EXPERIMENTAL AND NUMERICAL STUDIES ON THERMAL ANALYSIS OF HEAT PIPES FOR COMPUTER COOLING APPLICATIONS

by

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DEDICATION

This thesis is dedicated to my beloved parents for their prayers and tremendous sacrifices. They are always a constant source of inspiration and motivation in my life. Their support and love have pulled me throughout my difficult times. Not to forget my lovely wife, daughters and sons.

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LIST OF SYMBOLS

English Symbols

A_w Wick cross-sectional area m^2

C The FLOTRAN permeability expressed in m^{-2}, which is inverse of the physical permeability

C_p Specific heat J/kgK

f Friction coefficient

g Acceleration of gravity m^2/s

h_{fc} Heat transfer coefficient W/m^2 K

h_{nc} Heat transfer coefficient at natural convection W/m^2 K

K Wick permeability m^2

k Number of independent variables

k_{air} Thermal conductivity of air W/mK

k_e Effective thermal conductivity of the liquid-wick structure W/mK

K_{eff} Effective thermal conductivity of the heat pipe W/mK

k_l Liquid thermal conductivity W/mK

k_s Solid thermal conductivity W/mK

k_v Vapor thermal conductivity W/mK

k_w Thermal conductivity of wick material W/mK

L_{ad} Adiabatic section length m

L_c Condenser section length m

L_e Evaporator section length m

L_{eff} Effective length of the heat pipe m

Nu Nusselt number

P_l Liquid pressure (Pa)

P_v Vapor pressure (Pa)

ΔP Pressure drop (Pa)

Q Heat input W

Q_{hp} Heat input of single heat pipe (W)

q Heat flux (W/m^2)

Q* Coolant airflow rate (m^3/h)

q* Heat generate rate (W/m^3)

R Thermal resistance (°C/W)

R_0 Outside radius of the heat pipe (m)

R_b Base thermal resistance (°C/W)

R_{cb} The contact thermal resistance between heat source and the base plate (°C/W)

R_{ch} The contact thermal resistance between heat source and evaporator section (°C/W)

r_{eff} Effective pores radius of the wick (m)

R_f Fins thermal resistance (°C/W)

R_h Thermal resistance of half U-shape heat pipe (°C/W)

R_{hp} Heat pipe thermal resistance (°C/W)

R_t Total thermal resistance (°C/W)

R_v Vapor core radius of heat pipe (m)

R_w Wall inner radius of the heat pipe (m)

R_x Distributed resistance in x direction N/m^3

R_y Distributed resistance in y direction N/m^3

s Distance between two fins (m)

T Temperature °C

t Time (s)

T_a Ambient temperature °C

T_{ad} Adiabatic section temperature °C

T_b Base plate temperature ℃

T_c Condenser temperature ℃

T_e Evaporator temperature ℃

T_{int} Interface temperature ℃

T_{sr} Source temperature ℃

T_s Heat pipe wall (surface) temperature ℃

u Velocity in x direction m/s

u_1 Vapor suction velocity m/s

v Velocity in y directions m/s

v and *u* Subscripts refers to vapor and liquid regions respectively.

v_1 Vapor injection velocity m/s

x, y, z Space coordinates

Greek Symbols

β_0 Constant coefficient

β_j Interaction coefficient of linear

β_{jj} Interaction coefficient of quadratic

β_{ij} Interaction coefficient of the second-order terms

ε	Error
ρ_l	Liquid density kg/m^3
η	Normal vector
ρ_v	Vapor density kg/m^3
μ_v	Vapor dynamic viscosity
μ_l	Liquid dynamic viscosity Ns/m^2
φ	Wick porosity
σ_l	Surface tension N/m

LIST OF ABBREVIATION

CCD	Central Composite Design
CPU	Central Processing Unit of a computer microprocessor
DOE	Design of experiment
FEM	Finite Element Method
MHP	Miniature Heat Pipe
RSM	Response surface methodology

LIST OF PUBLICATIONS

International Journals

ELNAGGAR, M. H. A., ABDULLAH, M. Z. & ABDUL MUJEEBU, M. 2011. Experimental analysis and FEM simulation of finned U-shape multi heat pipe for desktop PC cooling. Energy Conversion and Management, 52, 2937-2944. **(ISI IF= 2.054)**

ELNAGGAR, M. H. A., ABDULLAH, M. Z. & MUJEEBU, M. A. 2011. Experimental Investigation and Optimization of Heat Input and Coolant Velocity of Finned Twin U-Shaped Heat Pipe for CPU Cooling. Experimental Techniques, (In press). **(ISI IF= 0.5)**

ELNAGGAR, M. H. A., ABDULLAH, M. Z. & ABDUL MUJEEBU, M. 2012. Characterization of Working Fluid in Vertically Mounted Finned U-Shape Twin Heat Pipe for Electronic Cooling. Energy Conversion and Management, 62, 31-39. **(ISI IF= 2.054)**

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ELNAGGAR, M. H. A., ABDULLAH, M. Z. 2011. Experimental Investigation And Optimization Of Coolant Flow Rate And Heat Input Of Finned Heat Pipe For Notebook Pc Cooling. 2nd Symposium of USM Fellowship Holders 2011, November 23-24, Vistana Hotel, Penang, Malaysia.

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KAJIAN EKSPERIMEN DAN BERANGKA KE ATAS ANALISA TERMA BAGI PAIP HABA UNTUK APLIKASI PENYEJUKAN KOMPUTER

ABSTRAK

Dalam industri komputer, peningkatan pembangunan dan permintaan bagi kuasa pemprosesan memerlukan reka bentuk yang cekap untuk pemproses menjalankan operasi dengan pantas; justeru teknik penyejukan diperlukan bagi menyelerakkan haba yang terlibat adalah penting. Oleh itu, kajian amat diperlukan bagi menyelidik peranti penyejukan berpotensi tinggi terutamanya penyejukan CPU. Dalam kajian ini, paip haba berbentuk pelbagai dan berkembar-U, dan paip haba mengufuk berbentuk-L telah dikaji secara eksperimen dan berangka. Analisa terma dijalankan pada kedua-dua mod perolakan tabie dan paksa. Simulasi telah dijalankan dengan dua model; pertama model 3D berdasarkan pemindahan haba secara konduksi yang mana paip haba secara keseluruhannya dimodelkan dengan anggapan sebuah media berkonduksi, tanpa mengambil kira keadaan yang berlaku di dalam paip haba. Kedua adalah model 2D bagi mencirikan bendalir bekerja di dalam paip haba. Sebuah pengalatan terbaik bagi reka bentuk eksperimen (DOE) digunakan untuk mengoptimum halaju penyejuk dan haba masukan bagi menghasilkan prestasi terbaik bagi paip haba. Keputusan menunjukkan halaju udara dan kuasa masukan mempunyai kesan ketara ke atas prestasi paip haba yang bersirip. Jumlah rintangan terma menurun dengan peningkatan haba masukan dan halaju penyejuk. Nilai terendah bagi jumlah rintangan terma untuk paip haba pelbagai bentuk U bersirip, paip haba berkembar dan bentuk L tunggal masing-masing adalah 0.181 °C/W, 0.125°C/W and 0.533 °C/W. Dalam simulasi berangka, air dan metanol

telah digunakan sebagai bendalir bekerja, dan air yang digunakan sebagai bendali bekerja menghasilkan perubahan kecil pada suhu dan kejatuhan tekanan berbanding dengan methanol sebagai bendalir bekerja. Kedua-dua bendalir bekerja; air dan methanol, ketelapan bahagian berliang dan tebal bahagian berliang memberikan kesan penting ke atas perbezaan suhu dan kejatuhan tekanan. Keputusan pengoptimuman dengan menggunakan D-optimal bagi perisian RSM menunjukkan prestasi paip haba berbentuk-L telah meningkat.

EXPERIMENTAL AND NUMERICAL STUDIES ON THERMAL ANALYSIS OF HEAT PIPES FOR COMPUTER COOLING APPLICATIONS

ABSTRACT

In computer industry, the growing development and demand for processing power necessitate efficient design of processors to conduct operations faster; consequently, the need for cooling techniques to dissipate the associated heat is quite obvious. Hence, it is highly desirable to explore high-performance cooling devices, especially for CPU cooling. In the present study, multi and twin U-shape vertical heat pipes, and single L-shape horizontal heat pipe, were investigated experimentally and numerically. Thermal analysis was performed under both natural and forced convection modes. The simulations were carried out in two models; the first was 3D model based on the heat transfer by conduction where the heat pipe as a whole was modeled by assuming it as a conducting medium, without taking into account the events occurring inside the heat pipe. The second was 2D model to characterize the working fluid inside the heat pipe. As an excellent tool for experimental design and optimization, design of experiment (DOE) was employed to optimize the coolant velocity and the heat input to get the best performance of the heat pipe. The results show that the air velocity and power input have important effect on the performance of finned heat pipes. The total thermal resistance decreases with increase in heat input and coolant velocity. The lowest value of the total thermal resistances for finned U-shape multi heat pipe, twin heat pipe and single L-shape heat pipe are 0.181 °C/W, 0.125°C/W and 0.533 °C/W respectively. In

the numerical simulation, water and methanol were used as working fluids, and the use of water as working fluid resulted in small temperature difference and pressure drop compared to that with methanol as working fluid. For both working fluids; water and methanol, the wick permeabilty and wick thickness have major effects on temperature difference and pressure drop. The result of the optimization using D-optimal of RSM software reveals that the performance of L-shape heat pipe is improved.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Effective cooling of electronic components is important for the successful functioning and high reliability of the electronic devices. The rapid developments in microprocessors necessitate enhanced processing power to ensure faster operations; consequently, the need for cooling techniques to dissipate the associated heat is quite obvious. Moreover, the present standard metallic heat sinks are obsolete in many ways and are not sufficient to address the increased cooling needs that are sought by many of today's electronic devices. Hence, it is highly desirable to explore high-performance cooling devices, especially for CPU cooling. Heat pipe has been identified and proved as one of the viable and promising options to achieved this purpose, due to its simple structure, flexibility and in particular, high efficiency.

1.2 Heat Pipe

Heat pipe is one of the most efficient heat transport devices; it makes use of phase change of the working fluid inside, in order to facilitate the heat transport. The heat pipes are best for cooling electronic devices as their thermal conductivity is several hundreds more than that of a copper rod. Heat pipe which was proposed by Gaugler in 1942 as a cooling strategy for electronic apparatus, is a promising alternative compared to the conventional cooling schemes. As shown in the Figure 1.1, the main perception of a heat pipe involves passive two-phase heat transfer device that facilitate minimum drop

in temperature by transferring large quantity of heat. By employing such devices, higher local heat removal is possible and uniform heat dissipation can be attained.

Several day-to-day gadgets such as heat exchangers, air-conditioners, refrigerators, transistors and capacitors employ heat pipes. Heat pipes are also used in desktops and laptops to decrease the operating temperature for better performance. Heat pipes are commercially presented since the mid 1960's. Electronic cooling has just embraced heat pipe as a dependable and cost-effective solution for sophisticated cooling application.

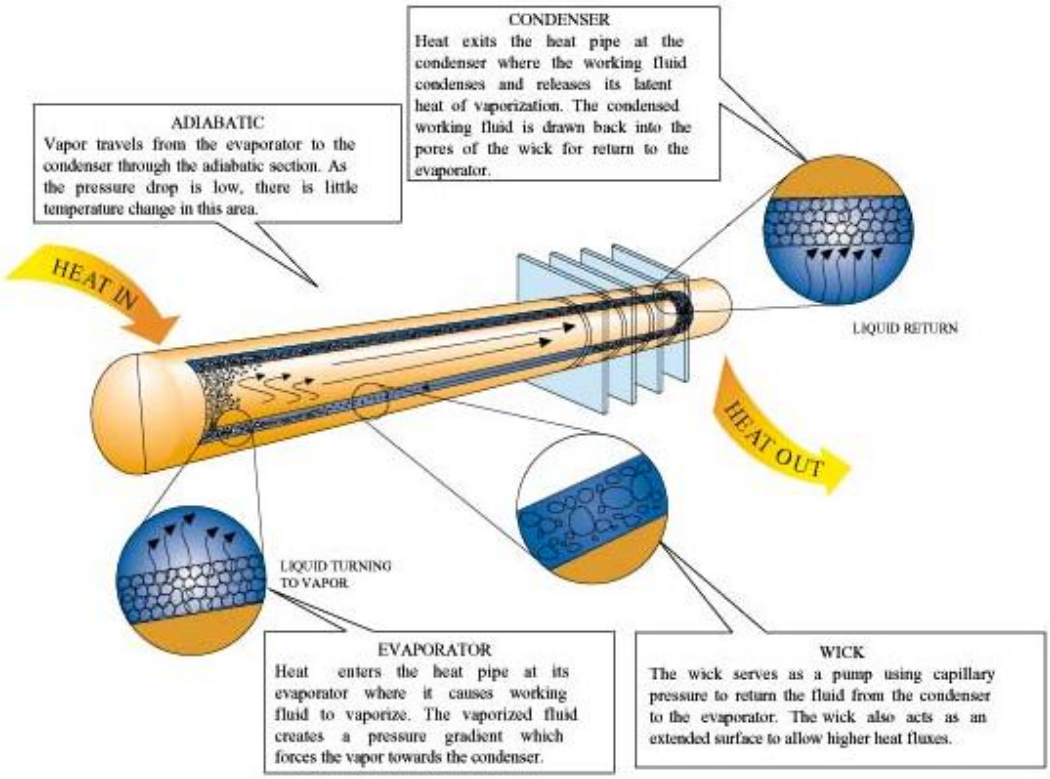

Figure 1.1: Heat pipe operation (http://www.electronics-cooling.com).

1.2.1 Historical background

Perkins tube can be historically traced as the first evolved concept of the heat pipe, and the thermosyphon, also named as Perkins pipes, was invented by Perkins in 1897 (Peterson, 1994). The thermosyphon was the precursor of the heat pipe. It operates without wick conductor; the heat transfer is achieved through the latent heat of evaporation and the liquid return to the evaporator due to gravity. Unwicked pipes were used long before the appearance of heat pipes in the construction industry; the important milestone in their development was the use of capillary forces in vapor-liquid heat conductors.

The idea of constructor in which the heat transfer was achieved using the evaporation and condensation of a working medium was proposed by Gaugler in 1942 (Dunn and Reay, 1982). In this device, there was a porous wick container in which the liquid was returned to the evaporator through it by capillary flow. This concept was re-invented by Grover and his co-workers at Los Alamos in 1963 (Ivanovskii, 1982). In that case, the working fluid return was by the capillary force. Grover verified the efficiency of heat pipes as a high performance heat transmission device and developed several applications. This development has brought about the rebirth of a high-performance device called the heat pipe.

1.2.2 Construction of heat pipe

There are three basic components of a heat pipe: container, working fluid and wick or capillary structure:

1.2.2.1 Container

Container is a metal seal, which is capable of transferring heat through it to the working fluid. This metal has good heat conductivity. Many factors affect the selection of material of the container. Among them wettability, strength to weight ratio, machinability and ductility, compatibility with external environment and working fluid, thermal conductivity , including weldability and porosity are very important. The container material must possess high strength to weight ratio, it must be non-porous in order to avoid any diffusion of vapor particles, and at the same time should ensure minimum temperature difference between the wick and the heat source owing to its higher thermal conductivity.

1.2.2.2 Working fluid

Selection of the working fluid depends primarily on the operating vapor temperature range. This is because the basis in the operation of the heat pipe is the process of evaporation and condensation of the working fluid. The selection of appropriate working fluid must be done carefully, taking into account the following factors:

- Must have very high surface tension
- Should demonstrate good thermal stability
- Wettability of wall materials and wick
- Should have high latent heat
- Should possess high thermal conductivity
- Should have low liquid and vapor viscosities, and
- it must be compatible with both wall materials and wick

The most important property of the working fluid is high surface tension so that the heat pipe works against gravity as it generates high force of the capillarity characteristic. Table 1 summarizes the properties of some working fluids with their useful ranges of temperature (Dunn and Reay, 1982).

Table 1.1: Heat pipe working fluids properties (Dunn and Reay, 1982)

Medium	**Melting Point (° C)**	**Boiling Point (°C)**	**Useful Range (°C)**
Helium	- 271	- 261	-271 to -269
Nitrogen	- 210	- 196	-203 to -160
Ammonia	- 78	- 33	-60 to 100
Acetone	- 95	57	0 to 120
Methanol	- 98	64	10 to 130
Flutec PP2	- 50	76	10 to 160
Ethanol	- 112	78	0 to 130
Water	0	100	30 to 200
Toluene	- 95	110	50 to 200
Mercury	- 39	361	250 to 650
Sodium	98	892	600 to 1200
Lithium	179	1340	1000 to 1800
Silver	960	2212	1800 to 2300

1.2.2.3 Wick or Capillary Structure

The wick develops the necessary capillary pressure which in turn facilitates the return of the working fluid from the condenser section to the evaporator section. The decrease in the pore size of the wick structure produces decreased wick permeability, which leads to increase the maximum capillary head generated by the wick. The thermal resistance at the evaporator section depends on the conductivity of the working fluid

through the wick. The common wick types in the electronics industry are explained as follows:

- **Metal sintered Powder wick**

As shown in the Figure 1.2 this type of the wick has a small pore size, resulting in low wick permeability, leading to the generation of high capillary forces for anti-gravity applications. The heat pipe that carries this type of wick gives small differences in temperature between evaporator and condenser section. This reduces the thermal resistance and increases the effective thermal conductivity of the heat pipe.

Figure 1.2: Metal sintered Powder wick (http://www.frostytech.com)

- **Grooved wick**

Grooved wick is shown in Figure 1.3; this type of wick generates a small capillary driving force, but is appropriate or sufficient for low power heat pipes which operate horizontally or with the direction of gravity.

Figure 1.3: Grooved wick (http://www.frostytech.com)

- **Screen Mesh wick**

Figure 1.4 shows the screen mesh wick, which is used in many of the products, and they have demonstrated useful characteristics with respect to power transport and orientation sensitivity.

Figure 1.4: Screen Mesh wick (http://www.frostytech.com)

1.2.3 Heat pipe theory and operation

In order for heat pipe to operate, the maximum capillary pressure must be greater than the sum of all pressure drops inside the heat pipe to overcome them thus the prime criterion for the operation of a heat pipe is:

$$\Delta P_c \geq \Delta P_l + \Delta P_v + \Delta P_g \quad (1.1)$$

where, ΔP_c is the maximum capillary force inside the wick structure; ΔP_l is pressure drop required to return the liquid from the condenser to the evaporation section; ΔP_v is the pressure drop to move the vapor flow from the evaporation to the condenser section; and ΔP_g is the pressure drop caused due to the difference in gravitational potential energy (may be positive, negative or zero, depend on the heat pipe orientation and a direction).

The basic steps of heat pipe operation are summarized as follows, with reference to Figure 1.1.

1 – The heat added at the evaporator section by conduction through the wall of heat pipe, enables the evaporation of working fluid.

2- The vapor moves from the evaporator section to the condenser section under the influence of vapor pressure drop resulted by evaporation of the working fluid.

3- The vapor condenses in the condenser section releasing its latent heat of evaporation.

4- The liquid returns from the condenser section to the evaporator section through the wick under the influence of capillary force and the liquid pressure drop.

1.2.4 Effective thermal resistance (or thermal conductivity) of heat pipe

Thermal resistance is the most important parameter of the heat pipe; many variables affect the value of effective thermal resistance, such as the shape of heat pipe, lengths of evaporator and condenser sections, working fluid and wick structure. The thermal resistance of the heat pipe is very small compared to the thermal resistance of solid metals due to the small difference between the evaporator and condenser temperatures, and hence the effective thermal conductivity of the heat pipe is too large and reaches up to 500 times more than solid copper rod (El-Nasr and El-Haggar, 1996).

1.2.5 Advantages of heat pipe

The heat pipe has many advantages compared with other cooling devices; few of them are listed below:

- As the heat pipes operate on a closed two-phase cycle, the effective thermal conductivity is very high which can transport large quantity of heat with very small temperature difference between evaporator and condenser sections.
- It can transfer the heat without any moving parts so that the heat pipe is calm, noise-free, maintenance-free, and is highly dependable.
- As the heat pipe size and weight are relatively small, it can be used in cooling electronic devices.
- Heat pipe is a simple device that can work in any orientation, and can transfer heat from a place where there is no opportunity and possibility to accommodate a conventional fan; for instance, in notebooks.

- Heat pipes demonstrate precise isothermal control because of which the input heat fluxes can be varied without having to make significant changes in the operating temperature (Yeh and Chu, 2002).
- The evaporator and condenser work independently, and it needs only common liquid and vapor so that the size and shape of the region of heat addition is different from the region of heat dissipation, provided that the rate of evaporation of the fluid does not exceed the rate of condensation of the vapor. Thus, the heat fluxes generated over smaller areas can be dissipated over larger areas with lower heat fluxes.

1.3 Heat pipe for electronic cooling

Due to the high effective thermal conductivity of heat pipes compared to that of traditional heat sinks, heat pipes have been proposed and selected for electronic cooling. (Groll et al., 1998) reported a meticulous review of the history and developments up to the year 1998, of the application of heat pipe technology for electronic cooling. Later on, (Vasiliev, 2005) provided an outline of miniature and micro heat pipes, conventional heat pipes, spaghetti heat pipes, loop heat pipes, pulsating heat pipes and some similar applications. (Maydanik, 2005) reported an exclusive review on developments in loop heat pipes and their applications. Few recent experimental works on the use of heat pipes in electronic cooling include those of (Naphon et al., 2009), (Wang et al., 2009), (Yong et al., 2010), and (Liu and Zhu, 2011). Cooling fins equipped with heat pipes for high power and high temperature electronic circuits and devices were simulated by (Legierski and Wiecek, 2001), and the superiority of the proposed system over the

traditional devices was demonstrated. (Kim et al., 2003) developed a cooling module in the form of remote heat exchanger using heat pipe for Pentium-IV CPU as a means to ensure enhanced cooling and reduced noise level compared to the fan-assisted ordinary heat sinks. (Saengchandr and Afzulpurkar, 2009) proposed a system that combined the advantages of heat pipe and thermoelectric modules, for desktop PCs.

Recently, (Liang and Hung, 2010) introduced heat sink with finned U-shape heat pipes were compatible for a wide range of high-frequency microprocessors and evaluated their thermal performance characteristics.

The present study focuses on various configurations of finned single, twin and multi heat pipes for desktop and notebooks PC-CPU and other electronic devices, in vertical and horizontal orientations.

1.4 Problem Statement

The growing development and demand for processing power in the computer industry necessitate efficient design of processors to conduct operations faster; consequently, the need for cooling techniques to dissipate the associated heat is quite obvious. Hence, it is highly desirable to explore high-performance cooling devices, especially for CPU cooling. The conventional way to dissipate heat from desktop computers was forced convection using a fan with a heat sink directly. However, with the smaller CPU size and increased power as encountered in modern computers, the heat flux at the CPU has significantly increased. At the same time, restrictions have been imposed on the size of heat sinks and fans, and on the noise level associated with the

increased fan speed. Consequently, there has been a growing concern for improved cooling techniques that suit the modern CPU requirements. As alternatives to the traditional heat sinks, two-phase cooling devices such as heat pipe and thermosyphon, have emerged as promising heat transfer devices; the effective thermal conductivity of a heat pipe can be 10 to 200 times more that of a solid copper rod of the same diameter (Chang et al., 2008).

In notebook computers, the processor's surface where most heat is generated is usually small, approximately 10 mm × 10 mm. For useful cooling, the heat must spread over a larger surface area away from the processor, as the space available near the processor is limited. Therefore heat must be drawn from the processor and conveyed to a place from where it can be dissipated by conventional means. This task is successfully achieved by a heat pipe as it can be accommodated in a highly constrained space in such a way that its evaporator section communicates with the heat source while the finned condenser section is exposed to the sink. Thus heat pipe is regarded as a promising way for cooling electronic equipments.

The differences in the shape of heat pipe affect its performance as the behaviors of the fluid and the wick structure inside the heat pipe play important role in the transmission of heat. However, few works on numerical characterization by taking into account the behavior of the working fluid considered only single horizontal heat pipe, and complex configurations such as multi and twin U-shape vertical heat pipes, and single L-shape horizontal heat pipe, have not been explored so far. Therefore, the present study is unique in solving this problem.

The decrease in the pore size of the wick causes low wick permeability, which increases the maximum capillary pumping head generated by the wick to overcome the total pressure drop within heat pipe; on the other hand, the permeability should be large in order to have small liquid pressure drop and therefore higher heat transport capability. Furthermore, the effective thermal conductivity in the liquid-wick region also plays important role on the heat pipe performance as the high value of this parameter gives a small temperature drop across the wick, which increases the thermal performance of the heat pipe. The effective thermal conductivity in the liquid-wick region depends on the material of the wick structure, the working fluid properties, thickness of the wick and the type of wick structure. These parameters present conflicting properties in most wick designs. Accordingly, an optimal wick design requires harmonization between these contradictory features. To resolve this issue D-Optimal approach of DOE Software is used to obtain the optimal solution to align the competing parameters.

Additionally, the increase of fan speed to cool the fins associated with the heat pipe, could lead to a sensation or noise, and such high velocities may not be required to achieve the cooling for a given heat input. This situation calls for the optimal conditions of fan speed and heat input, with the objective of maximizing the heat removal. Hence in the present study also aim to optimize the coolant velocity and heat input to get the best performance of the heat pipe.

1.5 Research Objectives

The objectives of this research are:

1. To study the thermal resistance (thermal performance) of vertical finned twin and multi U-shape and horizontal L-shape heat pipes under natural and forced convections at various heat inputs.
2. To perform numerical simulation of working fluid behavior inside the heat pipe in order to predict the velocity and pressure for liquid and vapor and the wall temperature, using FEM based ANSYS software and to validate by experimental results.
3. To study numerically the effect of thickness and permeability of wick structure at different working fluids on heat pipe performance.
4. To perform the optimization using Design-Expert Software (DOE) to get the best performance of the heat pipe.

1.6 Thesis Outline

This dissertation is organized in five main chapters. Chapter 1 addresses the fundamentals and the application of heat pipe for electronic cooling, the problem statement and research objectives. In Chapter 2, a comprehensive review of experimental and numerical studies on various types of heat pipes used for cooling the electronic devices and studies on the heat pipe components such as wick structure, working fluids and vapor flow are presented. Chapter 3 gives a detailed account of the materials and methods used in the current research. Deep analysis and discussion on the

results from experiments and numerical simulations are presented in Chapter 4 followed by the conclusion and suggestions for future work in Chapter 5. The dissertation ends up with references.

CHAPTER 2

LITERATURE REVIEW

2.1 Cooling methods of electronic equipments

The air-cooling is the most important technology that contribute to the cooling of electronic devices (Ledezma and Bejan, 1996). In the past, there were three main ways to cool the electronic equipment; 1) passive air cooling that dissipates heat using the airflow generated by differences in temperature, 2) forced air cooling that dissipates heat by forcing air to flow by using fans, and 3) forced liquid cooling that dissipates heat by forcing coolants like water to pass (Suzuki and Hirano, 1998).

The conventional way to dissipate heat from desktop computers was forced convection using a fan with a heat sink directly. The advantages such as simple machining, simple structure and lower cost has made heat sinks with plate fins very useful in cooling of electronic devices (Ismail et al., 2008). However, with the smaller CPU size and increased power as encountered in modern computers, the heat flux at the CPU has significantly increased (Webb, 2005). At the same time, restrictions have been imposed on the size of heat sinks and fans, and on the noise level associated with the increased fan speed. Consequently, there has been a growing concern for improved cooling techniques that suit the modern CPU requirements. As alternatives to the conventional heat sinks, two-phase cooling devices such as heat pipe and thermosyphon, have emerged as promising heat transfer devices with effective thermal conductivity over 200 times higher than that of copper (Chang et al., 2008).

2.2 Thermal Design Power (TDP)

The Thermal Design Power (TDP) has attracted the topmost interest of thermal solution designers and it refers to the maximum power dissipated by a processor across a variety of applications (Mahajan et al., 2006). The purpose of TDP is to introduce thermal solutions which can inform manufacturers of how much heat their solution should dissipate. Typically, TDP is estimated as 20% - 30% lower than the CPU maximum power dissipation. Maximum power dissipation is the maximum power a CPU can dissipate under the worst conditions such as the maximum temperature, maximum core voltage, and maximum signal loading conditions. Whereas the minimum power dissipation refers to the power dissipated by the processor when it is switched into one of low-power modes. As shown in Table 2.1, the maximum TDP ranges from 35 W to 77 W for modern processors such as Intel® Core™ i5-3400 Desktop Processor Series. While the maximum TDP for modern notebook computers ranges from 17 W to 35 W as shown in Table 2.2.

Table (2.1): Maximum TDP for modern desktop computer

(http://ark.intel.com/products/series/64902)

Product Name	Max TDP	Graphics
Intel® Core™ i5-3475S Processor (6M Cache, up to 3.60 GHz)	65 W	Intel® HD Graphics 4000
Intel® Core™ i5-3470T Processor (3M Cache, up to 3.60 GHz)	35 W	Intel® HD Graphics 2500
Intel® Core™ i5-3470S Processor (6M Cache, up to 3.60 GHz)	65 W	Intel® HD Graphics 2500
Intel® Core™ i5-3470 Processor (6M Cache, up to 3.60 GHz)	77 W	Intel® HD Graphics 2500
Intel® Core™ i5-3450S Processor (6M Cache, up to 3.50 GHz)	65 W	Intel® HD Graphics 2500
Intel® Core™ i5-3450 Processor (6M Cache, up to 3.50 GHz)	77 W	Intel® HD Graphics 2500

Table 2.2: Maximum TDP for modern notebook computers
(www.makeuseof.com/tag/thermal-design-power-technology-explained)

Processor Number	Cache	Clock Speed	# of Cores / # of Threads	Max TDP
32 nm				
i5-2557M	3.0 MB	1.70 GHz	2 / 4	17 W
i5-2540M	3.0 MB	2.60 GHz	2 / 4	35 W
i5-2537M	3.0 MB	1.40 GHz	2 / 4	17 W
i5-2520M	3.0 MB	2.50 GHz	2 / 4	35 W

2.3 Experimental studies of the heat pipe

Substantial amount of experimental works have been conducted on the heat pipe to identify its thermal performance through calculations of thermal resistance of the heat pipe. Most of the experiments proved that heat pipe is the best tool for cooling the electronic devices.

(El-Nasr and El-Haggar, 1996) investigated experimentally the effects of the number of wick layers, container materials, and working fluids on the effective thermal conductivities of several heat pipes. The results indicated that, increasing the number of wick layers inside the heat pipe improved the effective thermal conductivity of the heat pipe, and increased the heat flux transferred, with low temperature drop between the evaporator section and the condenser section. In addition, the working fluid at the operating temperature range of (313-373 K) has strongly affected the heat pipe effective

thermal conductivity at steady state while the container material had faintly affected the effective thermal conductivity of the heat pipe.

(Seok-Hwan et al., 2001) studied experimentally a new woven-wire-type wick for Miniature Heat Pipes (MHP), which had a high productivity and a large capillary limit. They used MHP with diameters of 3 mm or 4 mm which could be used for notebook- CPU cooling. The design factors discussed were evaporator length and condenser length, heat pipe length, fill ratio of working fluid, number of wick strand, inclination angle of installation and thermal load. The results showed that the minimum thermal resistance was achieved when the fill ratios were 29.3% and 31% respectively, for MHPs of 3 mm and 4mm, provided with woven-wire wicks.

A novel dynamic test method in order to quantify the thermal performances of heat pipes was introduced by (Tsai et al., 2010). This method was compared with the traditional steady-state methods. As shown in the Figure 2.1a, in the steady state test, DC power supply powered the heater. The cooling jacket connected to a constant temperature circulator with a 700 W heat dissipation capacity provides the necessary cooling effect to condensation section and the heat pipe was horizontally oriented. In the Dynamic test, the evaporator section was immersed in hot water working as power supply and the heat dissipated by using fans at condenser section with the heat pipe vertically oriented as shown in Fig. 2.1b. Some of the parameters affecting the thermal performance of heat pipes, such as fill ratio, bending angle, and shape of heat pipe under both dynamic and steady state tests were investigated. Experimental results demonstrated that the operation limitations were increased when the fill ratio was increased, leading to less temperature responses of heat pipes. The effects of parameters

in both the dynamic test and the steady-state test were almost analogical. Therefore, when high efficiency is of prime importance then dynamic test would take precedence over the steady state test.

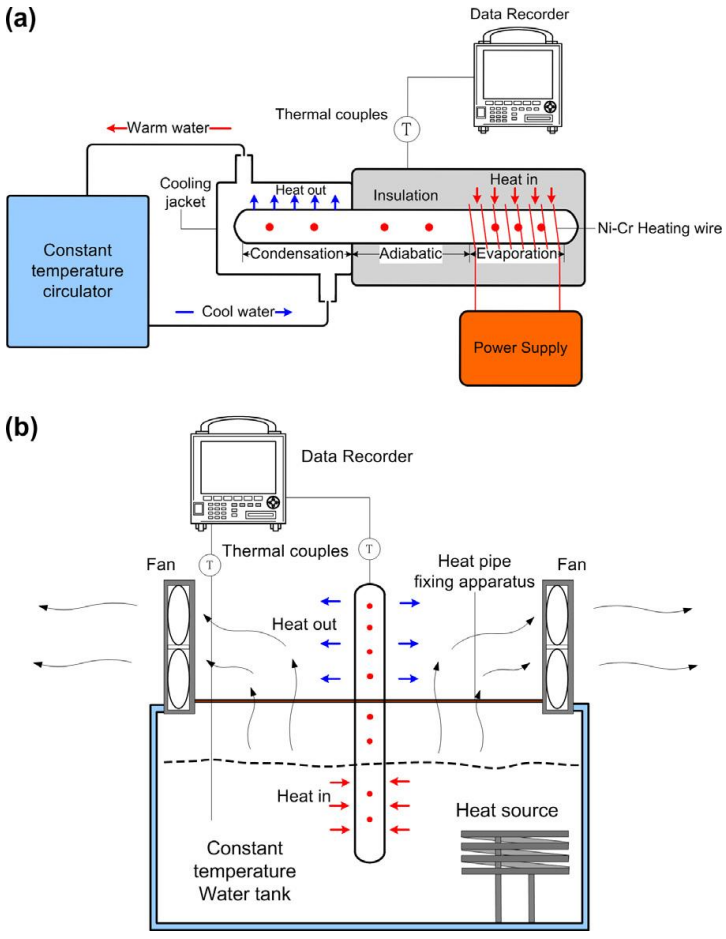

Figure 2.1: Experimental set-ups. (a) Steady-state test. (b) Dynamic test (Tsai et al., 2010).

Abundance of experiments have been performed on the heat pipes and further reviews will be carried out by studying the types of heat pipes.

2.4 Types of heat pipes

2.4.1 Cylindrical heat pipe

Cylindrical heat pipe with closed-ends is a common and conventional type of heat pipe. It involves circulation of working fluid and a wick to return the liquid. Basically, it consists of three sections, namely, evaporator, adiabatic and condenser.

(El-Genk and Lianmin, 1993) reported an experimental investigation of the transient response of cylindrical copper heat pipe with water as working fluid. The copper heat pipe with copper screen wick consisted of two layers of 150 meshes. The results showed that the temperature of the vapor was uniform along the heat pipe while the wall temperature drop was very small (maximum variation less than 5 K) between the evaporator section and the condenser section. When the heat input was increased or the cooling water flow rate was decreased, the steady-state value of the vapor temperature increased.

(Said and Akash, 1999) had studied experimentally the performance of cylindrical heat pipe using two types of heat pipes with and without wick, and water as the working fluid. They also studied the impact of inclined angle on the performance of heat pipe at different angles 30°, 60° and 90° with the horizontal. The results showed that the performance of the heat pipe with wick was better than the heat pipe without wick. The overall heat transfer coefficient was the best at the angle of 90 °.

(Mistry et al., 2010) carried out two-dimensional transient and steady-state numerical analysis to study the characteristics of a cylindrical copper-water wicked (80 mesh SS-304 screen) heat pipe with water as a coolant at a constant heat input. Finite

difference and Euler's explicit method (marching scheme) was utilized to solve the governing equations. As shown in Figure 2.2, a two-dimensional computational study utilizing the concept of a growing thermal layer in the wall and the wick region was carried out. The transient axial temperatures were experimentally determined and results of all the three sections of the heat pipe were then compared with that of 2D numerical solution. The time required to reach steady state was obtained. The transient and steady state predictions of temperatures from the two-dimensional model were in close agreement with the experimentally obtained temperature profiles.

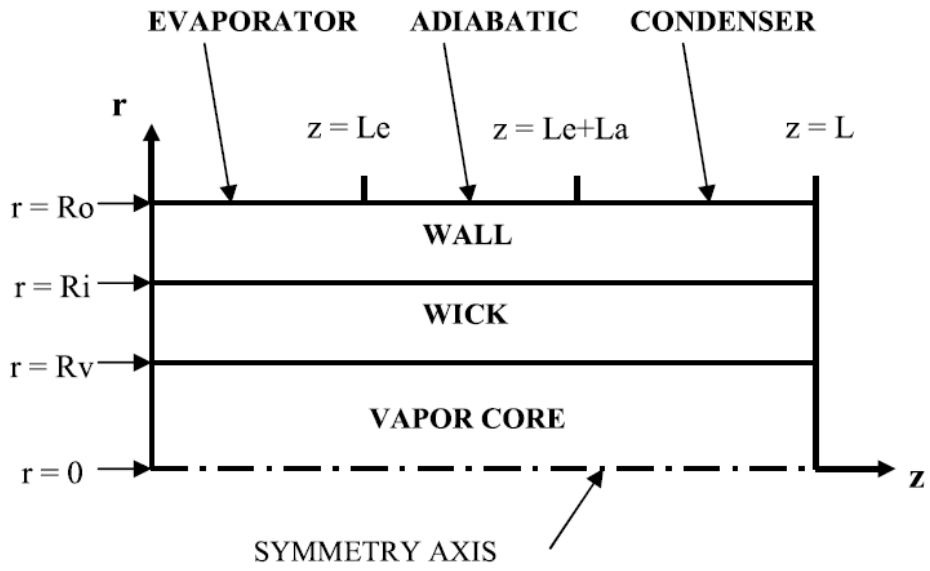

Figure 2.2: Coordinate system of the heat pipe (Mistry et al., 2010).

Further reviews of the cylindrical heat pipe will be elaborated in the numerical studies.

2.4.2 Flat heat pipes

(Wang and Vafai, 2000) presented an experimental investigation of the thermal performance of asymmetric flat plate heat pipe. As shown in the figure 2.3, the flat heat pipe consists of four sections which are the evaporation in the middle and three condenser sections. The heat transfer coefficient and the temperature distribution were obtained. The results indicated that the temperature was uniform along the wall surfaces of the heat pipe, and the porous wick of the evaporator section had significant effect on the thermal resistance. It was also showed that the heat transfer coefficient was 12.4 W/m^2 °C at the range of input heat flux 425-1780 W/m^2.

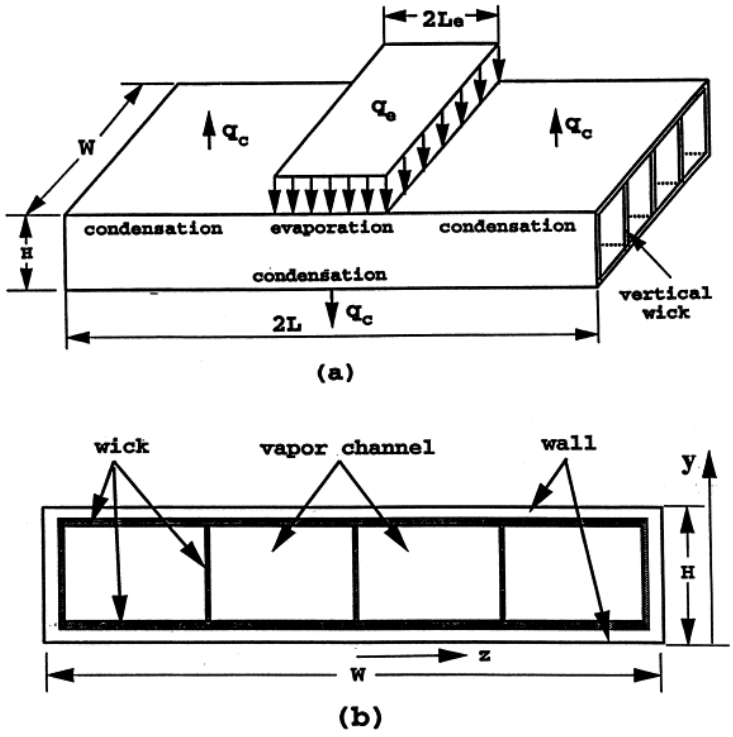

Figure 2.3: Schematic of the flat plate heat pipe: (a) geometry of the heat pipe and (b) cross-sectional view of the heat pipe (Wang and Vafai, 2000).

(Maziuk et al., 2001) modeled a flat miniature heat-pipe to determinate the thermal resistance and heat transfer coefficient. The wick structure of the heat pipe was copper sintered powder. They verified the model by comparing with the experimental results. The results indicated that the wick with copper sintered powder has strong effect to enhance the performance of the flat miniature heat pipe.

Thermal performance of a flat heat pipe thermal spreader was investigated by (Carbajal et al., 2007). They carried out quasi-3D numerical analysis in order to determine the field variable distributions and the effects of parametric variations in the flat heat pipe system. The flat heat pipe which operated as a thermal spreader was able to uniformly distribute the temperature at the condenser end, in contrast to a system having a solid aluminum plate subjected to similar boundary conditions and heat input.

2.4.3 Micro heat pipes

One of the characteristic features of micro-heat pipes which makes it different from the conventional heat pipes is that the sharp-angled corners replace the wick structure which provides the necessary capillary pressure for driving the liquid phase.

A substantial body of literature conceptualized micro-heat pipe as a key tool in electronics cooling since it was first proposed by (Cotter, 1984). Thus, one dimensional analytical models that analyze the liquid and vapor flow along micro-heat pipe were developed by (Babin et al., 1990), (Khrustalev and Faghri, 1994), (Longtin et al., 1994), (Peterson and Ma, 1996), (Ha and Peterson, 1998), (Ma and Peterson, 1998), (Sobhan