MODELLING AND OPTIMIZATION OF MICRO-CHANNEL AND THERMAL ENERGY STORAGE HEATSINKS FOR MICROELECTRONIC DEVICES

by

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1.1 SYMBOLS OF MICRO-CHANNEL HEATSINKS

SYMBOL	**DESCRIBTION**
A_b	micro-channel base area, m^2
A_c	micro-channel cross-sectional area $(= H_C.W_C)$, m^2
α	Aspect ratio = H_c / W_c.
C_p	Specific heat of fluid at constant pressure, J/kg K
D_h	Hydraulic diameter of micro-channel, m
f_{app}	Apparent Friction factor
G_v	Volumetric flow rate of the fluid, m^3/s
$G(\alpha)$	Non-dimensional aspect ratio function for friction factor and Nusselt number calculation
FEM	Finite Element Method
h	Heat transfer coefficient, $W/m^2\ {}^oC$
H_c	Height of the micro-channel, m
k	Thermal conductivity of the micro-channel material, $W/m\ {}^oC$
L	Length of the micro-channel, m
$\dot{m}$	Mass flow rate of the fluid, $(= p.G)$, kg/s
μ	Fluid viscosity, Ns/m^2
$Nu_{\sqrt{A_C}}$	Nusselt Number based on micro-channel cross-section area.
n_c	Number of channels in micro-channel heatsinks
ρ	Fluid density, kg/m^3
Q	Heat flux, W/m^2
R	Thermal Resistance per unit area, ${}^oC/W/\ cm^2$
$\mathrm{Re}_{\sqrt{A_C}}$	Reynolds number based on micro- channel cross- section area.
SLPF	Single Layer Parallel Flow
T	Micro-channel wall temperature, ${}^oC$
T_b	Maximum temperature of heat sink base, ${}^oC$
T_f	Coolant fluid temperature, ${}^oC$
T	Micro-channel wall temperature, ${}^oC$
T_{fi}	Coolant fluid temperature at inlet, ${}^oC$
$T_{b,L}$	Base temperature in left channel, ${}^oC$
$T_{b,R}$	Base temperature in right channel, ${}^oC$
t	Fin half thickness $(= W_f / 2)$, m
t_b	Micro-channel base thickness, m
v_f	Coolant fluid velocity, m/s
W_c	Width of a single micro-channel, m

W_f	Thickness of a micro-channel fin, m
W	Overall width of a heat sink, m
y^+	Non-dimensional length scale for friction factor calculation based on square root of channel area.
x, y, z	spatial variable, m

1.2 SYMBOLS OF THERMAL ENERGY STORAGE HEATSINKS

β	Coefficient of thermal expansion
D	Height of the storage, mm
D_f	Height of TES heatsink fin, mm
H	Total Enthalpy, J
H_v	Enthalpy per unit voloume, J/m^3
k'	PCM enhanced thermal conductivity, W/m.°C
k_l	Thermal conductivity, W/m°C
l	Length of the heatsink storage space, mm
μ	Dynamic viscosity of PCM, kg/ms
N	Number of fins
p	Pressure, Pa
ρ_l	Density of liquid PCM, kg/m^3
R	Output of ANN network
T_0	Reference temperature, °C
T_l	Temperature of liquid PCM, °C
T_s	Temperature of solid PCM, °C
T_{tr}	Transition temperature, °C
TES	Thermal Energy Storage
$\vec{v}$	Velocity of the liquid PCM, m/s
W	Fin thickness, mm
w	Wall of heat sink storage
δT	Maximum operating temperature to average transition temperature difference, °C
$\delta T(avg)$	Average of maximum operating temperature to average transition temperature difference, °C
δT_s	Stabilization time, s
$\delta T_s(avg)$	Average stabilization time, s

LIST OF PUBLICATIONS & SEMINARS

PEMODELAN DAN PENGOPTIMUMAN PENYERAP HABA MIKRO-ALUR DAN MUATAN TENAGA TERMA UNTUK PERKAKASAN MIKROELEKTRONIK

ABSTRAK

Pemodelan dan pengoptimuman penyerap haba mikro-alur dan penyerap haba muatan dikaji dalam penyelidikan sini. Penyerap haba mikro-alur merupakan teknologi penyejukan yang berkesan untuk menyingkirkan tenaga haba yang tinggi daripada kawasan yang kecil dan terhad di dalam perkakasan mikroelektronik. Dalam analisis di sini, penyerap haba mikro-alur dimodelkan menggunakan kaedah unsur terhingga dan sejurus itu digabungkan dengan teknik pengoptimuman untuk menghasilkan penyerap haba mikro-alur yang optima. Penyerap haba mikro-alur dimodelkan menggunakan kaedah unsur terhingga 1 dimensi dan 2 dimensi dan dibandingkan dengan jurnal teknikal. Kaedah yang dimajukan menggunakan masa yang jauh lebih sedikit berbanding dengan kaedah pengaliran cecair/gas dinamik (CFD). Kaedah unsur terhingga dikodkan dalam perisian Matlab mampu mengira dalam masa 3 saat untuk 8 unsur teratur bagi setiap lapisan mikro-alur menggunakan komputer Pentium 4 dengan 256 MB RAM. Masa pengiraan yang cepat menjadikan kaedah ini sesuai digunakan untuk pengoptimuman penyerap haba mikro-alur.

Daripada kajian yang dilakukan, analisis kaedah unsur terhingga 2 dimensi menghasilkan rintangan haba kurang 50 % dibandingkan dengan analisa menggunakan kaedah unsur terhingga 1 dimensi. Pengaliran haba dalam sirip mikro-alur yang selari dengan pengaliran cecair penyejuk dalam mikro-alur diabaikan apabila kaedah unsur tehingga 1 dimensi atau rangkaian rintangan haba digunakan tetapi ia menjadi berkesan apabila kaedah unsur terhingga 2 dimensi digunakan. Ini menunjukkan kaedah unsur terhingga 2 dimensi lebih tepat dalam mengambilkira pengaliran haba penyerap haba mikro-alur. Pengaliran haba ini menghasilkan kecerunan suhu dalam sirip dan tapak penyerap haba mikro-alur. Walau bagaimanapun pengenalan mikro-alur lawan alir selapis mengurangkan kecerunan suhu ini. Bukan sahaja kecerunan suhu dapat dikurangkan malah rintangan haba dapat dikurangkan sebanyak 18 % berbanding mikro-alur alir selari selapis. Akhirnya, kaedah pengoptimuman seperti Algoritma Genetik (GA) dan Kompleks Box digunakan untuk meningkatkan keupayaan penyejukan penyerap haba mikro-alur yang dihadkan oleh kuasa pam.

Eksperimen dan simulasi komputer yang terperinci ke atas pelbagai dimensi sirip penyerap haba muatan dijalankan untuk membina model tindak-balas terma untuk penyerap haba muatan. Model tindak-balas terma berupaya untuk mencari penyerap mutan haba yang optima untuk penyejukan yang lebih berkesan. Penyerap haba muatan diselidik mengunakan perisian komputer kaedah unsur terhingga komersil dan eksperimen. Dari simulasi komputer ke atas model penyerap haba muatan, faktor kualiti seperti rintangan haba dan masa stabil dikenalpasti dan dibandingkan dengan jurnal teknikal. Didapati perbandingan yang baik dapat dipeolehi dan seterusnya simulasi komputer dijalankan ke atas penyerap haba muatan dengan berbagai konfigurasi sirip untuk memperoleh faktor kualiti baru. Begitu juga dengan set eksperimen penyerap haba muatan yang dibina untuk memperoleh faktor kualiti. Kedua-dua maklumat yakni faktor kualiti baru dan konfigurasi sirip penyerap haba muatan diperoleh daripada simulasi komputer dan eksperimen digunakan untuk melatih rangkaian neural tiruan (ANN) yang digabungkan dengan algoritma genetik (GA) untuk mengoptimumkan penyerap haba muatan.

Konfigurasi penyerap haba muatan yang optimum diperoleh melalui ANN dan GA menggunakan data simulasi komputer dibandingkan dengan model simulasi yang menggunakan konfigurasi optimum. Perbandingan yang baik dapat dikenalpasti.

Eksperimen penyerap haba dilakukan dengan sempurna dan data yang diperoleh digunakan dalam ANN dan GA untuk mencari penyerap haba yang optimum. Akhirnya penyerap haba yang optimum yang diperoleh melalui ANN dan GA menunjukkan perbandingan yang baik dengan eksperimen penyerap haba yang menggunakan konfigurasi optima.

MODELLING AND OPTIMIZATION OF MICRO-CHANNEL AND THERMAL ENERGY STORAGE HEATSINKS FOR MICROELECTRONIC DEVICES

ABSTRACT

The modelling and optimization of micro-channel and Thermal Energy Storage (TES) heatsinks in electronic cooling are investigated in the present study. The micro-channels heatsinks is an efficient cooling technology to remove large amount of heat from very small and constrained areas of the high heat flux of microelectronic devices. In the present analysis, Finite Element Method (FEM) is developed to analyze micro-channel heatsinks and later combined with optimization tool to produce the optimal micro-channel heatsink. The micro-channel heatsink is modelled using one dimensional (1-D) FEM and two dimensional (2-D) FEM and compared with similar micro-channel in available literature. The method developed involves considerably less computational effort compared to computational fluid dynamic (CFD) methods. The FEM models implemented in Matlab codes computes within 3 seconds for 8 assembled element per micro-channel layer on a PC with Pentium 4 chipset and 256 MB RAM. The short computational time make it more suitable to be employed in optimization of micro-channel heatsinks.

It is observed from the study that a 2-D FEM analysis produced 50 % less thermal resistance compared to 1-D FEM analysis and thermal resistance network model. The heat flow in micro-channel fins along the stream-wise direction is neglected when 1-D FEM or thermal resistance network is used but comes into effect in 2-D FEM analysis. This shows 2-D FEM analysis is more accurate as it takes into account the different heat paths that exist in micro-channel heatsink investigation. This heat path develops temperature gradient in the base and fins of micro-channel heatsinks. To reduce the temperature gradient, the single layer counter flow micro-channel is proposed. It is to be found that single layer counter flow micro-channel heatsinks not only successfully reduces the temperature gradient but also reduces the thermal resistance by 18 % compared to the conventional parallel flow micro-channel heatsinks. The powerful optimization tools such as GA and Box Complex optimization are used to enhance the cooling capability of micro-channel heatsinks under the pumping power constraint.

A detailed experimental work and numerical simulation work on varying fin configuration of TES is investigated to develop the thermal response model of TES. The thermal response model is capable of finding the optimal TES heatsink for enhanced cooling purpose. The TES heatsink is investigated by using commercial finite element numerical tool and actual experimental study. From the numerical simulation of the TES model, the TES quality factors namely thermal resistance and stabilization time are determined and compared with the literature data. A good comparison was established and further simulation was carried out for varying TES heatsink fin configuration to obtain the new quality factors. Similarly the experimental setup of TES is built and the quality factors are determined from the experiment of varying TES heatsink configurations. Both the new quality factors and the varying TES heatsink fin configurations obtained from numerical simulation and experiment are used to train the Artificial Neural Network (ANN) which is later combined with GA to optimize the TES heatsink.

In ANN and GA optimization using numerical simulated TES heatsink configurations and quality factors, the optimized TES model quality factors compared well with the simulated model of the optimized configuration. Also, the experiment of TES heatsink for varying dimension of heatsink parameters are conducted successfully and the data collected is used in ANN and GA for optimization. In the final study, the optimized TES heatsink showed good agreement with the experimental TES model using the optimized configurations.

CHAPTER 1

INTRODUCTION

1.0 Introduction

In recent years, the microelectronic industry has seen exponential growth in integration, functionality and enhanced performance. The increase in IC power dissipation due to higher integration and functionality is in reverse proportion to the decrease in IC size. Consequently, the enormous heat flux generated by the electronic package causes material failure. The heat removal requirements have actually risen from 0.1-0.3 W typical of small scale integration devices used in the early 1960s, to 1-5 W in the large scale integration components and CMOS devices of mid-1980s, and to values in the range of 15-30 W for commercial equipment in the early 1990s (Bar Cohen,1994). In recent years commercial computer includes chip dissipating of 15 W/cm^2. Based on current trends, the thermal designer will have to contend with chip producing heat fluxes of nearly 100 W/cm^2 for smaller chips and 50 W/cm^2 for large chips. Currently, designers have placed an upper limit of 110-120°C and 65-85°C for electronic devices in military environment and commercial equipment respectively. Future electronic thermal control systems would appear to require chip to cool thermal resistances of less than 0.1 K/W and overall heat transfer coefficients of approximately 10,000-30,000 W/m^{2}K(1-3 W/cm^{2}K) with volumetric heat transfer coefficients greater than 200,000 W/m^{3}K(0.2 W/cm^{3}K)(Bar Cohen, 1994).

1.1 Microelectronic Devices

Microelectronics is related to the study and manufacture of electronic components which are very small. Many components of normal electronic design are available in microelectronic equivalent: transistors, capacitors, inductors, resistors, diodes and of course insulators and conductors can all be found in microelectronic devices. Digital integrated circuits consist mostly of transistors. These components are usually used in microelectronic devices such as computers, mobile phones and servers. These devices have wide applications including data storage, communication entertainment. In a microelectronic system, the hottest spot is the electronic component site where the heat is generated. The essence of thermal designer is the removal of this heat by providing an effective path for heat flow from the components themselves to the surrounding medium. The best thermal design will always be the most effective cooling system.

1.2 Cooling Technique Using Extended Surface or Fin

The removal of heat from electronic systems can be maximized if the thermal resistance of the cooling system is kept as minimum as possible. Low thermal resistance is achieved for heatsinks using high thermal conductivity material, narrow heat flow distance and large surface area for heat flow. Heatsinks are designed using high thermal conductivity material with fins offering extended surfaces to enhance the heat removal from heat generating components. Both high thermal conductivity and increased cooling surface area will reduce the total thermal resistance of the heatsink and thus effective cooling of electronic chips is achieved. Many researches are focused on low cost manufacturing methods of producing extended surfaces that incorporate more fins in smaller heatsink package sizes. Hence, optimization of extended surfaces is very important in the design of heatsinks. In the present study, two different types of heatsinks used in electronic system namely Thermal Energy Storage (TES) heatsinks and micro-channel heatsinks are investigated for optimization.

1.2.1 Micro-channel Heatsinks

Micro-channel heat sinks have very high cooling capability suitable for cooling high heat generating electronic system such as military radar system, mainframe and supercomputers (Tuckerman and Pease, 1981). Micro-channels are micro flow channels with hydraulic diameter ranging from 10 μm to 1000 μm. Micro-channel heat sinks are either micro-channels etched on the back of the silicon wafers or micro-channels on plates attached to the silicon chips.

The high cooling capability of micro-channel heatsinks is due to the large extended surfaces of micro-channel over its volume and single phase liquid cooling which has higher specific heat capacity compared to air cooling. Therefore the dimensions of micro-channel and the fluid flow property influence the cooling capability of the micro-channel system. Thus, optimization of micro-channel thermal resistance is carried out to yield the optimal dimensions of micro-channel that allows the minimum thermal resistance. Though there are several types of micro-channel, in the present study, single layer micro-channel heatsinks and stacked micro-channel heatsinks are investigated for optimization. Single layer micro-channel heatsinks have only one layer of micro-channels as shown in Figure 1.1 (Garimella and Singhal, 2004) are analysed and optimized under parallel flow and counter flow condition. In the single layer parallel flow heatsink, the cooling liquid flows in the same direction between adjacent micro-channels. However the cooling liquid flows in opposite direction between the adjacent micro-channels for single layer counter flow heatsink. Stacked micro-channel heatsinks have many layers of micro-channel bonded. In the present study, two to six layers of micro-channels with parallel flow of single phase cooling liquid in each channel are analysed and optimized. The micro-channel heatsink physical dimensions and thermal properties are modelled using finite element method (FEM).

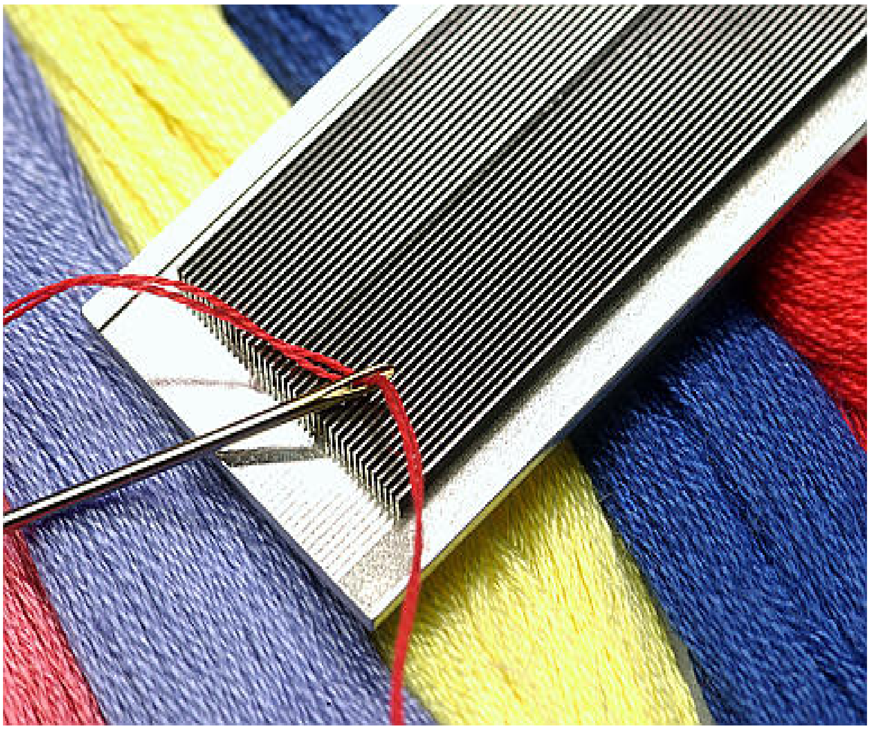

Fig 1.1: Single layer micro-channel heatsink

1.2.2 Thermal Energy Storage (TES) Heatsinks

Thermal energy storage systems have been developed to manage thermal control in variable power devices. The phase change material (PCM) embedded in the TES heat sink charges and discharges heat during the phase change process. However the phase change process stops once all the solid PCM in TES is converted to liquid during the melting process. Thus this process is time limited and this cooling technique is more suited for variable power system such as portable systems, outdoor communications enclosures and processor chips employing transient power management features such as multi-chip modules (MCM). There are several types of TES heatsink as shown in Figure 1.2 (Wirtz, et al. 2003) and Figure 1.3 (Bauer, et al. 2000). In the present study, the TES heat sink is fabricated using aluminium and embedded with paraffins. The TES heatsink fabricated for experiment is shown in Figure 1.4. The incorporation of TES in the temperature control system of an electronics module having a variable heat dissipation rate will improve system reliability and allow for a smaller, passive and cheaper module cooler.

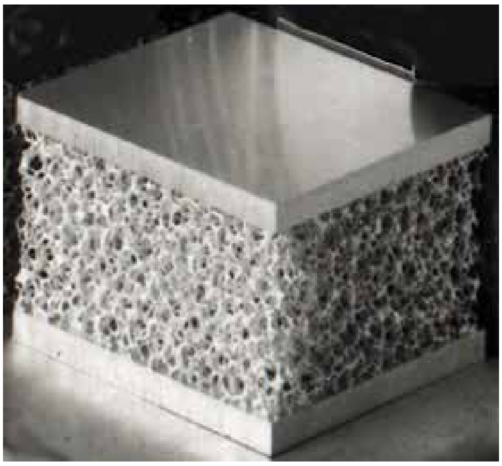

Fig. 1.2: Thin aluminium plates are bonded to the foamed aluminium.

Fig. 1.3: A balsa wood form encompasses a composite sample which consists of thin aluminium sheets bonded to foamed aluminium which is impregnated with a phase change material.

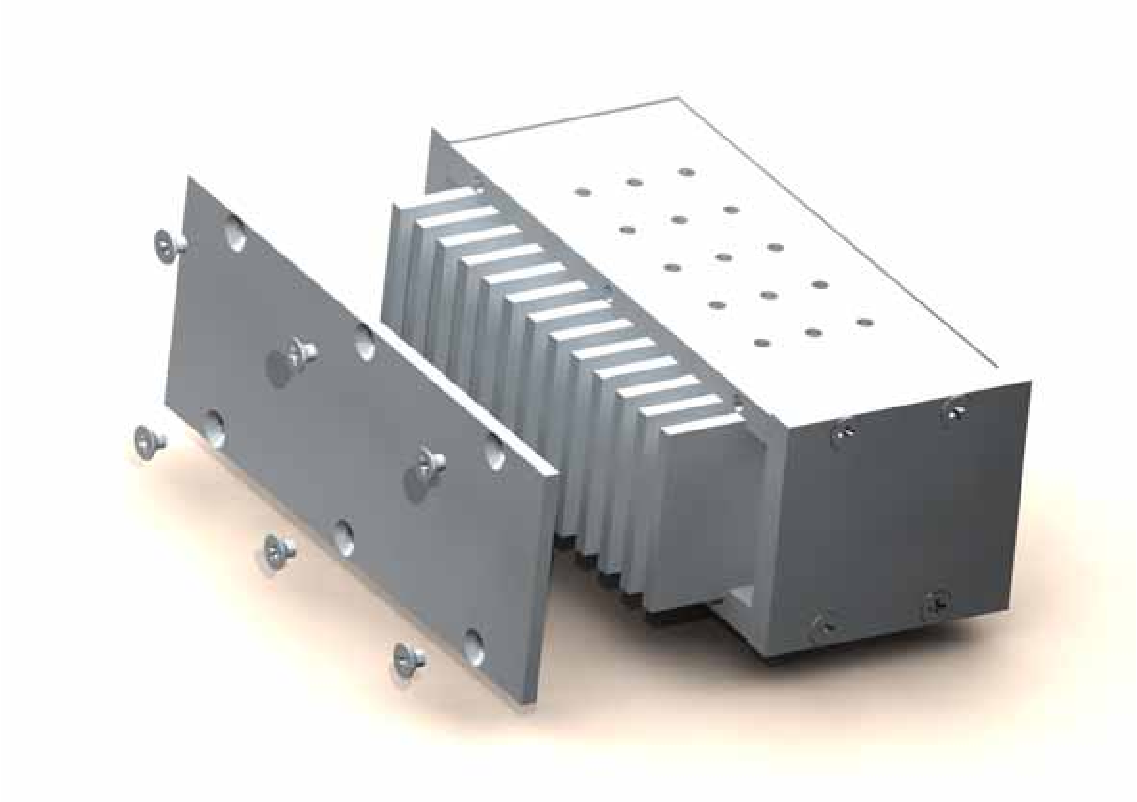

Fig 1.4: Plate fin thermal energy storage (TES) heatsink

The TES heatsink is modelled using ANSYS tool to generate thermal resistance and stabilization time in PCM melting process for various number of fin, height and thickness of fin and later trained using Artificial Neural Network (ANN). The ANN is a powerful prediction tool utilized to predict complex relationship. The ANN used here is trained to predict the thermal resistance and stabilization time for TES heatsink for unexhausted number of fins, fin height and fin thickness in the numerical simulation and experiment . This avoids the unnecessary time and financial cost resulting from try and error in finding the optimal TES heatsink. Later the ANN is embedded in genetic algorithms (GA) to find the minimum thermal resistance as well as maximum stabilization time of TES heatsink.

1.3 Finite Element Method (FEM)

The finite element method (FEM) is a powerful numerical technique to solve boundary value problems. A continuous domain is discretized to simple geometrical elements which are related to each other through nodal points. Application of the governing equations, loading and boundary conditions results in a system of equations which could be solved to find an approximate solution. The continuous and constant domain of micro-channels in the heatsink allows only few nodes to model the single element of micro-channel. Subsequently, the single element is assembled to represent the continuous and global configuration of micro-channel heatsinks. The governing equations contain the physical properties of the micro-channel whereas the thermal load imposed on the micro-channel heatsink is represented in loading conditions. The boundary conditions represent the inlet fluid flow temperature. Once the global element is obtained, the unknown temperature distribution on micro-channel heatsinks is computed. The maximum temperature from the temperature distribution is then taken to measure the thermal resistance of micro-channel heatsinks. The FEM modelling of micro-channel heatsinks are self-developed using Matlab programming. The FEM implementation and equations used is discussed in detail in Chapter 3. On the other hand, the thermal energy storage (TES) is modelled using commercial finite element analysis software tool, ANSYS. The thermal resistance and stabilization time of TES heatsinks are measured from the melting temperature variation obtained from ANSYS simulation analysis and recorded for varying TES configurations. The thermal resistance, stabilization time along with the TES configurations are then used to train the Artificial Neural Network (ANN).

1.4 Artificial Neural Network (ANN)

An Artificial Neural Network (ANN) is an information processing system that is inspired by the way biological nervous systems, such as the brain processes the information. The key element of this system is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurones) working together to solve specific problems. ANNs, like human, learn by example. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. The learning process is carried out by training the ANN with information or data. The data is used as input and output for ANN training. During the training process, the complex relationship between the output and input is recognized by ANN. In present study, the complex relationship is then stored where ANN uses the relationship study to predict thermal resistance and stabilization time for unexhausted number of fins, fin height and fin thickness in the numerical simulation and experiment . This avoids the unnecessary time and financial cost resulting from try and error in finding the optimal TES heatsink. Later the ANN is embedded in genetic algorithms (GA) to find the minimum thermal resistance as well as maximum stabilization time of TES heatsink. The detailed description of ANN implementation in TES heatsink optimization is given in Chapter 3.

1.5 Genetic Algorithms (GA)

Genetic algorithms (GA) are computational search models based on the natural processes of selection that exist in the genetics of species. Genetic algorithms work with a population of individuals, each representing a possible solution to a given problem. These individuals are then subjected to a series of evolution processes before they are evaluated and given a fitness score. The evolution processes involved in genetic algorithms are the selection process and the recombination process. The selection process involves selecting highly fit individuals for the recombination process. Recombination process involves the crossover and mutation processes. Detailed implementation and explanation of GA used in this research is given in Chapter 3.

1.6 Box Complex Optimization Technique

The Box Complex optimization method employs constrained direct-search optimization and can optimize complex multivariable system. It was developed by M.J. Box in 1965. This method creates new variables by modifying the old variables in an iterative manner. The new variables are then used in the problem function to find the optimal value. The process is iterative until the problem function converges to an optimal value. The detailed implementation of Box Complex optimization technique is given in Chapter 3.

1.7 Problem Statement

The heat flux generated from the chip continues to rise rapidly as the chip size diminishes. To address the high heat removal, micro-channel heatsink is developed to establish very low thermal resistance path for heat flow from chip to surrounding medium. In general, the analysis and investigation of micro-channel heatsink is carried out on limited geometrical range under fixed value of parameters and with limited conditions such as classical fin analysis and fluid flow. By this way, the thermal resistance of the micro-channel heatsink is often overestimated. The physical parameters such as fin thickness, channel width, channel length, number of layers, aspect ratio and fluid flow affect the thermal resistance of the micro-channel heatsink.

All these parameters should be taken into account in the analysis and optimization for efficient heat removal function of micro-channel heatsink. The available commercial finite element softwares requires substantial amount of time to perform analysis and optimization as it is not a customized micro-channel heatsink thermal and fluid solution software. Similarly, the modelling, analysis and optimization of TES heatsink using commercial computational fluid dynamic software consumes enormous time and effort. Consequently, the work carried out on optimization of TES heatsink are based on discrete configurations. This leads to optimized configuration that was obtained without thorough investigation and based on trial and error analysis. Hence, in order to remove the heat from the components effectively, there is a need to optimize micro-channel and TES heatsink in more global and proper way.

1.8 The Objective of Research

The research focuses on optimization of the TES heatsinks and micro-channel heatsinks. However the approach for both optimizations is different as explained below:

1.9 Objectives and Scopes

Objective 1 : To model and optimize stacked micro-channel heatsink and single layer counter flow heatsink using GA and Box Complex technique.

Objective 2 : To develop the thermal response system for TES heatsink using numerical (ANSYS) and experiment method and data from both methods are used to train ANN and finally by combining the trained ANN with GA to optimize TES.

Scope of Objective 1 :

i. Stacked micro-channel heatsink and single layer counter flow are developed using finite element method (FEM) and compared with established literature work for validation.

ii. The developed FEM stacked micro-channel heatsink and single layer counter flow is embedded in GA for optimization.

iii. The stacked micro-channel optimization solved using GA includes the following :

    a. Minimization of thermal resistance of double stack micro-channel for different pumping power and different channel length.

    b. Effects of channel length on optimum channel width, optimum channel width to fin width and optimum aspect ratio.

    c. Minimization of thermal resistance of stack micro-channel heatsink having different number of micro-channel layers.

iv. The single layer counter flow micro-channel optimization include the following :

    a. The minimization of thermal resistance and aspect ratio using GA and Box Complex technique for different pumping power. The two minimization technique are compared.

b. Minimization of thermal resistance of single layer counter flow and single layer parallel flow for different pumping power using GA.

Scope of Objective 2 :

i. TES heatsink is modelled and simulated using numerical finite element software (ANSYS) and compared with literature work for validation. Futher simulation is carried out for variety of fin dimensions to generate TES quality factors. The fin dimensions and quality factors are used as data to train ANN. The trained ANN is used as prediction tool.

ii. The trained ANN is combined with GA to optimize TES heatsink quality factors.

iii. An experimental setup of TES heatsink is built and varying dimension of fins are tested to generate the TES quality factors. The varying dimension and TES quality factors data are used to train ANN and later by combining with GA, the TES heatsink quality factors are optimized.

1.10 Thesis Organization

The thesis consists of four chapters with the first chapter gives the introduction and overview of the overall research carried out. The literature review and the significance of the present research compared to earlier study are highlighted in chapter two. Basically this chapter describes the literature review of TES heatsink and micro-channel heatsink, applications of ANN, GA and Box Complex optimization technique. In chapter 3, the research methodology namely the formulation of FEM model for micro-channel heatsink and TES heatsink modelling in the commercial numerical simulation are discussed in detail. The interface between the micro-channel and TES models with GA, ANN and Box Complex optimization techniques are also described. This is followed by chapter four which shows the results and discussions of the research carried out. Finally the last chapter gives conclusion of the research and also recommends the future work that can be carried out.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Heatsinks are designed to dissipate as much heat as possible from the electronic chips. This is crucial to reduce overheating of chips and to increase the chip fatigue life factor. A good heatsink should have minimal thermal resistance in order to dissipate as much heat as possible. Though variety of heatsinks exist, heat flux and cost influence the heatsink required by any specific electronic system. In the present analysis, micro-channel heatsinks used in high heat generating electronic chips and Thermal Energy Storage (TES) heatsinks used for cooling of transient power system are analysed and optimized. The application of optimization tool namely Genetic Algorithms (GA) and Box Complex optimization technique is explained in detail along with the prediction tool, Artificial Neural Network (ANN).

2.1 Micro-channel Heatsinks

According to the updated ITRS roadmap (2000), for the period from 1999 to 2005, the chip heat flux for cost-performance products is projected to increase from 28 W/cm^2 to 47 W/cm^2. To maintain a junction temperature (temperature of chip heat source) of 85°C, with an ambient temperature of 45°C, the junction to ambient thermal resistance has to be reduced by more than half from 1.15°C/W in 1999 to 0.42°C/W by 2005. This is a significant challenge to the heatsink designers. One potential solution is to attach a micro-channel heatsink to the chip and coolant such as water is pumped through the micro-channels in closed loop arrangement to remove the heat generated. Due to the small size of the micro-channels, the heat transfer coefficient is very high.

The micro-channel heatsink is defined by some physical parameters such as length, width, channel width, fin width and height of channel. By controlling these physical parameters as well as external parameters such as pumping power, the most minimal thermal resistance can be obtained. The number of micro-channels can be increased by bonding micro-channel layers. Both the single layer and multi or stacked layer micro-channel is studied and optimized in the present work. In single layer micro-channel analysis, both the counter flow and parallel flow arrangement of coolant fluid is investigated and compared.

2.2 Single Layer Micro-channel Heatsinks

In the earlier study, Tuckerman and Pease (1981) designed a micro-channel heatsink, consisting of single layer parallel micro flow passages of 50 μm wide and 302 μm deep where the thermal resistance obtained was as low as 9×10^{-6} K/(W/m^2) for a pumping power of 1.84 W. Based on this work, variety of analysis was carried out for parallel flow micro-channel heatsink. Though the parallel flow micro-channel heatsink have the ability of removing high heat flux, it is still unable to eliminate the large temperature variation at the base of the heatsinks. Missaggia and Walpole (1991) introduced a heatsink with alternate water flow directions in adjacent channels, known as single layer counter flow. Vafai and Lu (1999) introduced the double layer counter flow micro-channel heatsink which has two layers of heatsinks with coolant in the top and bottom layer heatsink flowing in opposite directions.

Qu and Mudawar (2002) analysed the pressure drop and heat transfer characteristics of a single layer micro-channel heat sink both experimentally and numerically. The heat sink was fabricated from copper and fitted with a polycarbonate plastic cover plate. The heat sink consisted of an array of rectangular micro-channels of 231 μm width and 713 μm height. Water was employed as the cooling liquid and two heat flux levels, 100 W/cm^2 and 200 W/cm^2, defined relative to the platform area of the heat sink, were tested. The Reynolds number ranged from 139 to 1672 for 100 W/cm^2 and 385 to 1289 for 200 W/cm^2. The three-dimensional heat transfer characteristics of the heat sink were analysed numerically by solving the conjugate heat transfer problem involving simultaneous determination of the temperature field in both the solid and liquid regions. The measured pressure drop and temperature distributions show good agreement with the corresponding numerical predictions. These findings are focused on general characters of heat transfer and flow in micro-channels heatsink and concluded that conventional Navier–Stokes and energy equations can adequately predict the fluid flow and heat transfer characteristics of micro-channel heat sinks.

Maranza et al. (2004) showed that conduction in the walls of single layer counter flow mini and micro-channels can get a quite multidimensional character. The wall heat flux density, for small Reynolds number, can become strongly non-uniform where most of heat is transferred to the fluid flow at entrance of mini-micro-channel. Two analytical models of channel between parallel plates are proposed: one dimensional and two dimensional based on thermal quadrupole method. It is shown that one dimensional analysis model, for small flow rates may lead to underestimation of heat transfer coefficients. Another conclusion is that axial (stream-wise) conduction in the walls of a mini-micro counter flow heatsink yields a loss of efficiency which means that an optimal wall conductivity that maximizes this efficiency exist. This is a pioneering work and thus the author was not able to compare with previous work.

Zhang et al. (2004) and Zhang et al. (2005) investigated aluminium single layer micro-channel heatsink with channel width of 210 μm and aspect ratio of 10 for cooling flip chip ball grid array packages. Experiments were carried out with heatsinks and water as coolant where thermal resistances of 0.44 to 0.32 C/W obtained for 1.2 cm x 1.2 cm heatsink footprint and 0.59 to 0.44 C/W for 1 cm x 1 cm heatsink footprint.

Recently, Hestroni et al. (2005) investigated heat transfer by comparing experiments with theory and numerical results. Their work showed energy dissipation on heat transfer is negligible under developing or developed both hydrodynamically and thermally. Also, the stream wise temperature gradient and axial conduction found to be significantly affecting the heat transfer in micro-channels up to 40 %. It is interesting to note these findings are parallel to the present work.

Chong et al. (2002) have optimized counter-flow in single layer and double layer micro-channel heatsinks using the Box Complex optimization technique which in comparison to GA consumes more time for convergence. In their work, single layer counter flow operating in laminar condition out performed the heatsinks under turbulent flow conditions for minimal thermal resistance. However, the optimization was carried out using one dimensional analysis that ignores axial (stream-wise) conduction. Also, the optimization had limited range of pumping power, pressure drop and flow rates.

In the present work, thermal resistance of single layer counter flow micro-channel heatsinks with uniform heat load distribution at the base are obtained using finite element method (FEM) and compared with methods available in the literature. Often the solutions of commercial finite element software are very time consuming thus making it very time costly for model optimization. To avoid this problem, the single layer counter flow and parallel flow is modelled using self developed FEM in Matlab and this suits the current interest of interfacing the code with optimization tools which are also coded in Matlab. But firstly, the nature of single layer counter flow and the conventional single layer parallel flow (SLPF) modelled using FEM is compared for thermal resistances by varying the aspect ratio of the channel. Finally the thermal resistance is minimized using Genetic Algorithms (GA) and compared with thermal resistance minimized using Box Complex optimization technique (Box, 1965) described in Rao (1978). Both methods were applied to the optimization of micro-channel heatsinks in earlier works but so far no comparisons between the two methods were discussed. The better performing optimization method is selected to be used for optimizing the stacked micro-channel heatsinks and TES heatsinks.

2.3 Stacked Micro-channel Heatsinks

Following the Tuckerman and Pease (1981) work on single layer parallel flow micro-channel heatsink, many other researches on parallel flow micro-channel heatsink study were carried out. Phillips (1987) showed that minimum thermal resistance was achieved by designing heat sinks that allows turbulent flow conditions. However the variation in aspect ratio and fluid velocity to achieve turbulent flow condition was limited. Phillips (1990) published a comprehensive review of all micro-channel work to date. Analyses of developing and developed flow, both laminar and turbulent, were presented. Parametric variations of fin to channel width ratio, channel height and aspect ratio, substrate thickness, and channel length were performed.

Salman (1989) carried out analytical investigation on convective heat transfer in micro-channel under limited condition of constant heat flux to the fluid with hydro-dynamically and thermally fully developed flow. Zhimin and Fah (1997) developed a thermal resistance model assuming uniform distribution of heat load on the base of the heat sink. Their model considered the sum of thermal resistances due to the bulk temperature rise, convection, constriction and conduction. Though they studied the optimum thermal design of the heat sink over wide flow and heat transfer regimes, their model is still limited to three flow constraints namely constant volume flow rate, constant pressure drop and constant pumping power. Knight et al. (1991) reported optimal configuration micro-channel heat sinks gave 35 percent lower thermal resistance as compared to that obtained by Tuckerman and Pease (1981) under turbulent flow. However the required pumping power is almost five times higher. Choquette et al. (1996), Sasaki and Kishmoto (1986), Missaggia et al. (1989) and

Landram (1991) have also done extensive thermal optimization studies for micro-channel heatsinks. For the conventional air-cooled heatsink, Cohen and Iyenger (2002) considered various aspects such as minimum material consumption, minimum pumping power along with minimum thermal resistance From all their work, it is noted that, their optimum results were normally obtained under a limited geometrical range (for micro-channel heat sink) for some parameters and based on classical fin analysis.

In recent work, Sung and Mudawar (2005) developed a new hybrid device combining slot jet impinging into a micro-channel, thus capitalizing upon the merits of both cooling configurations. The three dimensional heat transfer characteristics of this device that was developed showed excellent agreement with experimental measurements. The model found lower temperatures were achieved by decreasing jet width and micro-channel height. These findings are used to recommend a simplified hybrid cooling geometry in pursuit of both lower temperatures and smaller temperature gradients across the heated surface. However, it is to be noted that the single layer counter flow micro-channel is still favourable to eliminate the temperature gradient compared to using the hybrid system which are costly.

Wei and Joshi (2003) developed one dimensional thermal resistance network that showed for fixed pumping power, the overall thermal resistance for a two layered micro-channel stack was 30 % less than for the single layered micro-channel due to doubling of heat transfer area even though the dimensions of micro-channel were not optimized. Later, Wei and Joshi (2004) investigated the effects of number of layers in the stack, pumping power per unit area of heatsink and channel length on the optimal thermal resistance by optimizing the channel configuration. This was done by embedding the thermal resistance network in Box Complex optimization technique.

To develop optimization scheme, it is essential to have an analytical description of heat transfer process in the heatsink. Heat transfer in micro-channel is a conjugate one, combining heat conduction in the solid and convection to the cooling fluid. Due to complex nature of this flow, it is challenging to develop a comprehensive analytical solution for the governing differential equations. Therefore, most analytical studies adopt the classical fin analysis method, which models the solid walls separating micro-channels as thin fins, and simplifies the heat transfer process by introducing major approximations as one dimensional heat transfer and uniform fluid temperature. While the classical fin analysis method provides as simple method to describe the heat transfer performance of micro-channel heatsink, its accuracy can be greatly compromised by its simplifying assumption that heat flows only in one direction.

A more accurate description of the fluid flow and heat transfer characteristics of a micro-channel heat sink necessitates the use of direct numerical simulation method. Weisberg et al. (2003) performed a two dimensional numerical analysis by assuming both hydraulically and thermally fully developed flow within the micro-channels. This work focuses on heatsink parameters that satisfy the general assumptions of the flow. Fedorov and Viskanta (2004) developed a three dimensional numerical model by eliminating the approximation of fully developed flow, accounting for development of both velocity and temperature fields. However no detailed comparison between the earlier work or experiments and their numerical predictions was provided to validate their numerical analysis.

As can be seen from the literature review presented, the analysis and investigation of micro-channel heatsink is carried out on limited geometrical range under fixed value of parameters and with limited conditions such as classical fin analysis and fluid flow. In the present study, the optimization is carried out in large geometry range with only pumping power of micro-pump as the constraint. The physical parameters such as fin thickness, channel width, channel length, number of layers and aspect ratio of micro-channel heatsink affect the thermal resistance of the stacked micro-channel heatsink. The fluid flow is modelled using the developing flow and developing thermal condition for micro-channel duct. The micro-channel heatsink is modelled using one dimension and two dimension FEM and optimized using GA and the resulting thermal resistance is compared with available literature. The development of one dimensional and two dimensional finite element method (FEM) considered in the present analyses are given in detail in the analysis chapter.

2.4 Thermal Energy Storage (TES) Heatsinks for Electronic Cooling

Thermal energy storage systems have been developed to manage thermal control in variable power devices such as communication systems used in hostile environment such as military and fireman walkie talkie. They are capable to store energy during peak power operation and release it during periods of reduced power operation. Phase change materials (PCM) used in TES heatsinks undergoes phase transformation at the transition temperature, T_{tr}, which provides load leveling capability via latent heat effect. The large amount of heat absorbed or released by the PCM during the phase change process requires lower mass or volume, which is often important in real applications. Leoni and Amon (1997) used paraffin as the PCM to control the operating temperature of wearable electronics and Bauer and Wirtz (2000) had described a TES composite that incorporates pentaglycerine as the PCM. Pentaglycerine that undergoes solid-state phase transistion, eliminates the effect of orientation or g-loading that exist for PCM that possess solid-liquid phase transistion. However pentaglycerine is hazardous when it is exposed to human or living creatures.

The performance of a TES heatsink is measured by its quality factors. The quality factors of TES systems are volumetric storage capacity and the thermal resistance. A good TES system requires extended time periods for heat storage as well as low thermal resistance. The extended time period is also known as stabilization time. There will be a finite thermal resistance between the heat source and the PCM storage volume. Another thermal resistance connects the storage volume to the system heat exchanger. As a consequence, at the transient temperature of the PCM mass will lag behind the temperature of the heat source. This effect is characterized as maximum operating temperature to transition temperature difference. The thermal resistance is measured by using the maximum operating temperature to transition temperature difference.

Heat transfer during melting and solidification of the PCM in a storage system with internal fins has been studied numerically and experimentally by several authors. Al-Jandal (1992) studied experimentally the effects of the fin, metal honeycomb and copper matrix structure on the total melting and solidification time. The results showed that the average thermal conductivity enhancement factors for solidification are in ratio of 1.7 and those for melting in ratio of 3.3. Natural convection has a significant effect on the acceleration of the melting. The average thermal conductivity enhancement factor is determined as a ratio of solidification or melting time with fins and without fins.

Bugaje (1997) conducted experiments on the use of methods for enhancing the thermal response of paraffin wax heat storage tubes by the incorporation of aluminum fins and star structures. The conclusion was that internal fins performed much better than star matrices, reducing the loading time in ratio of 2.2 and unloading time in ratio of 4.2. Though different shapes of fins are studied, the fin configuration was not part of their analyses. It is to be noted that the fin configuration has also impact on loading and unloading time and neglecting it would result in heatsink parameters not to be optimized to overall optimal condition.

Padmanabhan and Murthy (1996) presented a finite difference method analysis for phase change in cylindrical annulus with axial rectangular fins between inner and outer tubes. The analysis lead to the development of the PCM volume melt/frozen fraction formula. The melting and solidification time showed decreasing trend with the increase in the number of fins. There were no available experiment data to compare their result. Humpries and Griggs (1977) carried out a numerical analysis on rectangular phase change housing, using straight fins as a heat transfer enhancer in two-dimensional grids. The data was generated over a range of realistic sizes, material properties and different kinds of thermal boundary conditions. This resulted in a design handbook for phase change energy storage. However their work is limited to analytical study and no optimization was carried out. In another work, Henze and Humprey (1980) presented a simplified numerical model on a transient and thin fin equation, which predicts the fraction of melted PCM, and the shape of the liquid-solid interface as a function of time. The model indicates that melting the PCM in a pure conduction mode with closely spaced thin fins material is preferable to melting PCM with thicker fins spread further apart, even in the presence natural convection. However their model is focused only in reducing the thermal resistance but ignores the importance of stabilization time. Lamberg et al. (2004) developed an analytical model which predicts the solid-liquid interface location and temperature distribution of the fin in melting and especially, in solidification processes with a constant end wall temperature in a finned two-dimensional PCM storage. Experiment of phase change material in aluminium storage was conducted to validate the analytical model. The melting temperature variation from the experiment of two storages embedded with PCM is used as comparison data for the present analysis.

The analysis by Regin et al. (2005) showed the difference between numerical analysis and experiment can be reduced significantly when the phase change temperature range and natural convection in the liquid phase are considered instead of considering the process to be conduction dominated only. The study mainly describes the melting behaviour of PCM in TES.

Recently, Nayak et al. (2006) investigated heatsinks with PCM and thermal conductivity enhancers (TCE) numerically. With respect to the distribution of TCE and PCM materials, the heatsink design are classified into two, namely heatsink with PCM distributed uniformly in a porous TCE matrix, and PCM with fins made out of TCE material. A transient finite volume method is used to model the heatsink, PCM and TCE. The performance of heatsinks with various volume fractions of TCE for different configurations is studied with respect to variation of heat source(or chip) temperature with time, melt fraction and dimensionless temperature difference within PCM. For the case of porous TCE matrix, the results shows that melt convection has considerable effect on development of solid-liquid interface. However, the effect of convection becomes insignificant beyond certain volume fraction of TCE. For the case of PCM with fins, the performance of heatsink improves if the TCE material is distributed in the form of thinner fins.

From the literature, there was no work focused on the optimization of TES heatsinks to determine minimum thermal resistance with maximum stabilization time simultaneously. Realizing this, Zheng and Wirtz (2004) designed a hybrid thermal energy storage (TES). The thermal resistance was minimized and the stabilization time was maximized. They optimized TES heatsink geometric for given heat loading constraints using commercial optimizer. However the fin height influence on optimal heatsink was neglected.

The available optimization work mostly focused on reducing the thermal resistance or maximizing the stabilization time separately and not simultaneously. Above all the fin configurations was not exhausted during the optimization. The enormous time required for numerical simulated TES heatsink as well as the complexity of mathematical model of phase change process limits the optimization work. However in the present study, artificial neural network which is easily understood and far less time consuming is combined with genetic algorithms to optimize the TES heatsink's quality factors. All the rectangular flat fin configurations such as width, height and fin spacing are taken into considered in the optimization. Both experiment and commercial finite element analysis software are used to model the TES heatsink. The data such as TES model dimension and quality are used in ANN where the ANN can automatically learn the complex relationships between those provided data and predict the TES model dimension and quality factors instantaneously. This feature makes the technique very useful in modelling processes such as phase change process which mathematical modelling is very difficult and time consuming. Finally by combining ANN with GA, the TES heatsink optimizer is realized.

2.5 Genetic Algorithm (GA)

Genetic algorithm (GA) is computational models based on the natural processes of selection that exist in the genetics of species. The computational model was first proposed by Holland (1975) though the concept was already referred to as “genetic algorithms” by Bagley (1967). Both Goldberg (1989) and Davies (1991) have given detailed explanation on the various processes involved in the algorithm.

Genetic algorithm works with a population of individuals, each representing a possible solution to a given problem. These individuals are then subjected to a series of evolution processes before they are evaluated and given a fitness score. The evolution processes involved in genetic algorithms are the selection process and the recombination process. The selection process involves selecting highly fit individuals for the recombination process. An example of the selection process is the roulette wheel selection process described by Goldberg (1989). Recombination process