures, and orientations. It is found that the capillary limit is the

dominant heat transfer limitation for the miniature heat pipes. Chien and Chang (2002) experimentally investigated the effect of particle size and coating thickness of the porous surface on evaporator thermal resistance. Popova *et al.* (2006) described the fabrication processes of a flat heat pipe and the experimental investigation conducted to determine its thermal performance. Effects of the amount of the working fluid, pure water, and the working temperature on the thermal performance of the fabricated thin flat heat pipe are presented. The reported theoretical and experimental works on heat pipe are useful in the enhancement of thermal and hydraulic performance of flat plate heat pipe. In the present investigation, studies are carried out to analyze the thermal performance of flat plate heat pipe for various heat input with different working fluid charge amount.

## 2. PHYSICAL MODEL

Design of a FPHP includes selection of the container, quantity of the working fluid, design of geometric structure and design of wick layers. Container made up of copper isolates the working fluid from outside environment. It should be therefore leak-proof, maintains the pressure difference across its walls, and enables transfer of heat to take place from and into the working fluid. Compatibility with both working fluid and external environment and having high thermal conductivity which ensures minimum temperature drop between the heat source and the wick are important considerations. The material should be non-porous to prevent the diffusion of vapor. Dimensions of the heat pipe are given in the Table 1. Thermal conductivity of the container material varies with operating temperature of heat pipe. Properties of copper material can be calculated based on temperature of heat pipe. The flat copper plates of 2 mm thickness is used to fabricate the square flat plate heat pipe. The inner side of the flat plate has been cleaned in order to free from contaminates that will degrade the performance of the heat pipe.

Table 1 Physical dimensions of FPHP

Flat Plate Heat Pipe Dimensions (All dimensions are in mm)	
Length	133
Width	133
Height	35
Wick thickness	2
Container wall thickness	2

Selection of working fluid is based on operating vapor temperature range. Within the approximate temperature range, several possible working fluids may exist and a variety of characteristics could be examined in order to determine the acceptability of these fluids for the application considered. Selection of the working fluid is also based on thermodynamic considerations which are concerned with the various limitations to heat flow occurring within the heat pipe like viscous, sonic, capillary, entrainment and nucleate boiling levels. Among various limitations, the lowest limitation such as capillary limitation in this study is considered as one of the important heat transport limitation. In the heat pipe design, a high value of surface tension is desirable in order to enable the heat pipe to operate against gravity and to generate a high capillary driving force. Vapor pressure over the operating temperature range must be sufficiently great to avoid high vapor velocities, which creates large temperature gradient and cause flow instabilities. Vapor flow within heat pipe is assumed to be laminar and vapor is considered to be incompressible. High latent heat of vaporization is preferable to transfer large amounts of heat with minimum fluid flow, and hence to maintain low pressure drops within the heat pipe. Thermal conductivity of the working fluid should preferably be high in order to minimize the temperature gradient. The resistance to fluid flow can be minimized by selecting fluids with low values of vapor and liquid viscosities. Properties of working fluid are calculated at operating temperature of heat pipe. Liquid is charged at atmospheric temperature. Air is used as cooling medium for condenser surface. The convective heat transfer coefficient between condenser surface and air is assumed to be constant.

Wick is a porous structure made of copper in various ranges of pore sizes. The wick structure generates capillary pressure to transport the working fluid from condenser to evaporator. The maximum capillary pressure and corresponding maximum heat transport capacity of the flat plate heat pipe are determined by Equation (1) and (2)

$$P_{\text{cmax}} = \frac{2\sigma}{r_c} \quad (1)$$

$$Q_{\text{cmax}} = \frac{P_{\text{cmax}}}{L_{\text{eff}}} \times \left[ \frac{2(fR_e)_v \mu_v}{\rho_v A_v h_{fg} D_{h,v}} + \frac{\mu_l}{K \rho_v A_w h_{fg}} \right]^{-1} \quad (2)$$

Selection of the wick for a heat pipe depends on many factors, several of which are closely linked to the properties of the working fluid. The maximum capillary head generated by a wick increases with decrease in pore size. The wick permeability increases with increasing pore size. The average pore size of wick structure measured by Scanning Electron Microscope is 18.5  $\mu\text{m}$ . The permeability of the sintered wick structure is  $9.15 \times 10^{-13} \text{ m}^2$ . Heat transport capability of the heat pipe is raised by increasing the wick thickness. The overall thermal resistance at the evaporator also depends on the conductivity of the working fluid in the wick. The effective thermal conductivity of the water saturated wick structure is estimated at 4.45 W/m K by the following equation (3).

$$k_{\text{eff}} = k_l \left[ \frac{2k_l + k_w - 2(1-\varepsilon)(k_l - k_w)}{2k_l + k_w + (1-\varepsilon)(k_l - k_w)} \right] \quad (3)$$

The wicks structure offers more resistance to heat transport as the effective thermal conductivity is low. The thermo physical properties of container and working fluid are given in Table 2.

### 3. EXPERIMENTAL SET UP

The set up consists of a FPHP at the centre with an axial fan provided at the condenser side for forced convection cooling, an electrical heater mounted on the top of the plate to heat the evaporator, calibrated thermocouples and data acquisition device as shown in Fig.3. Heat pipe is provided with a vacuum gauge at the charging line to observe the variation of absolute pressure inside the heat pipe during operation. The measurement uncertainty for vacuum gauge is 2.22%. The heater is located at the center of the FPHP, for uniform heating. A variable voltage transformer is connected to the heater to supply constant heat load (105.8W). Data acquisition system is used to scan the data and store for every 10 seconds. Steady state of the system is attained when temperature difference in 5 minutes is 0.1°C. All measuring points are located on the outside surface of the FPHP. Temperatures at evaporator, condenser and an adiabatic surface on heat pipe are sensed by T-type thermocouples. Number of thermocouples used are 17, for the measurement of temperature distribution, with a measurement uncertainty up to  $\pm 0.4$  °C. High temperature copper cement with thermal conductivity of 1.15W/mK at 260°C is used to fix thermocouples. Aluminum embedded electric resistance heater of size 133mm×36mm×19mm is used to achieve variable input heat flux at the evaporator. The heater is fixed on the evaporator section using Armstrong heat sink paste to reduce contact resistance. Heat losses by radiation and convection to the surroundings are minimized by applying glass wool insulation to the outside of evaporator (heater), part of condenser and adiabatic section. Surface of FPHP, except condenser and evaporator area is insulated with 7.5 mm glass wool for adiabatic section and heater is insulated with 50 mm thick glass wool. The condenser is cooled by natural convection and forced convection. Heat pipe is initially tested without any working fluid and then tested with varying charges of water, acetone, methanol and ethanol as working fluids. Heater temperature has been maintained at 80°C as most of the electronic components work well at this temperature. The uncertainty for measurement of power input per unit area based on error analysis is found to be 2.98%.

Table 2 Thermo-physical properties of container material and working fluid

Material	Parameters	Value
Copper (David Reay and Peter Kew, 2006)	Thermal conductivity	401 W/m k
	Specific heat	385 J/kg K
	density	8960 kg/m <sup>3</sup>
Wick	Porosity	0.32
	Permeability	9.15×10 <sup>-13</sup> m <sup>2</sup>
	Pore size	0.00001848 m
Water (David Reay and Peter Kew, 2006)	Thermal conductivity	0.61706 W/m K
	Specific heat	4.18 kJ/kg K
	dynamic viscosity	0.00078068 Ns/m <sup>2</sup>
	density	995.3 kg/m <sup>3</sup>
	latent heat	2427 kJ/kg
Water vapor (David Reay and Peter Kew, 2006)	Thermal conductivity	0.02162 W/m K
	Specific heat	1.975 kJ/kg K
	dynamic viscosity	0.000011097 Ns/m <sup>2</sup>
	density	0.16146 kg/m <sup>3</sup>

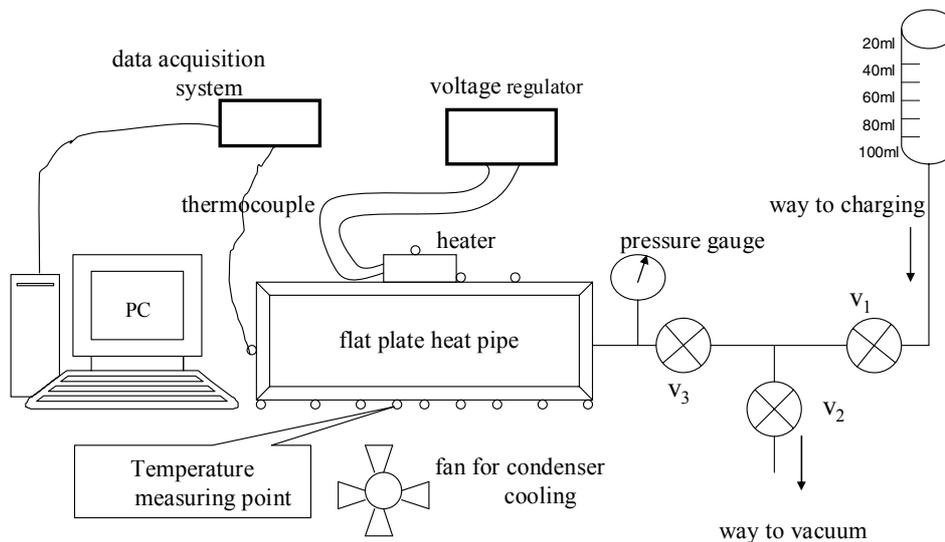


Fig.1. Experimental apparatus for measuring heat pipe performance

### 4. RESULTS AND DISCUSSION

Figure 2 shows that condenser attains steady state at a faster rate by forced convective cooling than natural convective cooling. As the condenser is placed against gravity and heater is placed at the top of heat pipe, overcharging maintains the condenser at low temperature due to presence of liquid film on condenser surface. This can be observed from Fig.3

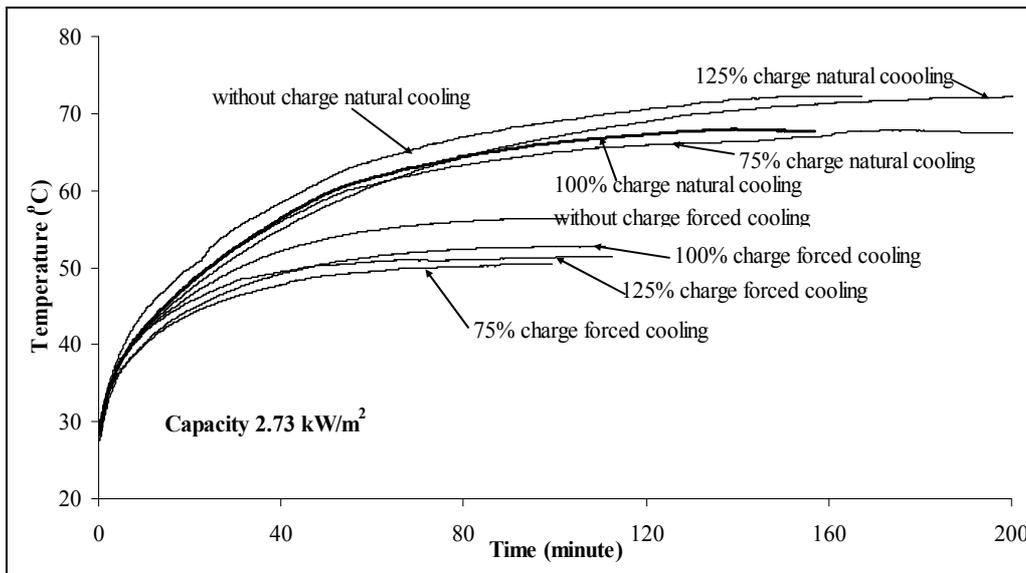


Fig.2. Transient temperature distribution of condenser with different charge amount of water.

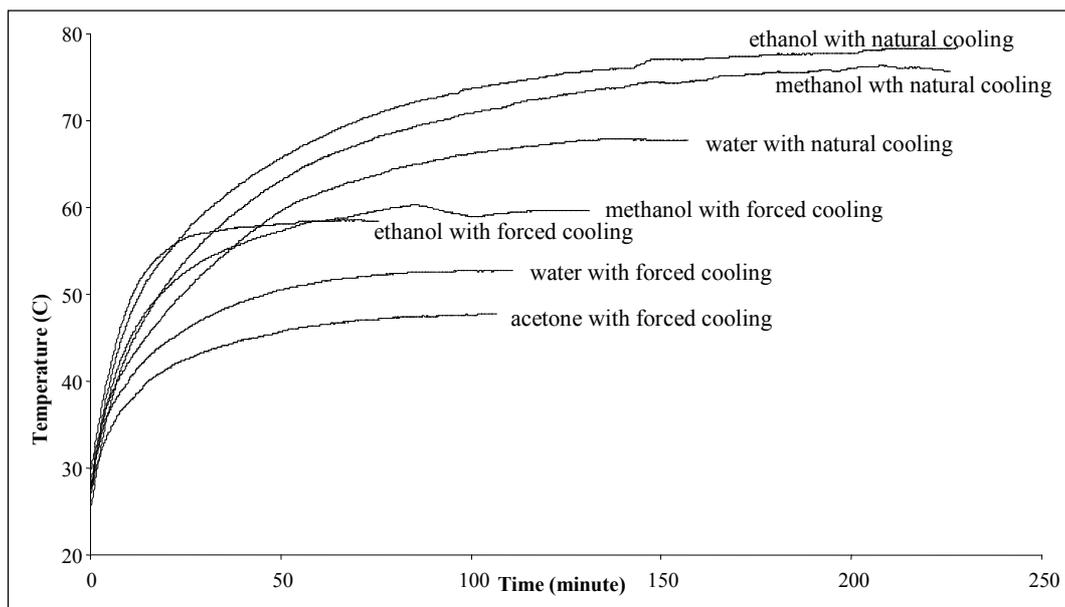


Fig.3. Transient temperature distribution of condenser with 100% charge

If heater is placed at the bottom of the heat pipe, the extra working fluid forms a layer of liquid film on the evaporator surface, which increases heat transfer resistance and suppresses bubble formation; hence the evaporator surface temperature increases. Condenser temperature is maintained at 40°C and 70°C respectively for forced and natural convection cooling. Overcharging is preferred for forced convection cooling; temperature variation due to overcharging is not significant. In case of heat pipe without charge the condenser temperature is lower than that with normal charge because heat pipe is evacuated and heat transfer takes place only by conduction and radiation.

It is evident from Fig. 4 that use of acetone maintains lower heater temperature due to its low boiling point compared to water, which has a high boiling point compared to acetone. But at higher heat load, water is better, as its latent heat of vaporization is higher compared to that of acetone. At 6.38kW/m<sup>2</sup> of heat flux, heat pipe with 75% water operates at lower temperature compared to heat pipe with same amount of acetone. If heat pipe is operated at 100% charge for water and acetone then both attain same temperature at 6.38kW/m<sup>2</sup> of heat flux. So the operating temperature depends on charge amount, type of working fluid and heat load.

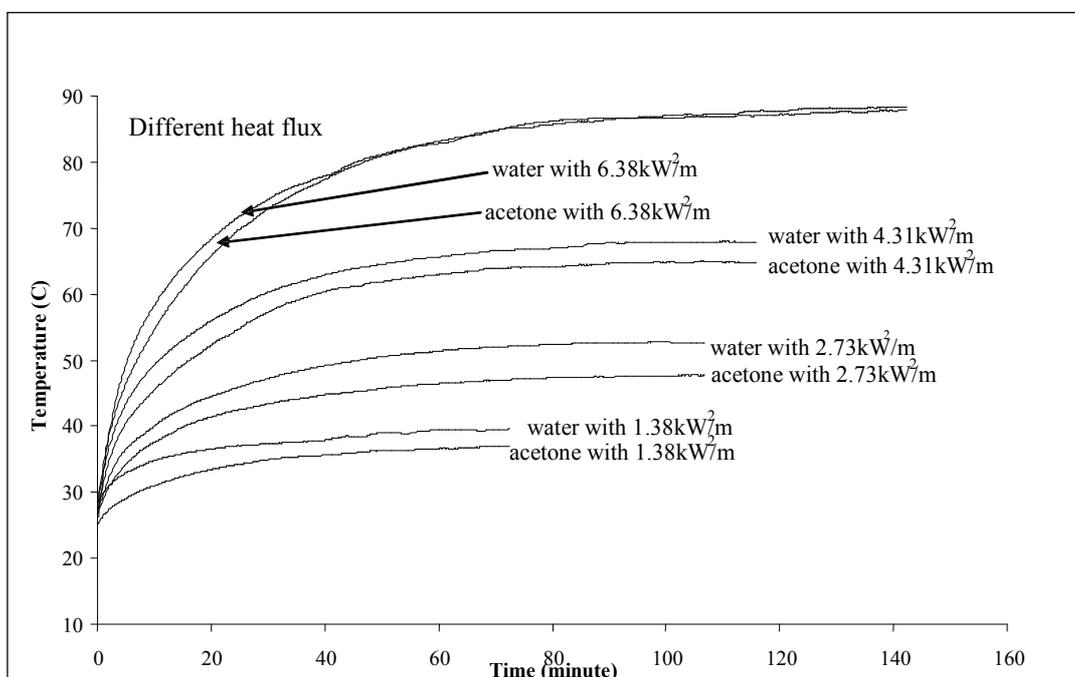


Fig.4. Condenser temperature comparison with 100% charge for water and acetone

Figure 5 shows effect of heat flux on condenser and evaporator temperature difference for square flat plate heat pipe. At lower heat flux almost all working fluids work at low temperature difference and no significant effect is observed for different working fluids. Heat pipe without working fluid acts as a solid heat sink and always has high temperature difference. Acetone and ethanol have lower latent heat of vaporization in comparison with methanol and water. But boiling point of acetone, methanol and ethanol are lower than that of water. Hence at lower heat flux these fluids are better than water, whereas at higher heat flux water is best among the four fluids considered. Limitations of the FPHP, constructed indigenously, are calculated and its heat spreading performance, obtained experimentally is in agreement with the theoretical calculations. The heat transport of FPHP is limited by capillary action attributed to low permeability of the wick material used.

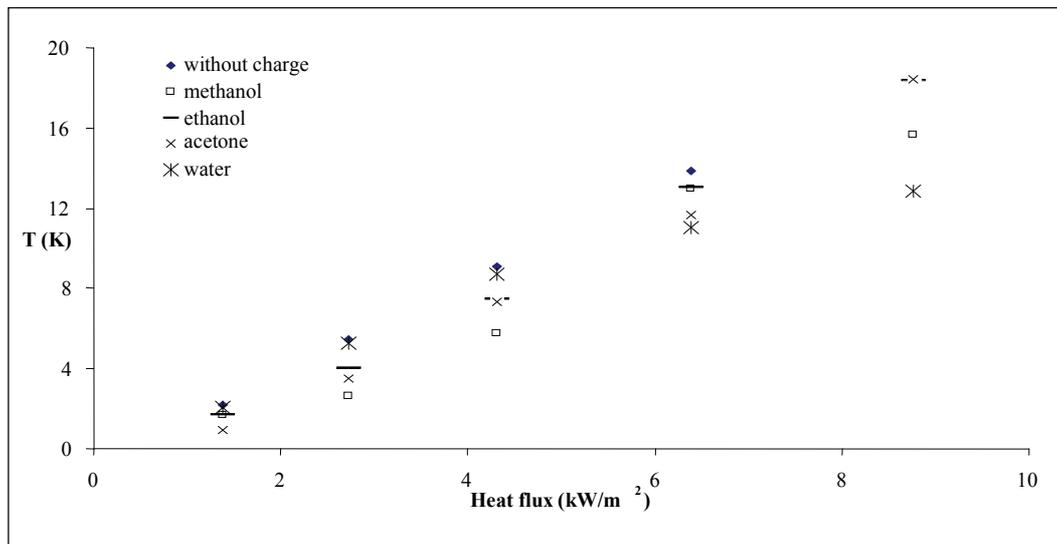


Fig.5. Effect of heat flux on temperature difference for different working fluids

## 5. CONCLUSIONS

A square flat plate heat pipe has been constructed with copper powder as wick material and copper plate as heat pipe container. The heat pipe has been tested with water, methanol, ethanol and acetone as working fluids. Comparison has been made for heat pipe without working fluid under the same operating conditions. It acted as a solid heat sink and always had high temperature difference between condenser and evaporator compared to heat pipe with working fluids. Performance of a FPHP has also been studied with different charges of working fluids for natural and forced convection cooling. Operating temperature of the heat pipe depends on the charge amount, type of working fluid and heat load. The effect of heat flux on condenser and evaporator temperature difference for different working fluids has been obtained.

## NOMENCLATURE

A	cross sectional area	(m <sup>2</sup> )	<b>Subscripts</b>	
$D_{h,v}$	hydraulic radius	(m)	eff	effective
f	friction factor		f	fluid
$h_{fg}$	latent heat of vaporization	(J/kg)	l	liquid
K	permeability	(m <sup>2</sup> )	v	vapor
$k_l$	thermal conductivity of liquid	(W/m k)	w	wick
$k_w$	thermal conductivity of wick	(W/m k)	cmax	maximum capillary limitation
L	length of the heat pipe	(m)		
P	pressure	(Pa)		
$Q_{cmax}$	maximum capillary heat transport	(W)		
q	heat flux	(W/m <sup>2</sup> )		
$r_c$	capillary radius	(m)		
Re	Renolds number			
$\Delta T$	change in temperature	(K)		
t	time	(s)		
T	temperature	(K)		

## Greek symbols

$\varepsilon$	porosity	
$\mu$	dynamic viscosity	(Ns/m <sup>2</sup> )
$\rho$	density	(kg/m <sup>3</sup> )
$\sigma$	surface tension coefficient	(N/m)

## REFERENCES

- Bin Xiao, Amir Faghri, 2008, A three-dimensional thermal-fluid analysis of flat heat pipes, *Int. J. Heat Mass Transfer*, vol. 51: p. 3113–3126.
- Huang, X. Y., Liu, C. Y., 1996, The pressure and velocity fields in the wick structure of a localized heated flat plate heat pipe, *Int. J. Heat Mass Transfer* vol. 39, no. 6: p. 1325-1330.
- Kim, B. H., Peterson, G. P., 1995, Analysis of the critical Weber number at the onset of liquid entrainment in capillary driven heat pipes, *Int. J. Heat Mass Transfer* vol. 38, no.8 : p. 1427-1442.
- Leong, K.C., Liu, C.Y., Lu, G.Q., 1997, Characterization of Sintered Copper Wicks Used in Heat Pipes, *Journal of Porous Materials* vol. 4: p. 303-308.
- Ming-Ming Chen, Amir Faghri, 1990, An analysis of the vapor flow and the heat conduction through the liquid-wick and pipe wall in a heat pipe with single or multiple heat sources, *Int. J. Heat Mass Transfer*, vol.33, no.9 : p.1945-1955.
- Pruzan, D. A., Klingensmith, L. K., Torrance, K. E., Avedisian, C. T., 1991, Design of high-performance sintered-wick heat pipes, *Int. J. Heat Mass Transfer*, vol. 34, no.6: p. 1417-1427.
- Raffaele Savino, Yoshiyuki Abe, Raimondo Fortezza, 2008, Comparative study of heat pipes with different working fluids under normal gravity and microgravity conditions, *Acta Astronautica* vol. 63: pp. 24– 34.
- Sun, K. H., Liu, C. Y., Leong, K. C., 1995, The effective length of a flat plate heat pipe covered partially by a strip heater on the evaporator section, *Heat Recovery Systems & CHP* vol. 15, no.4: p. 383-388.
- Tan, B.K., Huang, X.Y., Wong, T.N., Ooi, K.T., 2000, A study of multiple heat sources on a flat plate heat pipe using a point source approach, *Int. J. Heat Mass Transfer* vol. 43: p. 3755-3764.
- Vadakkan, U., Garimella S. V., Murthy, J. Y., 2004, Transport in flat heat pipes at high heat fluxes from multiple discrete sources, *Journal of Heat Transfer ASME* vol.126: p. 347-354.
- Wang, Y. Vafai, K., 2000, An experimental investigation of the transient characteristics of a flat-plate heat pipe during start-up and shutdown operations, *Journal of Heat Transfer ASME*, vol. 122: p. 525–535.
- Wang, Y., Vafai, K., 2000, Transient characterization of flat plate heat pipes during startup and shutdown operations, *Int. J. Heat Mass Transfer* vol. 43: p.2641-2655.
- Yimin Xuan, Yuping Hong, Qiang Li, 2004, Investigation on transient behaviors of flat plate heat pipes, *Experimental Thermal and Fluid Science*, vol. 28: p.249–255.
- Cao, Y., Gao, M., Beam, J.E., Donovan, B., 1996, Experiments and analysis of flat miniature heat pipes, *IEEE*: p.1402-1409.
- Liang-Han Chien, Chang, C.C., 2002, Experimental study of evaporation resistance on porous surfaces in flat heat pipes, *Inter Society Conference on Thermal Phenomena, IEEE*: p. 236-243.
- Popova, N., Schaeffer, Ch., Avenas, Y., Kapelski, G., 2006, Fabrication and thermal performance of a thin flat heat pipe with innovative sintered copper wick structure, *IEEE*: p. 791-796.
- Amir Faghri, 1995, *Heat Pipe Science and Technology*, Taylor & Francis Group, Great Britain, 908 p.
- Chi, S. W., 1976, *Heat pipe theory and Practice*, Hemisphere Publishing Corp, New York, 256 p.
- David Reay, Peter Kew, 2006, *Heat Pipes (Theory, Design and Applications)*, Fifth edition, Butterworth-Heinemann Publication.