

# ANALYSIS AND FEASIBILITY OF AN EVAPORATIVE COOLING SYSTEM WITH SESSILE DROPLET EVAPORATION TO PROVIDE COOLING FOR MICROPROCESSORS

By

Soma Chakraborty

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## Abstract

The study investigates the cooling requirements for the Intel Xenon Processor and the Intel Core i7-900 Processor using diffusion based evaporation of sessile droplets. An analytical model is developed to determine the capacity of a single layer of droplets to provide sufficient cooling. It is found that a single layer can provide sufficient cooling for the processors with tiny droplets. A numerical model is developed to analyze a tiered system that fits within the space restrictions corresponding to the current heat sinks with larger droplets and fewer of them. The results of the numerical modelling work found that a minimum of 41 posts connecting each of the tiers were required to cool the Xenon Processor and 42 posts for the Core i7-900 Processor. It was also found that a minimum of 3 tiers were required for the Xenon Processor, with a droplet radius of 2 mm, and 4 tiers for the Core i7.

**Keywords:** Evaporative cooling, Sessile droplets, Microprocessors, Evaporation, Cooling, Thermal management

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## Nomenclature

|                  |  |
|------------------|--|
| $A_{tot}$        | Total area of substrate (m <sup>2</sup> )  |
| $A_{exp}$        | Exposed copper surface where there is no droplet (m <sup>2</sup> )                             |
| $c(T_s)$         | Saturated water concentration in surrounding air at substrate temperature (kg/m <sup>3</sup> ) |
| $c(T_\infty)$    | Saturated water concentration at ambient temperature (kg/m <sup>3</sup> )                      |
| $D$              | Water vapour diffusivity in air (m <sup>2</sup> /s)  |
| $H$              | Relative humidity (%)  |
| $h_p$            | Height of post (m)   |
| $\Delta h_{fg}$  | Specific enthalpy of vaporization (J/kg)   |
| $\Delta h_{vap}$ | Specific enthalpy of vaporization at the interfacial liquid phase temperature (J/kg)           |
| $j(x)$           | Evaporation flux distribution ( $\mu\text{L}/\text{mm}^2\text{min}$ )                          |
| $k_L$            | Thermal conductivity of liquid phase (W/mK)  |
| $k_{Cu}$         | Thermal conductivity of copper (W/mK)  |
| $l_{sp}$         | Distance between post and droplet (m)  |
| $l_{sd}$         | Distance between the droplets (m)  |
| $\dot{m}_{ev}$   | Evaporation rate of droplet (kg/s)   |
| $N_d$            | Number of droplets   |
| $N_p$            | Number of posts  |

|                        |  |
|------------------------|--|
| $Nu$                   | Nusselt number   |
| $Pr$                   | Prandtl number   |
| $Re$                   | Reynolds number  |
| $q_{TDP}$              | Thermal design power for microprocessor (W)  |
| $r_p$                  | Radius of post (m)   |
| $r_d$                  | Radius of droplet (m)  |
| $T_{Liq}$              | Temperature of liquid phase ( $^{\circ}C$ )  |
| $T_t$                  | Temperature of top surface of substrate ( $^{\circ}C$ )                                  |
| $T_L$                  | Temperature at bottom of lowest substrate tier ( $^{\circ}C$ )                           |
| $T_{\infty}$           | Atmospheric temperature ( $^{\circ}C$ )  |
| $T_{CASE\ MAX}$        | Maximum temperature for specific thermal design power for microprocessor ( $^{\circ}C$ ) |
| $\mu$                  | Dynamic viscosity (kg/ms)  |
| $\phi_{isoth}(\theta)$ | Non-dimensional flow that depends on contact angle ( $\theta$ )                          |
| $\rho$                 | Density of air (kg/m <sup>3</sup> )  |
| $\theta$               | Contact angle ( $^{\circ}$ )   |
| $v$                    | Velocity of air (m/s)  |

# Chapter 1

## Introduction

### 1.1 Motivation

Adequate cooling is a major challenge to future development of faster and denser high powered microprocessor. The continually increasing thermal power dissipation by microprocessor of more than 100 W, at an average heat flux that is approaching or exceeding  $50 \text{ W/cm}^2$  needs to be removed, while keeping the microprocessor temperature below  $85.0^\circ\text{C}$  [1]. From the highest echelons of the scientific community to the average consumer, everyone wants a faster, smaller piece of technology. Drones, laptops, cell phones, and so many more technological innovations are being limited by their conventional cooling systems. The evolution of the computational technology shows a trend that the technology is shrinking down from large corporate computers (in the early days) to tablets. The technology continues to be made smaller and more efficient. For

the advancement of miniaturization, every instance of technological advancement requires more efficient and compact thermal management. The reason why researchers care about the cooling system of micro technology is because current methods of cooling are not compact enough.

The thermal design power of the Intel Xenon Processor and Intel Core i7-900 Desktop Processor is approximately 130 W [2, 3]. Heat sinks and fans require a great deal of space. An example of a standard heat sink and fan arrangement for the Intel Xenon Processor is shown in Figure 1. The volume of the heat sink used for the Intel Xenon Processor is  $91.5 \times 91.5 \times 25.5$  mm and the Intel Core i7-900 Desktop Processor is  $104 \text{ mm} \times 104 \text{ mm} \times 81.3 \text{ mm}$  [2, 3]. The power load is getting higher in smaller spaces, so for technology advancement something better and more compact than conventional cooling is required. The ability to pack more power into these devices relies on providing an equivalent amount of heat removal. As a result, forward movement is necessary by utilizing something more compact for microelectronics cooling.

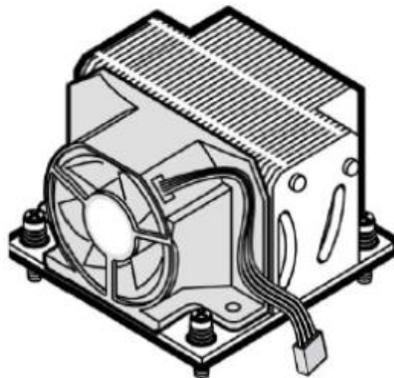


Figure 1: Passive/active combination heat sink (with removable fan) for Intel Xenon Processor [2].

Nature can give us inspiration for compact cooling. For example, human perspiration involves evaporating sessile droplets used for thermal management; sessile sweat droplets evaporate from the skin surface to regulate the body temperature when conduction and convection are insufficient, as shown in Figure 2. Latent heat of vaporization of water has a great influence on the evaporation of sweat droplet for heat management of human body.

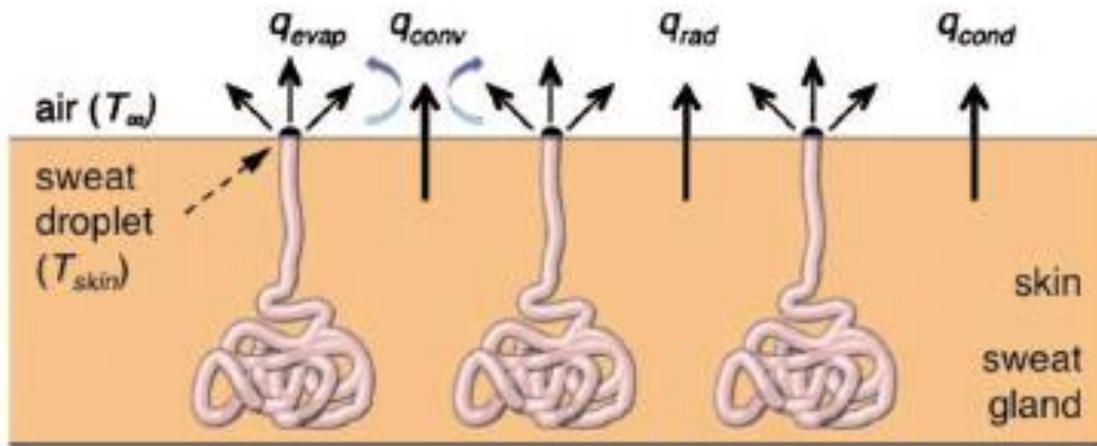


Figure 2: Schematic representation showing heat dissipation from human skin [4].

From engineering feats, such as buildings and bridges, to plant inspired medicinal advances – examining nature's design has aided in the development of almost every aspect of our everyday lives, and often without our realization of it. This design concept is commonly known as biomimicry. For example, Velcro is inspired by burrs, improved wind turbines inspired by whales' fins, tails and flippers, tidal power systems inspired by solar fish, and IBM is trying to make a

computer inspired by the human brain [5]. When the human body perspires by tiny droplet evaporation, there is no need for the droplets to coalesce and form a larger body of water at the surface of the skin for the heat to dissipate. While dogs may only be able to use the total surface area of the tongue for evaporative cooling, in case of human, body sweat droplets are excreted from much of the skin area, which allows humans to achieve a relatively high cooling rate [6]. Perspiration provides a model for a heat management system used in nature, which is partially mimicked for the work presented in this thesis.

## 1.2 Background

### 1.2.1 Importance of sessile droplets

Evaporating sessile droplets occur in a number of natural and engineered systems such as bio-medical applications [7], inkjet printing [8], DNA mapping [9, 10], and painting [11]. In nature, perspiration is one example of the utility of evaporating sessile droplets. Hence, there is potential to exploit this natural cooling mechanism to develop compact and efficient evaporative cooling systems for microelectronics cooling. For example, a system that mimics human perspiration could potentially replace the current thermal management strategy

for microprocessors, which is generally accomplished through forced-air convection with a finned array and a fan. Engineering such a system would require a substrate with a continuously-fed array of evaporating sessile droplets, and several tiers. In order to assess whether or not such a system could remove enough heat to compete with traditional thermal management systems, numerical modelling is required to simulate the conditions and explore the feasibility. The feasibility is assessed for diffusion limited evaporation of sessile droplets so that a fan is not required. In the following paragraph diffusion limited and thermal conduction limited evaporation are discussed.

### 1.2.2 Diffusion limited versus thermal conduction limited evaporation

In diffusion limited evaporation, the droplet evaporation is driven by the concentration gradient of water vapour between the droplet surface and the atmosphere. If the air surrounding the droplet is quiescent, the diffusive transport of the vapour is the mechanism that limits the evaporation rate, which implies that the vapour concentration,  $c$ , in the gas in close vicinity of the droplet surface is at the saturation level, i.e.  $c=c_s$ . The reference value is the concentration far away from the droplet, i.e.  $c=c_\infty$ . For water vapour in air this value is set by the relative humidity  $H$  as  $c_\infty = Hc_s$  [12]. Vapour diffusion can be

assumed as a quasi-steady process because the droplet lifetime is longer than the characteristic time scale for diffusion [11].

Most of the expressions of evaporation rate for sessile droplet are diffusion limited [11, 13, 14]. Since the vapour diffusion is in quasi-steady process this is the most conservative and slowest evaporation case. In other words, diffusion is preventing the evaporation; vapour must move away to enable further evaporation. If vapour is removed from the upper side of the droplet by air movement or blowing of a fan, it is not diffusion limited any more. Then the questions that arise are: what limits the evaporation in this case and it is governed by which phenomena?

The convection through the vapour phase has been shown to be negligible for similar evaporating sessile droplets [15], so the droplet evaporation must be limited by the thermal conduction through the liquid in the droplet. The energy balance of local evaporation flux associated with the thermal conduction,  $j(\phi)$ , can be written as

$$\left( -k_L \frac{\partial T_{Liq}}{\partial r} \right) = j(\phi) \Delta h_{vap} \quad (1)$$

where  $\Delta h_{vap}$  is the specific enthalpy of vaporization at the interfacial liquid phase temperature,  $k_L$  is the thermal conductivity of liquid phase,  $r$  is the radial position,  $T_{Liq}$  is the temperature of liquid phase. Eq. (1) can be used to calculate the local evaporation flux  $j(\phi)$  associated with the thermal conduction.

Recently Mahmud and MacDonald [15] have experimentally investigated the evaporation flux distribution and modes of interfacial energy transport for continuously fed evaporating sessile droplets and conclude that the thermal conduction through the vapour phase is negligible compare to the thermal conduction through the liquid phase. They found that the local evaporation flux distribution associated with thermal conduction varied along the surface of the droplet and thermal conduction provided a majority of the energy required for evaporation.

With utilizing thermal conduction limited evaporation, more heat can be removed from the surface. A numerical model of a sessile droplet with thermal conduction based evaporation can provide thermal properties at the interface to determine the required temperature profile to accomplish the heat removal. The evaporation flux distribution associated with the thermal conduction and the temperature profile along the droplet surface generated by the numerical model will help to enable control and improvement of evaporation rates in the regime relevant to application, such as evaporative cooling systems, which will lead to improved performance and better design.

### 1.2.3 Importance of modelling for simulated skin system

To assess the feasibility of cooling a microprocessor with an evaporative cooling system based on human perspiration, a numerical model is required to effectively capture the geometry and temperature distribution of a compact tiered system. Numerical modelling can provide a quicker and cheaper approach to analyze the feasibility of a tiered evaporative cooling system with sessile droplets compared to experimental analysis, in addition it can provide the capability to explore a number of configurations.

### 1.2.4 Cooling requirement for microprocessor

The central processing unit (CPU) is the heart of modern computers. Intel has been the leader in CPU market share worldwide, having the majority share for the past two decades. Intel had nearly 84% of the global microprocessor market [16] and 94% of the PC server market [17]. Recently, smartphones have taken the place as a primary method of computing, where Qualcomm leads the market at 42% as of 2015 [18]. These data demonstrate that when designing thermal management systems for computing applications, it is desirable to examine the design specifications of Intel or Qualcomm.

To express the thermal output of a given processor, thermal design power (TDP) is the primary metric used by CPU manufacturers and should be used for processor thermal solution design targets [19]. TDP represents the heat dissipated by the CPU while running a commercially useful software load. Intel has also built thermal controls into their designs to modulate clock frequency or reduce voltage.  $T_{CASE MAX}$  is the temperature measured at the geometric top-center of the CPU casing which is also known as the integrated heat spreader [20]. Thus,  $T_{CASE MAX}$  is the maximum temperature limit specified by the manufacturer, and TDP is the corresponding heat dissipation rate at this temperature. Figure 3 shows the location of  $T_{CASE}$  for a microprocessor.

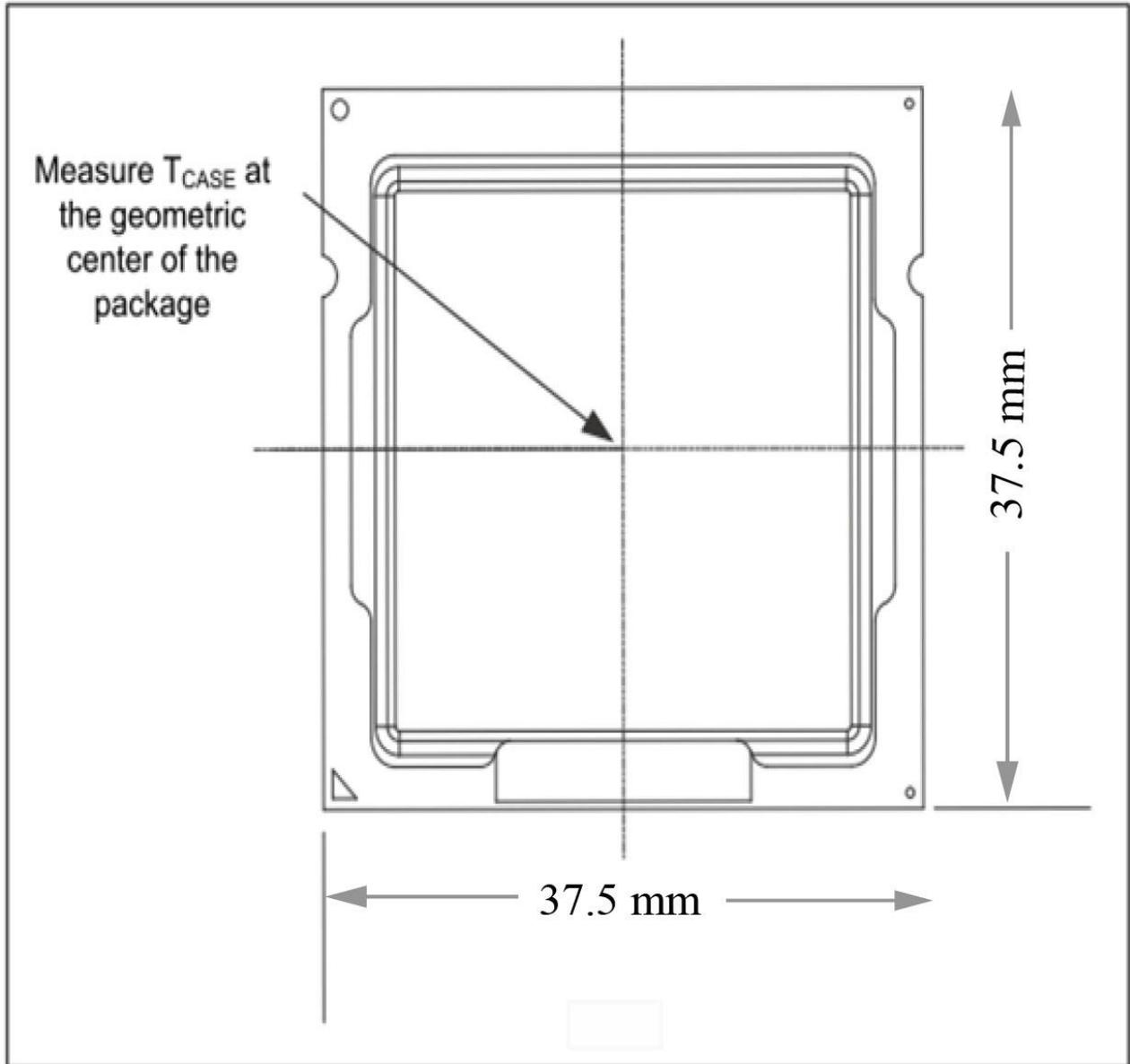


Figure 3: Location for measuring  $T_{CASE MAX}$  [20].

In this study, the value of TDP and  $T_{CASE MAX}$  are used for the Intel Xenon Processor E5-1600/E5-2600/E5-4600 product family (8/6 core thermal profile 1U) and

the Intel Core i7-900 Desktop Processor. The thermal profile for processors is plotted in Figure 4 [2, 3].

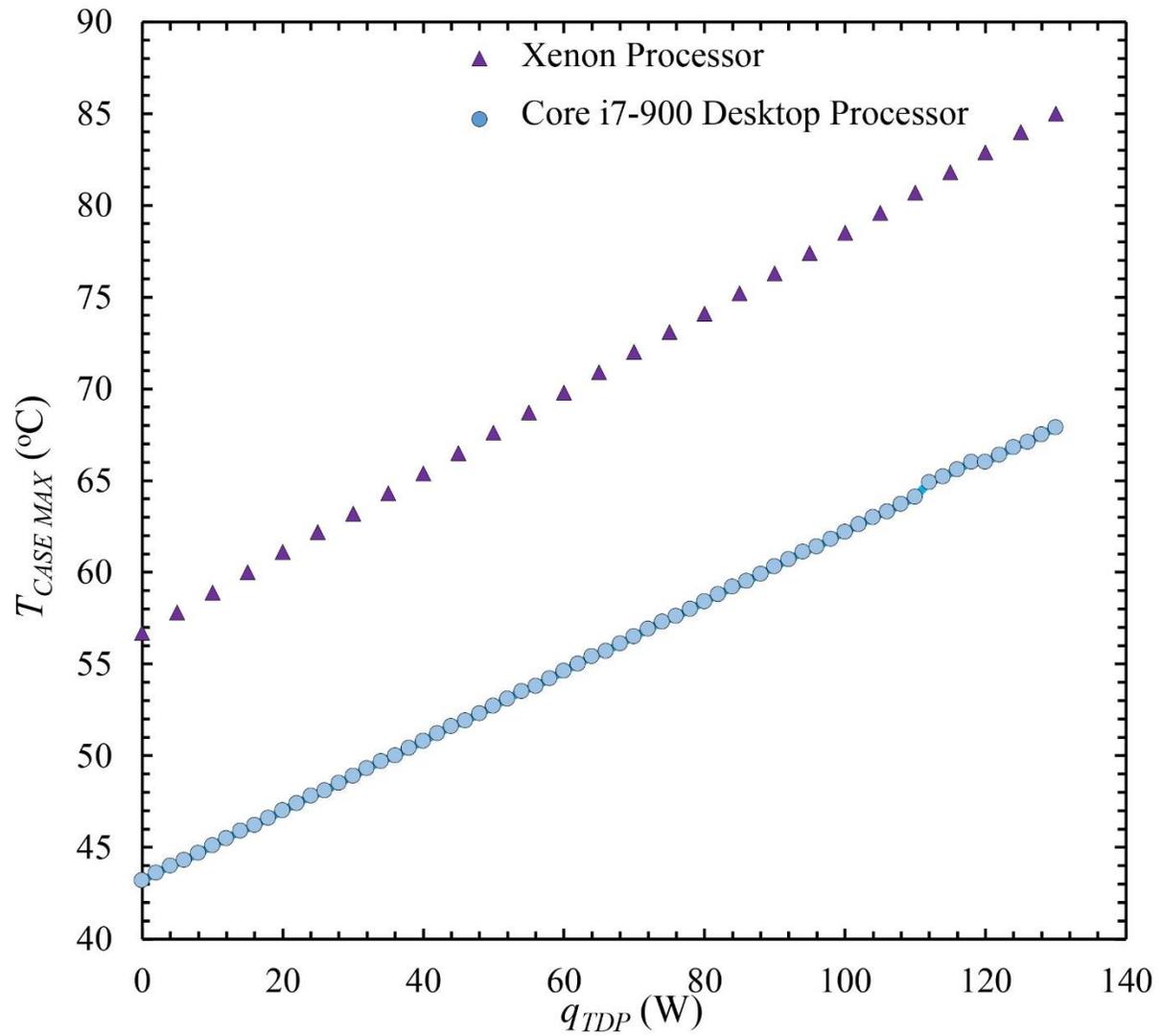


Figure 4: Thermal profile of two types of microprocessors.

## 1.3 Literature review

### 1.3.1 Engineering model for “simulated skin”

The evaporation rate of sessile droplets depends on a number of factors, including droplet radius, contact angle, relative humidity, and the diffusion coefficient [13, 14, 21, 22], which is determined from experimental and theoretical analyses of the evaporation of sessile droplets [13, 15, 23-26]. Most of the past work on evaporating sessile droplets has focused on single droplets, with much of the work focusing on drying droplets [13, 14, 25], or recent work on a single continuously-fed droplet [15]. The exception is the study by Kokalj et al. [4], in which they developed an analytical model for a single-layered array of evaporating sessile droplets on a porous membrane inspired by human skin, to examine geometrical and environmental parameters such as relative humidity on cooling performance. Their model showed that heat dissipation increased in the membrane with denser droplets (when compared to human skin), by an enhancement factor of 10 at 5000 pores/cm<sup>2</sup> and pore radius of 35 μm. They provided three physical interpretations; the first being that heat dissipation was significantly enhanced by increasing the density and the size of the droplets until the membrane was fully covered while overcoming a local vapour field effect from nearby droplets. The second is that evaporative cooling is effective when a cold membrane is placed in hot ambient air. The third one is that the cooling rate increased as the droplet temperature increased while being less affected by the

relative humidity. They have also examined the fusion limit of droplets, proving the importance of droplet array versus film evaporation in their model. Since physics of droplet evaporation is complex, many analytical and numerical models are based on assumptions that there is negligible heat transfer between droplet and substrate [13, 24, 27, 28], and pinned wetting line throughout the evaporation [11, 13, 29, 30]. The above literature review suggests that until now there is no study in the literature on numerical modelling for an arrayed droplet evaporative cooling with a continuously fed droplet system, or with a tiered system.

### 1.3.2 Studies on evaporation flux of sessile droplet

In order to build an effective evaporative cooling system with sessile droplets, evaporation rates need to be as high as possible for a particular condition. There are number of studies which have investigated the distribution of the evaporation flux along the interface [13, 25, 28, 31] and modes of interfacial energy transport [32, 33] for evaporating sessile droplets. Evaporation flux fluctuates according to the availability of energy required for evaporation. It has been found that for heated substrate the three phase contact line has the highest evaporation flux values whereas the apex has the lowest evaporation flux values [15, 25, 32, 34].

A recent study of evaporation flux distribution was performed for sessile droplets on a hydrophilic and hydrophobic flat surface by molecular simulation under three different evaporation modes such as diffusion dominant mode, substrate heating mode and environment heating mode [34]. It shows that edge evaporation flux is enhanced for all three modes of hydrophilic substrate with sessile droplet. Another recent study by Mahmud and MacDonald [15] also shows that evaporation flux varies along the interface with a continuously fed sessile droplet. Hu and Larson [13] predicted that a spherical droplet having a contact angle of  $90^\circ$  will have uniform evaporation flux along the interface for diffusion limited evaporation. The three phase contact line and shape of the droplet have a significant effect on evaporation flux. However, it is still not clear about the distribution of evaporation flux along the interface of continuously fed sessile droplet on a heated substrate. So, in order to build an effective evaporative cooling technology with sessile droplet, a proper numerical model of evaporation flux distribution for sessile droplet on a heated surface is necessary.

### 1.3.3 Different types of microelectronics cooling

Several thermal management cooling techniques for microelectronics are reviewed by many researchers [35-38]. Chu et al. [38] has discussed internal module cooling, external module cooling and immersion cooling for computers.

Air cooled heat sink is a popular external module cooling where heat is conducted through the base, up into the fins and then transferred to the air flowing in the spaces between the fins by convection. However, they generate noise and require a large space [39].

Compared to air, water cooling can provide more efficient cooling [38]. Liquid cooling for thermal management of electronics can be classified as indirect and direct liquid cooling. Direct liquid cooling is used in microchannel, microelectromechanical systems (MEMS) based micro cooling device, pool boiling and spray cooling. Indirect liquid cooling is generally used in cold plates and heat pipes. Liquid coolants may be utilized in both single and two-phase (utilizing boiling heat transfer in phase change) applications [38].

A number of numerical and experimental studies have been performed for single or multiple layer microchannels where the heat removal is performed under single phase flow of liquid or under two phase flow of boiling condition [40-42]. The total microchannel cooling system with a micropump and heat exchanger is expensive and requires surface treatment for better cooling. It is difficult to make a proper integration of micropump with microchannel [43].

Darabi and Ekula [44] designed an integrated system having micropumps for cooling the microchip and concluded that the designed system can effectively cool the device.

Pool boiling or immersion is another direct cooling method. Temperature overshoot is a problem that has been associated with the pool boiling of fluorocarbon liquids. This behavior is characterized by a delay in the inception of boiling on the heated surface [38].

Cold plates is an indirect liquid cooling method consisting of a solid metal where heat is first conducted through the metal shell and removed through forced convection by liquid on the other side of the shell [39]. A simple water-copper heat pipe is capable of transferring heat in the order of  $100 \text{ W/cm}^2$  [45]. However, due to large thermal resistance between heating and cooling ends, heat pipes are not efficient [46]. Active cooling solutions, ranging from traditional fin-fan heat sinks, though possibly with very low profile [35], to advanced cooling technologies such as pool boiling, cold plate and microchannel seem not to be practical due to more noise and large space constraints; so evaporative cooling technologies would be a promising method for microelectronics [24].

### 1.3.4 Current state-of-the-art for miniaturized droplet based evaporative cooling systems

There have been a number of studies on evaporative cooling applications for microelectronics including droplet spray cooling [47], bio-inspired cooling of

microelectronics devices using a temperature sensitive hydro gel [48, 49] and evaporating sessile droplets on a porous membrane inspired by human skin [4].

Spray cooling utilizes evaporation to directly cool a heated surface since it has high heat flux removal technology. Spray cooling involves the dispersion or atomization of liquid droplets from a nozzle, which then impact the heated surface. The droplets either directly evaporate or spread to form a thin film, which then rapidly evaporates. There are three regimes in spray cooling based on the cooling curve of wall temperature versus heat flux: single phase regime, two phase regime and critical heat flux (CHF). The single-phase regime controls the overall process. The rate of heat transfer rapidly increases during the two-phase regime and CHF [47]. Different parameters in spray cooling such as characteristics of spray, characteristics of heating surface, properties of fluid, and external environment have a significant impact on heat transfer performance [50].

Spray cooling has been implemented in a wide range of high heat flux applications such as microprocessors [51], CRAY X-1 supercomputer [47], electric automobiles [52] and spacecraft [53-55]. Companies such as SprayCool (Parker) and Air Products have developed a commercially available thermal management system that controls spray cooling techniques [56] while spray cooling holds potential for very high flux, its major limitations include the requirements for expensive pumps and nozzle systems. The disadvantages of spray cooling are the complexity of the cooling arrangement, the high pressure

(3 to 15 bar) prevailing in the entire cooling system, and the risk of nozzle clogging. Another problem is the densely packed bond wires lying side by side which often obstruct direct spraying of the chips. Heat transfer in spray cooling is accomplished by droplet induced forced convection, evaporation at the liquid vapour interface of thin liquid film, nucleate boiling in thin liquid film, secondary nucleation and transient conduction where a vapour blanket occurs in the film boiling which reduces thermal conduction surface to the liquid [47].

Cui et al. [48] and Zhi Huang et al. [49] demonstrate a novel passive cooling solution device for handling microelectronics such as “perspiration cooling” using a temperature sensitive hydrogel (TSHG). Cui et al. [48] found that bio-perspiration (BP) cooling is more effective at higher ambient temperatures than convection [48]. They have established a CFD model with verification by experimental data and used it to study the impacts of different usage conditions on the BP-Cooling performance [48]. They also made a semi-empirical formula that can be used to predict the heat transfer coefficient of BP-cooling. However, they did not show any application of TSHG for cooling the microprocessor or its prospect for using it for a microprocessor.

It is pointed out that none of the above studies discussed about the numerical modelling for a tiered evaporative cooling system for different microprocessor with different thermal design power. These existing methods for evaporative cooling for microtechnology are not compact enough for the increasing cooling demands. To assess the feasibility of cooling a microprocessor with an

evaporative cooling system based on human perspiration, a numerical model is required to effectively capture the geometry and temperature distribution of a compact tiered system.

## 1.4 Thesis objectives

In this study, a numerical model has been developed to simulate a tiered evaporative cooling system with arrays of evaporating sessile droplets and posts are required to connect the tiers. The length of the posts is taken as twice of the droplet diameter to avoid droplet interaction with the substrate layer above it and to arrange space for the vapour to diffuse. It has been used to analyze the feasibility of such a system for removing the heat from a microprocessor, the Intel Xenon Processor E5-1600/E5-2600/E5-4600 product family and the Intel Core i7-900 Desktop Processor, while maintaining the temperature below the maximum acceptable limit and confining the system to the same space used by the current heat sinks with forced convection cooling. The feasibility is assessed for the simplest and most conservative case, which is diffusion limited evaporation of sessile droplets, so that a fan is not required. This work answers the question of whether an evaporative cooling system with evaporating sessile droplets can effectively cool a microprocessor in the same space constraints as existing cooling methods.

Considering the above points, the objectives of the thesis are as follows:

1. Analyze the feasibility of an evaporative cooling system with sessile droplets for removing the heat from two types of microprocessors.
2. Develop an analytical model to determine the capacity of a single layer to provide sufficient cooling and determine the size of the droplets required to meet the cooling needs.
3. Build a numerical model of tiered evaporative cooling system for Intel Xenon Processor and Intel Core i7-900 Desktop Processor.
4. Determine the configurations that successfully remove the heat load while also having the easiest to manufacture arrangements, namely the minimum number of posts connecting each of the tiers, and the minimum number of tiers required.
5. Develop a numerical model for the evaporation flux distribution and interfacial temperature profile associated with thermal conduction for a single droplet.

## 1.5 Methodology

The methodology used in this thesis is as follows:

1. An analytical model is developed first to determine the feasibility of a single layer droplet array for cooling microprocessors. An analytical model can be

used to predict system behaviour easily. Since experimental analysis is a costly and lengthy process, modelling is a quicker and cheaper approach to assess the feasibility.

2. A numerical model is developed with tiered evaporative cooling system after assessing the feasibility of a single layer with the analytical model. The evaporative cooling system behaviour can be simulated, and the feasibility and system performance can be analyzed from the numerical model. With the increase in capacity of computational tools, such as COMSOL Multiphysics, numerical models are becoming more cost effective and faster than experimental study.
3. Simulations of multiple configurations with minimum number of posts connecting to each tier or minimum number of tiers to analyze which configurations are more efficient and feasible for microprocessor cooling.
4. A numerical model is developed with thermal conduction to determine the temperature distribution along the interface, which will help to implement enhanced evaporation rates in future work.

## 1.6 Thesis outline

In chapter 2 of this thesis, an analytical model is presented for a single layer array of evaporating sessile droplets and varying droplet radius for different microprocessors, and the results from analytical modelling are also discussed. In chapter 3, the numerical modelling for tiered droplet evaporative cooling is developed and discussed for 2.5 mm and 2 mm droplet radius for different microprocessors at different thermal design powers. In chapter 4, the numerical modelling for thermal conduction based evaporation flux for single droplet is developed and discussed. The results and discussion is in chapter 5. Finally, chapter 6 will conclude the entire thesis, and include recommendations for future research work.

## **Chapter 2**

### **Analytical Model**

The main purpose of the thesis is to develop a numerical model for a tiered droplet evaporative system for microelectronics cooling. Before developing the numerical model, an analytical model is developed to determine the capacity of a single layer of droplets to provide sufficient cooling and calculate the size of the droplets required to meet the cooling needs. Analytical solutions are usually derived from the basic physical principles and free from numerical dispersion and other truncation errors that may occur in numerical simulations. Using analytical solutions, a better understanding of the diffusion limited evaporative cooling for single layer droplet array can be made. The analytical model is developed and described in this chapter. This chapter also discusses the results of analytical modelling for the Xenon Processor and Core i7-900 Desktop Processor. The constrained size of heat sink of both microprocessors is used in

the analytical modelling to determine the temperature of the bottom surface of the substrate,  $T_L$ .

## 2.1 Analytical model for single layer arrayed droplet evaporation

A simple one-dimensional analytical model is developed to analyze the feasibility of a single layer of sessile droplets, with diffusion-based evaporation, to provide cooling for a microprocessor. The droplet radii used in the simulation are varied from 0.25 to 2.5 mm to provide a range of evaporation rates. For this work, the evaporative cooling system is loosely inspired by the human perspiration system, with sessile water droplets evaporating on a thin copper substrate with a thickness of 2 mm, as shown in Figure 5, that are assumed to be hemispherical in shape, bounded, and continuously fed from a fluid reservoir beneath them, similar to the continuously fed droplets described in past experimental work [15].

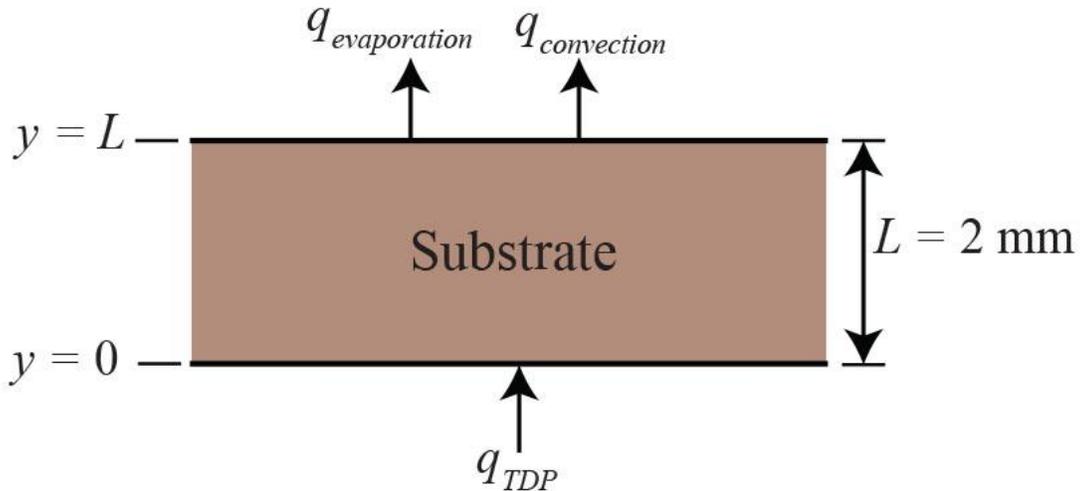


Figure 5: Schematic of the copper substrate used for the analytical model.

The copper substrate is mounted directly on top of the microprocessor, and the boundary conditions include the heat transfer from the microprocessor on the bottom surface, denoted as thermal design power ( $q_{TDP}$ ), and on the top surface, the heat transfer due to evaporation of the sessile droplets and natural convection from the exposed copper surface, as depicted in Figure 5. The processor manufacturer provides values for the maximum temperature ( $T_{CASE\ MAX}$ ) corresponding to each value of  $q_{TDP}$  [2, 3]. The values for  $T_{CASE\ MAX}$  obtained from the specifications for the Xenon Processor and Core i7-900 Processor are summarized in Table 1 for the maximum listed  $q_{TDP}$  value of 130 W. The copper substrate is assumed to have a thermal conductivity ( $k_{Cu}$ ) of 401 W/mK [57], exchange heat with the environment at a constant temperature ( $T_{\infty}$ )

of 25°C (298K), and for natural convection from the exposed surface an effective heat transfer coefficient ( $h$ ) was calculated to be 15 W/m<sup>2</sup>K [57]. The dimensions of the heat sink specified for the Xenon Processor are 91.5 mm × 91.5 mm × 25.5 mm and for the Core i7-900 Desktop Processor are 104 mm × 104 mm × 81.3 mm. For a representative comparison of evaporative cooling system with the current heat sinks, in the case of the Xenon Processor, the copper substrate is set to have the same length and width (91.5 mm) and limit the height of the tiered configurations to be at or less than 25.5 mm. Similarly, for the Core i7-900 Desktop Processor, the copper substrate is set to have the same length and width (104 mm) and limit the height of the tiered configurations to be at or less than 81.3 mm. The spacing between the droplets was selected as half of the droplet radius to reduce the risk of coalescence and inter droplet interaction [4].

## 2.2 Boundary conditions

The boundary conditions used in the analytical modelling are shown in Figure 5. The copper substrate is modelled assuming one-dimensional heat transfer with heat conduction in the  $y$ -direction, so the energy equation simplifies to

$$\frac{\partial T}{\partial y} \left( k_{Cu} \frac{\partial T}{\partial y} \right) = 0. \quad (2)$$

At the bottom surface of the copper substrate,  $y=0$ , heat is provided from the microprocessor with the following boundary condition

$$-k_{Cu} \frac{\partial T}{\partial y} \Big|_{y=0} = \frac{q_{TDP}}{A_{tot}}, \quad (3)$$

where  $A_{tot}$  refers the total surface area of the substrate. At the top surface of the substrate, there is heat transfer due to the droplet evaporation and natural convection from the exposed copper surface resulting in the following boundary condition at  $y=L$

$$-k_{Cu} \frac{\partial T}{\partial y} \Big|_{y=L} = \frac{q_{evaporation}}{A_{tot}} + \frac{q_{convection}}{A_{tot}}, \quad (4)$$

with

$$\frac{q_{evaporation}}{A_{tot}} = \frac{N \dot{m}_{ev} \Delta h_{fg}}{A_{tot}}, \quad (5)$$

$$\frac{q_{convection}}{A_{tot}} = \frac{h A_{exp} [T_t - T_\infty]}{A_{tot}}, \quad (6)$$

where  $N$  is the total number of sessile droplets,  $\dot{m}_{ev}$  is the total evaporation rate of each droplet,  $T_t$  is the temperature of the top surface of the substrate,  $T_L$  is the temperature of the bottom surface of the substrate,  $A_{exp}$  is the area of the exposed copper surface where there are no water droplets, and the enthalpy of vaporization was obtained from Dash et al. [58], where  $T_t$  is in K, as:

$$\Delta h_{fg} = 2.7554 \times 10^6 - 3.46 T_t^2. \quad (7)$$

## 2.3 Diffusion-based evaporation rate

In this study, the feasibility for the most conservative case of evaporating sessile droplets has been investigated, which is evaporation driven only by diffusion, and does not require any external power for a fan. For the evaporation rate, an expression developed by Girard et al. [14] has been used, for the evaporation of sessile droplets on an isothermal substrate

$$\dot{m}_{ev} = -DR \left[ c(T_s) - Hc(T_\infty) \right] \phi_{isoth}(\theta) \quad (8)$$

where  $D$  is the water vapour diffusivity in air,  $R$  is the droplet contact radius,  $c(T_s)$  is the saturated water concentration in the surrounding air at the substrate temperature,  $c(T_\infty)$  is the saturated water concentration at the

ambient temperature,  $H$  is the relative humidity, which is assumed to be 44% for this modelling work, and  $\phi_{isoth}(\theta)$  is a non-dimensional flow that depends on the contact angle  $(\theta)$ , which is derived by Hu and Larson [13] to be  $0.27(\theta)^2 + 1.30$  for isothermal surfaces. The copper substrate is not isothermal in the analytical model, since it is heated from below by the microprocessor, but a study by Hu et al. [21] showed that for droplets with a contact angle of  $90^\circ$ , the isothermal and non-isothermal expressions have similar results [11]. Since the expression for the isothermal case is simpler, it is used for the modelling work. The temperature dependent diffusion coefficient is as follows [59]:

$$D = D_\infty \left( \frac{T_i}{T_\infty} \right)^2 \quad (9)$$

A polynomial fit expression for the temperature dependent saturated water concentration was developed from the tables given in [57] as

$$c(T_s) = 9.2 \times 10^{-12} T_i^5 + 1.6 \times 10^{-9} T_i^4 + 2.9 \times 10^{-7} T_i^3 - 2.4 \times 10^{-6} T_i^2 + 8.2 \times 10^{-4} T_i - 1.2 \times 10^{-3} \quad (10)$$

The values of the input parameters used in the analytical model are given in Table 1. These parameters are assumed to be constant during the evaporation process.

**Table 1 – Parameters used in the analytical model for  $q_{TDP}$  130 W [2, 3, 57].**

| Parameters   | Water                 | Xenon Processor | Core i7 Processor |
|--|-----------------------|-----------------|-------------------|
| Vapour concentration, $c(T_\infty)$ (kg/m <sup>3</sup> ) | 0.0231                | –               | –                 |
| Diffusion coefficient, $D_x$ (m <sup>2</sup> /s)         | $2.05 \times 10^{-5}$ | –               | –                 |
| $T_{CASE\ MAX}$ (°C)                                     | –                     | 85.0            | 67.9              |

## 2.4 Analytical model results for Xenon Processor

The results of the analytical modelling are summarized in Table 2 for the Xenon Processor. The solutions were generated using MATLAB. Eq. 8 indicates that the evaporation rate is linearly proportional to the droplet radius, thus larger droplets have higher evaporation rates, but the number of droplets that can be placed on the substrate is inversely proportional to the square of the radius, which results in a net increase of the total evaporation rate as the droplet radius is increased. The higher evaporation rates mean that more energy is removed from the substrate and the temperature decreases as a result, as observed from the modelling results shown in Tables 2 and 3. For the Xenon Processor, a  $T_{CASE\ MAX}$  value of 85.0°C is required at 130 W, which is accomplished with a single layer of 5,184 droplets having a radius of 0.5 mm, as noted in Table 2.

**Table 2 – Substrate temperature for the Xenon Processor at 130 W with varying droplet radii for a single layer.**

| Droplet radius (mm) | Maximum number of droplets* | Surface area of droplets (cm <sup>2</sup> ) | $T_L$ (°C) |
|---------------------|-----------------------------|---|------------|
| 0.5                 | 5184 (72×72)                | 40.7  | 78.0       |
| 1                   | 1296 (36×36)                | 40.7  | 94.0       |
| 1.5                 | 576 (24×24)                 | 40.7  | 104.1      |
| 2                   | 289 (17×17)                 | 36.3  | 114.6      |
| 2.5                 | 196 (14×14)                 | 38.5  | 119.3      |

\* subject to the substrate area

## 2.5 Analytical model results for Core i7-900 Desktop Processor

The analytical model also determined the value of  $T_L$  for the Core i7-900 Desktop Processor. Table 3 provides the results for the Core i7-900 Desktop Processor. For the Core i7-900 Processor, a  $T_{CASEMAX}$  value of 67.9°C is required at 130 W, which is accomplished with a single layer of 27,556 droplets having a radius of 0.25 mm, as noted in Table 3.

**Table 3 – Substrate temperature for the Core i7-900 Processor at 130 W with varying droplet radii for a single layer.**

| Droplet radius (mm) | Number of droplets* | Surface area of droplets (cm <sup>2</sup> ) | $T_L$ (°C) |
|---------------------|---------------------|---|------------|
| 0.25                | 27556 (166×166)     | 54.1  | 57.7       |
| 0.5                 | 6724 (82×82)        | 52.8  | 72.3       |
| 1                   | 1681 (41× 41)       | 52.8  | 87.6       |
| 1.5                 | 729 (27×27)         | 51.5  | 97.8       |
| 2                   | 324 (18×18)         | 40.7  | 111.0      |
| 2.5                 | 225 (15×15)         | 44.2  | 114.9      |

\* subject to the substrate area

These results show that it is possible to provide sufficient heat removal for these microprocessors using only a single layer of evaporating sessile droplets; however, the number of droplets is quite large, which would make it challenging to manufacture a substrate capable of these numbers of bounded droplets and the holes required to continuously feed the droplets from below. Since the current heat sinks have a height that is larger than a single layer of evaporating droplets, the feasibility for multiple tiers of larger droplets to provide the heat removal can be examined, which may lead to reduced manufacturing complexity. Due to the complexity of modelling multiple tiers, a numerical model is developed to simulate the cases with more than one tier.

## Chapter 3

### Numerical Model

In this chapter, a numerical model for a tiered evaporative cooling system of different types of microprocessor is developed. The system is modelled as a three-dimensional tiered system, as shown in Figure 6(a). To provide support for the tiers and thermally connect the tiers, a series of posts are required, as shown in Figure 6(b). The tiered system is aiming to provide sufficient heat removal without requiring the complex high precision manufacturing necessary to produce a single layer with thousands of small droplets that was found from the analytical model above. Therefore, droplet radii of 2 mm and 2.5 mm are used in the numerical model, and the maximum height of the tiers is restricted by the height of the current heat sinks. The model was implemented in COMSOL Multiphysics, which uses the finite element method. A numerical model for the evaporation flux distribution and interfacial temperature profile associated with the thermal conduction for single droplet is also developed.

A three-dimensional numerical model is built by using the heat transfer module package in the COMSOL Multiphysics software. Heat transfer in solid physics is used for the governing equations, boundary conditions are inputted according to the conditions listed in Section 3.1.1 below, and the stationary study solver is used to solve the equations.

### 3.1 Geometrical parameters for Xenon and Core i7-900 Desktop Processor

In Figures 6(b)-6(c) the arrangement of posts and droplets is shown along with the corresponding variables for the dimensions, with the values summarized in Table 4. The height of each post is set as twice the droplet radius to provide space for the vapour to diffuse and prevent droplet interaction with the substrate layer above it. The maximum number of tiers that can fit within the heat sink space constraints for the Xenon Processor are 4 for droplets with radii of 2 mm and 2.5 mm. The maximum number of tiers that can fit within the heat sink space constraints for the Core i7-900 Processor is 13 for the droplets with 2 mm radius and 12 for the droplets with 2.5 mm radius.

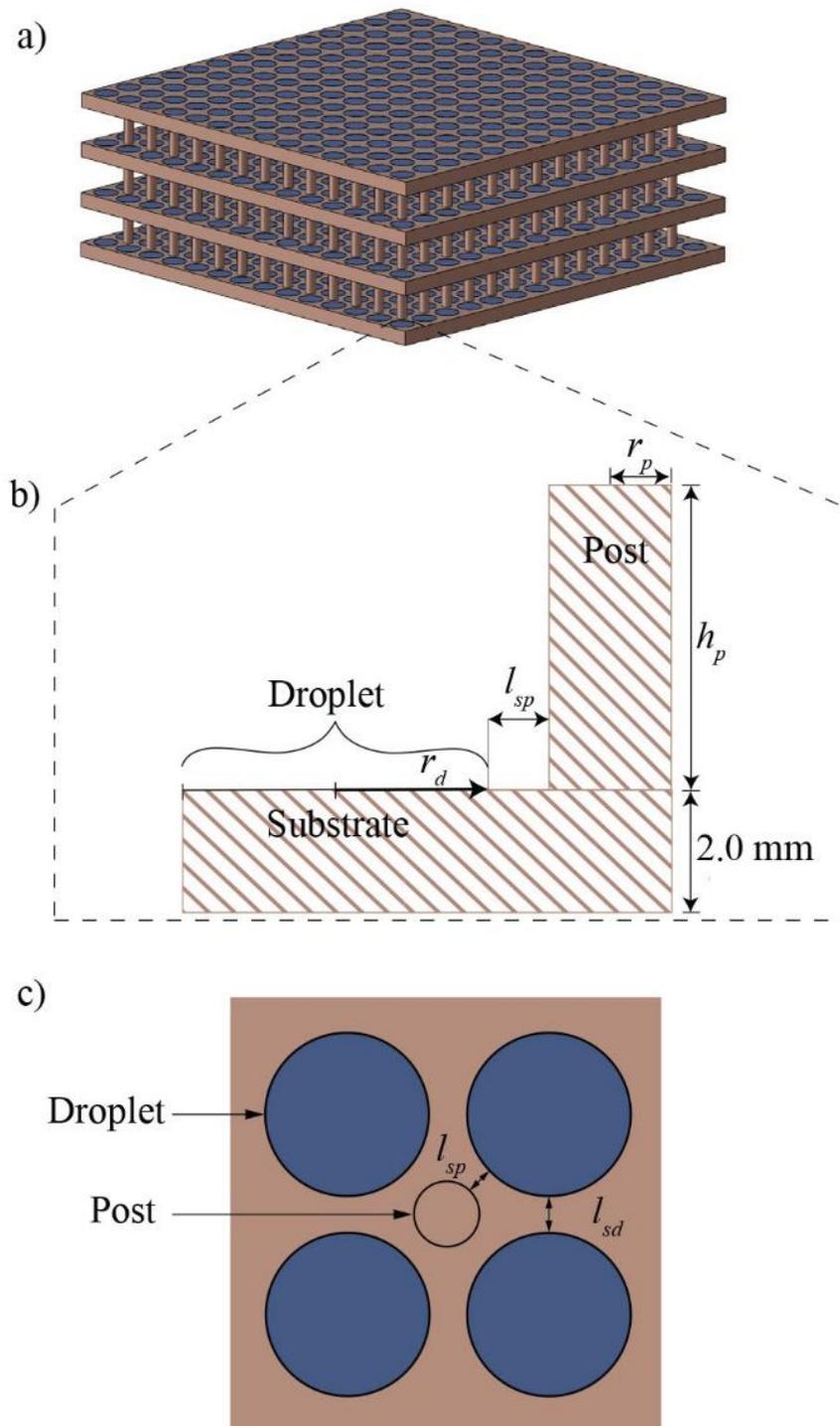


Figure 6: Illustration of the a) three-dimensional diagram of 2.5 mm droplet radius with posts and tiers b) specification of posts and tiers upon substrate c) specification of droplet and posts upon substrate.

**Table 4 - Geometrical parameters for different types of microprocessors for numerical modelling**

| Parameter  | Intel Xenon Processor          |                              | Intel Core i7-900 Desktop Processor |                              |
|--|--------------------------------|------------------------------|-------------------------------------|------------------------------|
|  | Droplet radius, $r_d$ (2.5 mm) | Droplet radius, $r_d$ (2 mm) | Droplet radius, $r_d$ (2.5 mm)      | Droplet radius, $r_d$ (2 mm) |
| Number of droplets, $N_d$                        | 196 (14 × 14)                  | 289 (17 × 17)                | 225 (15 × 15)                       | 324 (18 × 18)                |
| Maximum number of posts, $N_p$                   | 169 (13 × 13)                  | 256 (16 × 16)                | 196 (14 × 14)                       | 289 (17 × 17)                |
| Radius of post, $r_p$ (mm)                       | 1                              | 1                            | 1                                   | 1                            |
| Distance between post and droplet, $l_{sp}$ (mm) | 1                              | 0.78                         | 0.80                                | 0.47                         |
| Distance between droplets, $l_{sd}$ (mm)         | 1.25                           | 1                            | 1.25                                | 1                            |
| Height of post, $h_p$ (mm)                       | 5                              | 4                            | 5                                   | 4                            |

### 3.1.1 Boundary conditions

The heat transfer from the substrate is modelled with similar conditions to the analytical model described above, but is implemented in three dimensions.

The boundary conditions can be summarized as follows:

1. The posts are made of copper and physically connected to the substrate tiers, resulting in continuous thermal conduction.
2. A constant general inward heat flux ( $q_{TDP}/A_{total}$ ) is applied for the bottom of the lowest tier of copper substrate to simulate mounting directly on top of the microprocessors.
3. An outward heat flux ( $N \dot{m}_{ev} \Delta h_{fg} / A_{drop}$ ) is applied for each water droplet based on the evaporation rate expression listed as Eq. (8) and dependent on the local substrate temperature.
4. Convective heat flux, with a constant heat transfer coefficient of  $15 \text{ W/m}^2\text{K}$  for natural convection, is used on all the exposed surfaces of the substrate.

## 3.2 Numerical model of evaporation flux distribution associated with thermal conduction for single droplet

In this thesis, a diffusion-based evaporation rate is used in the numerical model for the tiered droplet evaporative cooling systems. However, for a more thorough understanding of the evaporation rate applied to a sessile droplet in evaporative cooling technology, it is necessary to build a numerical model of a sessile droplet with thermal conduction. It was discussed earlier that diffusion limited evaporation is conservative and not reflective of the best evaporative cooling systems. In order to design effective evaporative cooling systems using evaporating sessile droplets it is necessary to determine evaporation flux through the interface. The numerical model determined the evaporation flux distribution associated with thermal conduction and temperature gradient along the interface. To increase evaporation rates, a clear perception of the evaporation flux distribution along the droplet surface is valuable to enable targeted improvement. In this thesis, the evaporation flux distribution with the interphase is calculated for different  $T_{CASEMAX}$  temperatures of microprocessors at  $q_{TDP}$  130 W which is described later in results section.

The developed numerical model was implemented in COMSOL Multiphysics. The sessile droplet is modelled as a three-dimensional single water droplet with

thermal conduction based evaporation, as shown in Figure 7. In order to provide support for the droplet, a copper substrate is required. One droplet is used to determine the evaporation flux and temperature profile of the droplet along the interface, which is useful to understand and improve the evaporation rate for sessile droplets and enhance evaporative cooling technology.

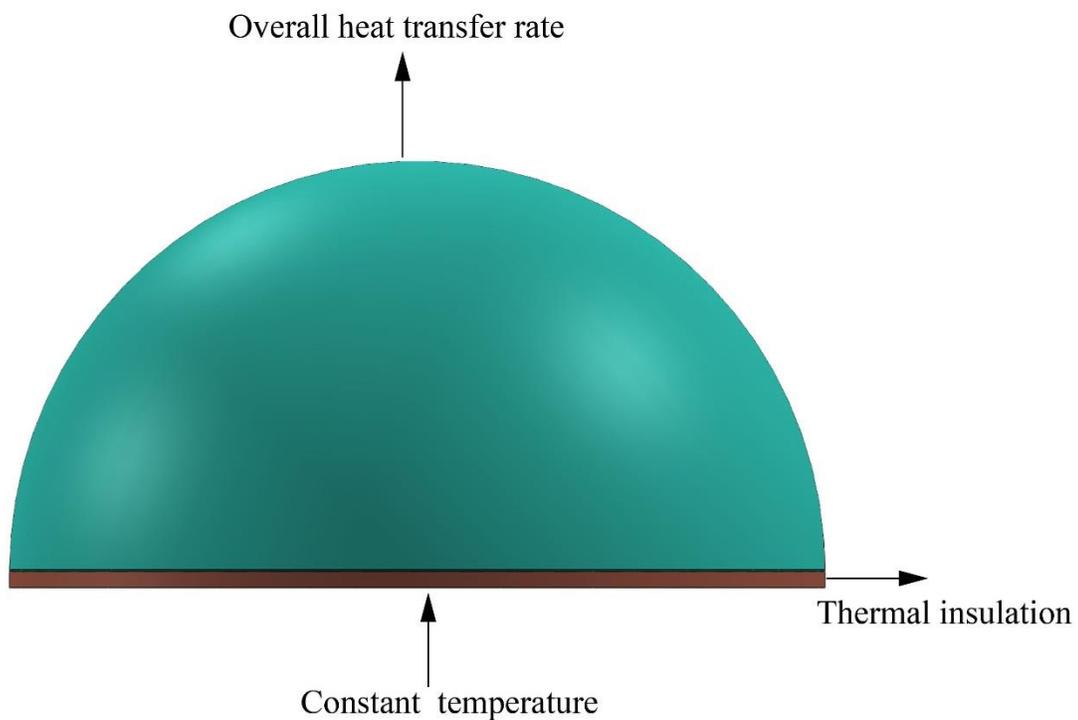


Figure 7: Boundary conditions of numerical model for thermal conduction based evaporation of a single droplet.

### 3.2.1 Boundary conditions

The boundary conditions used in the numerical model are as follows (see Figure 8):

1. Constant temperature (85.0°C for Xenon Processor and 67.9°C for Core i7-900 Desktop Processor) is applied for the lower portion of copper substrate (single water droplet is mounted directly on top of the copper substrate)
2. Constant overall heat transfer rate  $\left[ (q_{TDP} \times A_{droplet}) / A_{total} \right]$  is applied across the surface of the single water droplet. Where  $A_{droplet}$  is surface area of droplet and  $A_{total}$  is surface area of substrate.
3. Thermal insulation is applied along the side of the substrate.

### 3.3 Challenges/Weaknesses of the numerical model

Although the numerical model was developed appropriately, the following are some challenges or weakness in the modelling, which are not considered in this thesis:

1. The effect of droplet interference is not considered in the numerical model.

The droplets in this work are very close to each other, and the impact of

the distance between the droplets on the evaporation rate can be analyzed in a future study. Compared to the isolated droplet, the evaporation of arrayed droplets is subject to interdroplet interaction and can be reduced by the local vapour field created by neighboring droplets. It will be important to know whether or not the droplets are interfering with each other and try to sort out how to consider this effect in the model for increased precision. It could result in a reduced evaporation rate, which is not considered in this work.

2. The clearance or the space to diffuse the vapour sufficiently away from the droplet is not considered in the numerical model, and the distance of the layer is limited by the height of the posts. As the droplet evaporates the vapour may build up between the layers. There is a possibility that the diffusion might be inhibited by the vapour buildup due to the proximity by the other droplet and confinement of the layers around it. In future work it will be beneficial to check if the vapour is diffusing properly or not.

# Chapter 4

## Results and Discussion

In this chapter, simulation results obtained from the numerical model are presented and discussed. The results obtained from the analytical model are validated with the simulation result for 2 mm and 2.5 mm droplet radius. The complexity of the tiered evaporative cooling system depends primarily on two variables: the number of tiers and the number of posts. It may be advantageous to minimize either of these variables to generate an evaporative cooling system that is simple to produce. Therefore, the model has two cases: (i) to determine the lowest number of posts required to provide sufficient cooling with the maximum number of tiers used (limited by the height restrictions imposed by the current heat sink dimensions), and (ii) to determine the lowest number of tiers required to provide sufficient cooling with the maximum number of posts included (one in between each droplet). The modelling is performed for the case of the maximum listed thermal design power of 130 W, as used in the analytical model, and an additional case to assess the feasibility at a lower thermal design

power of 80 W. The Xenon Processor and the Core i7-900 Desktop Processor list a  $T_{CASEMAX}$  value of 74.1°C and 58.4°C respectively for a  $q_{TDP}$  value of 80W [2, 3].

## 4.1 Validation of numerical model with analytical model

The temperature of the bottom surface of the substrate,  $T_L$ , for a single layer droplet array using 0.25 mm to 2.5 mm droplet radius is determined with the numerical model and compared to the analytical model for different microprocessors (130 W). Figures 8-9 show satisfactory agreement between the results obtained from numerical model with that of analytical model.

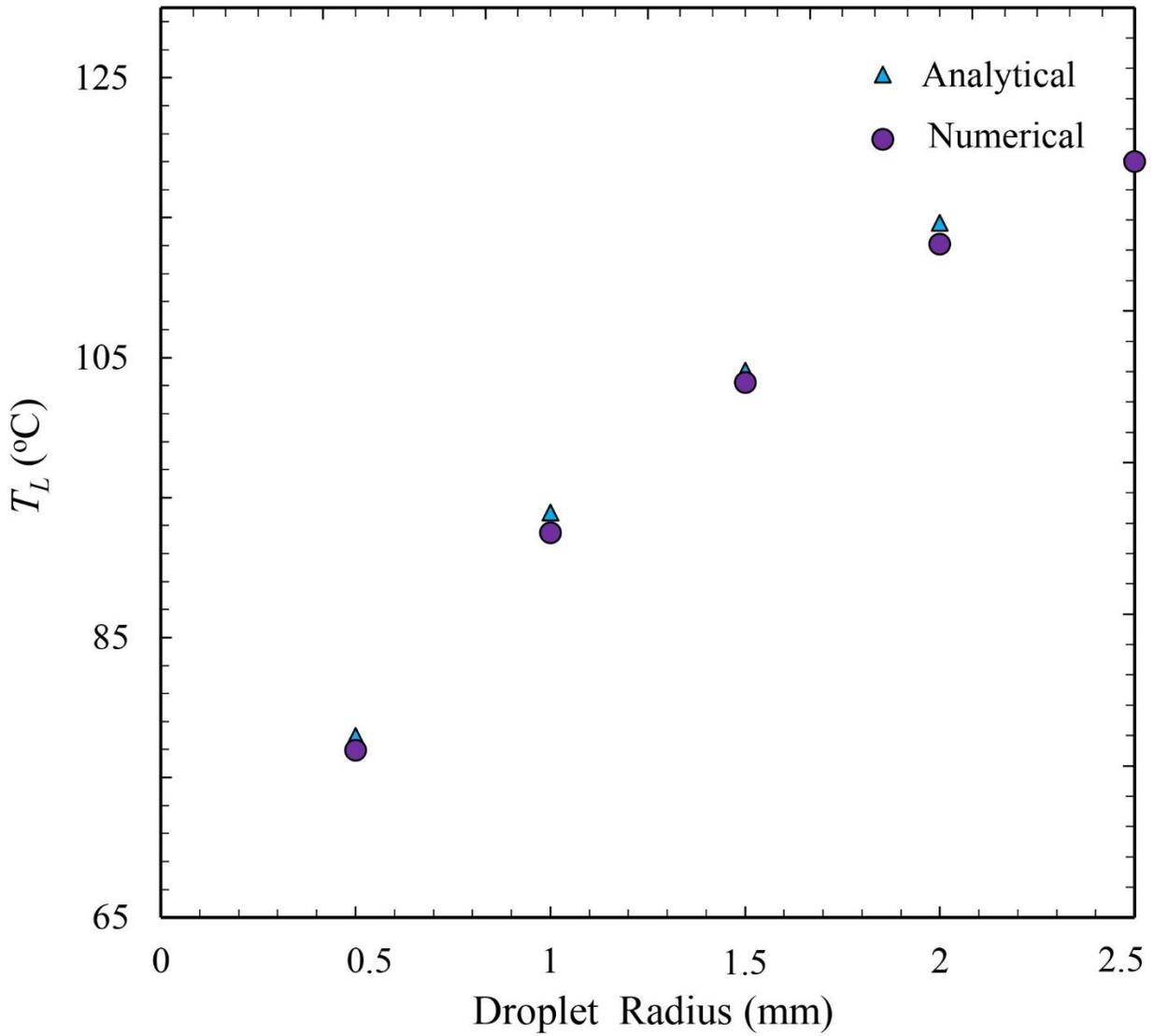


Figure 8: Substrate temperature in the lowest tier  $T_L$  (°C) versus different droplet radii, comparing analytical modelling and numerical modelling for the Intel Xenon Processor.

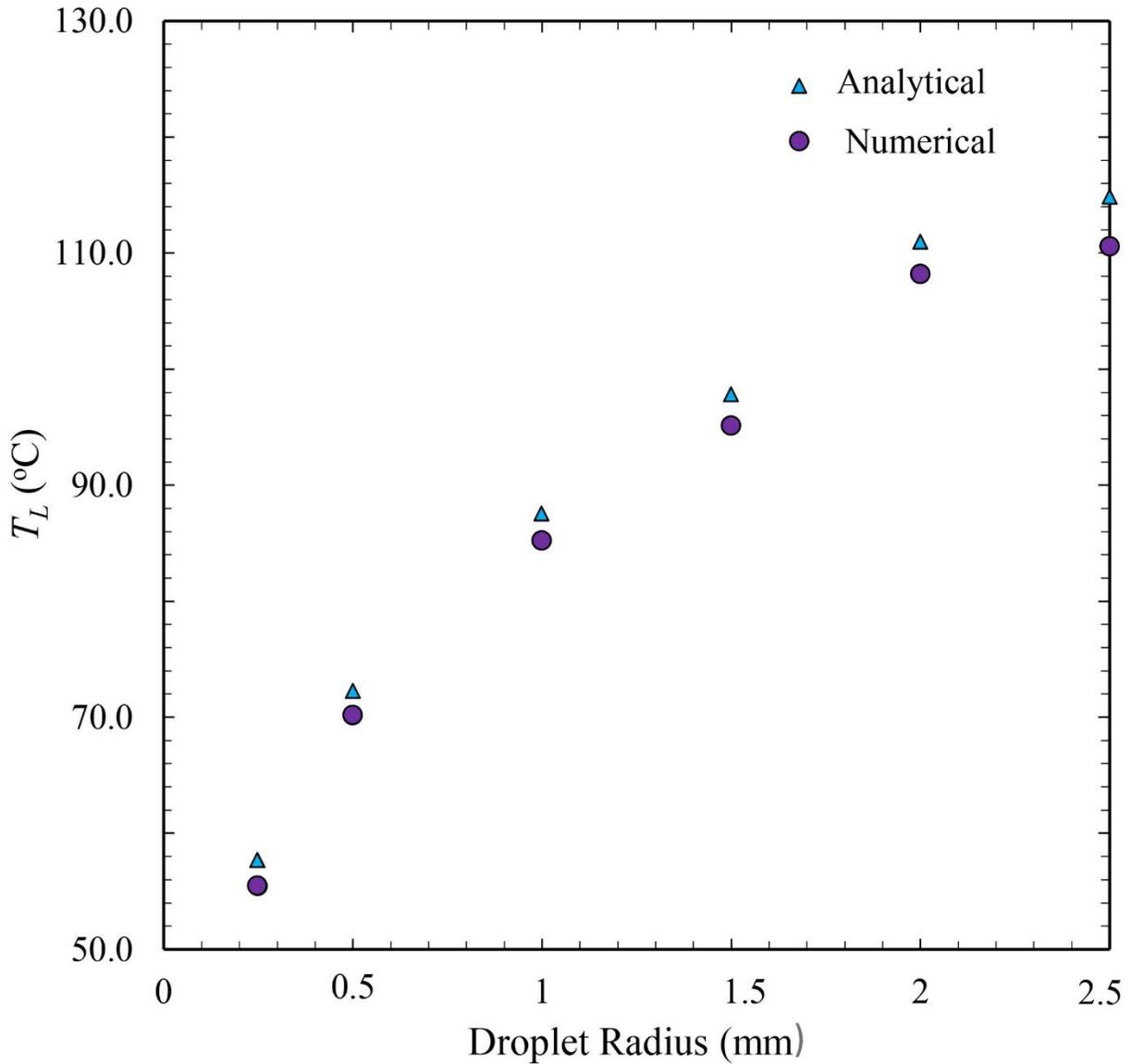


Figure 9: Substrate temperature in the lowest tier  $T_L$  (°C) versus different droplet radii, comparing analytical model and numerical model for the Intel Core i7-900 Desktop Processor.

## 4.2 Lowest number of posts using maximum number of tiers for Xenon Processor

Figure 10 shows the maximum substrate temperature of the lowest tier ( $T_L$ ) plotted against the number of posts used to connect each substrate tier. It can be observed that as the number of posts increases, the substrate temperature decreases, which is to be expected since the increasing number of posts enables increased thermal conduction between the tiers, resulting in higher temperatures for the upper tiers and increased evaporation rates as a result. From the simulation results, it is found that  $T_L$  reached the required value of 85.0°C for 130 W with 66 posts for  $r_d = 2.5$  mm and 41 posts for  $r_d = 2$  mm. For a  $q_{TDP}$  value of 80 W, the minimum number of posts to reach a  $T_L$  of 74.1°C is 37 posts for  $r_d = 2.5$  mm and 26 posts for  $r_d = 2$  mm. Manufacturing less than 100 posts with 4 tiers (for  $r_d = 2$  mm) may provide a more simple evaporative cooling system than the single layer with thousands of small droplets described above. Interestingly, for 4 tiers the total number of droplets is 784 for a  $r_d = 2.5$  mm and 1,156 for a  $r_d = 2$  mm, which is much less than the 5,184 droplets required for the single layer of  $r_d = 0.5$  mm droplets found for the Xenon Processor in the single layer case.

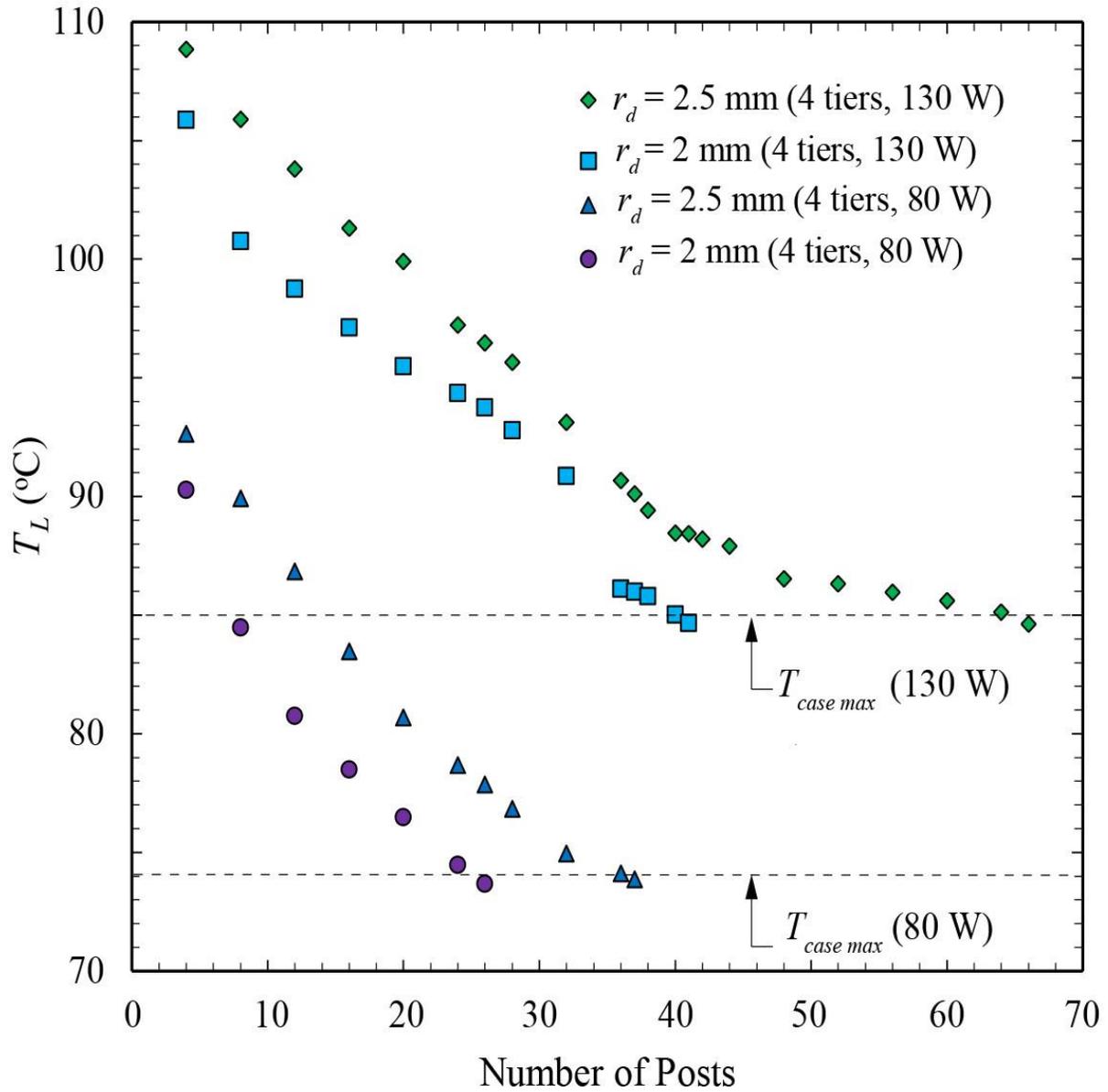


Figure 10: Maximum value of the substrate temperature in the lowest tier  $T_L$  (°C) versus the number of posts connecting each substrate tier for the Xenon Processor with 4 tiers.

### 4.3 Lowest number of posts using maximum number of tiers for Core i7-900 Desktop Processor

Figure 11 shows the variation of  $T_L$  versus the number of posts for the Core i7-900 Processor. From the simulation results, it is found that  $T_L$  reached the required value of  $67.9^\circ\text{C}$  for 130 W with 48 posts for  $r_d = 2.5$  mm and 42 posts for  $r_d = 2$  mm. For a  $q_{TDP}$  value of 80 W, the minimum number of posts to reach a  $T_L$  of  $58.4^\circ\text{C}$  is 32 posts for  $r_d = 2.5$  mm and 28 posts for  $r_d = 2$  mm. For 12 tiers the total number of droplets is 2,700 for a  $r_d = 2.5$  mm and 4,212 for a  $r_d = 2$  mm for 13 tiers, which is much less than the 27,556 droplets required for the single layer of  $r_d = 0.25$  mm droplets found for the Xenon Processor in the single layer case.

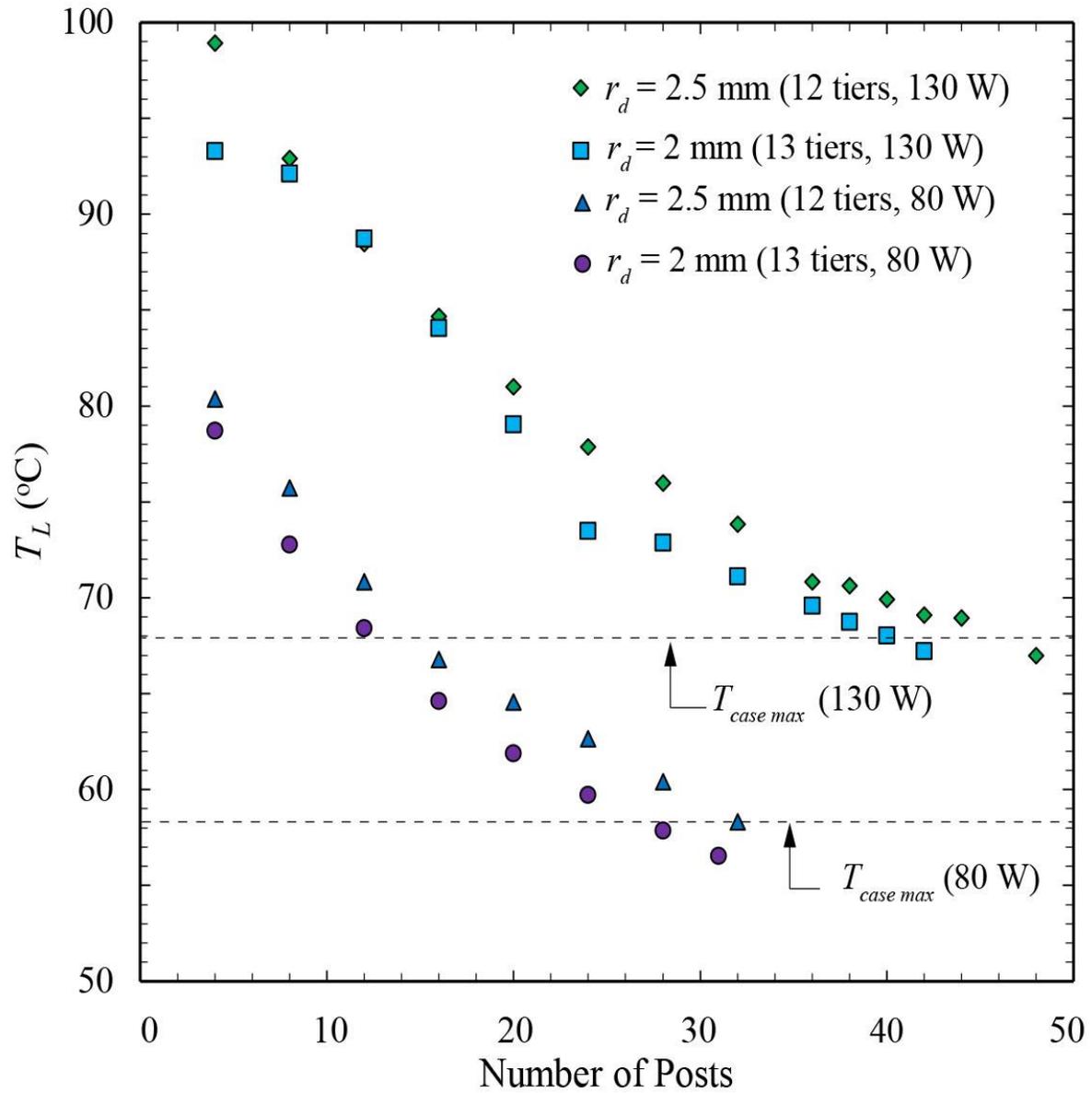


Figure 11: Maximum value of the substrate temperature in the lowest tier,  $T_L$  (°C), versus the number of posts connecting each substrate tier for the Core i7-900 Desktop Processor with 12 tiers and 13 tiers.

## 4.4 Lowest number of tiers using maximum number of posts for Xenon Processor

In this section, the results are shown for the lowest number of tiers using the maximum number of posts in between the droplets for the Intel Xenon Processor for the different values of  $q_{TDP}$ . The results of the simulations for the minimum number of tiers with the maximum number of posts are summarized in Table 5. For the Xenon Processor, only 4 tiers are required for  $r_d = 2.5$  mm (130 W) and 3 tiers are required for all other cases to reach the required substrate temperature. The number of droplets required for the 130 W cases with the Xenon Processor are 784 for  $r_d = 2.5$  mm (4 tiers) and 867 for  $r_d = 2$  mm (3 tiers).

**Table 5 - Minimum number of tiers utilizing with maximum number of posts for different types of microprocessors.**

| Type of microprocessor<br>( $q_{TDP}$ , W) | Minimum number of tiers<br>(total layer height, mm) |              | $T_L$ (°C)     |              |
|--|---|--------------|----------------|--------------|
|  | $r_d = 2.5$ mm                                      | $r_d = 2$ mm | $r_d = 2.5$ mm | $r_d = 2$ mm |
| Xenon (130)                                | 4 (25.5)  | 3 (16)       | 79.1           | 81.7         |
| Xenon (80)                                 | 3 (18.5)  | 3 (16)       | 72.6           | 68.8         |
| Core i7 (130)                              | 5 (32.5)  | 4 (22)       | 64.1           | 64.0         |
| Core i7 (80)                               | 4 (25.5)  | 4 (22)       | 57.0           | 53.0         |

## 4.5 Lowest number of tiers using maximum number of posts for Core i7-900 Desktop Processor

In this section, the evaluation of the lowest number of tiers using the maximum number of posts in between the droplets for Intel Core i7-900 Desktop Processor for the value of  $q_{TDP}$  130 W and 80 W is discussed, with the results summarized in Table 5. The simulation results show that for the Core i7-900 Processor 5 tiers are required for the 130 W case with  $r_d = 2.5$  mm and 4 tiers are required for all the other cases. The number of droplets required for the 130 W cases with the Core i7 Desktop Processor are 1125 for  $r_d = 2.5$  mm (5 tiers) and 1296 for  $r_d = 2$  mm (4 tiers).

These findings indicate that reducing the number of tiers reduces the number of droplets required, but there is also a requirement for more posts. So, whether the number of tiers should be minimized or the number of posts will depend on the complexity and cost of the specific manufacturing processes. Overall, the feasibility of an evaporative cooling system using evaporating sessile droplets driven by diffusion has been demonstrated for cooling two different microprocessors.

The temperature distribution for the tiered droplet evaporation cooling system is illustrated in Figure 12 using the maximum number of posts (169) for  $r_d = 2.5$  mm with the minimum number of tiers (4). The temperature can be seen to

decrease from the bottom layer to the top layer with a relatively small temperature difference between tiers on account of the maximum number of posts being utilized. The warmest point can also be seen to be the bottom of the lowest tier, which was the reference temperature for this study,  $T_L$ , and is the point of contact between the evaporative cooling system and the processor.

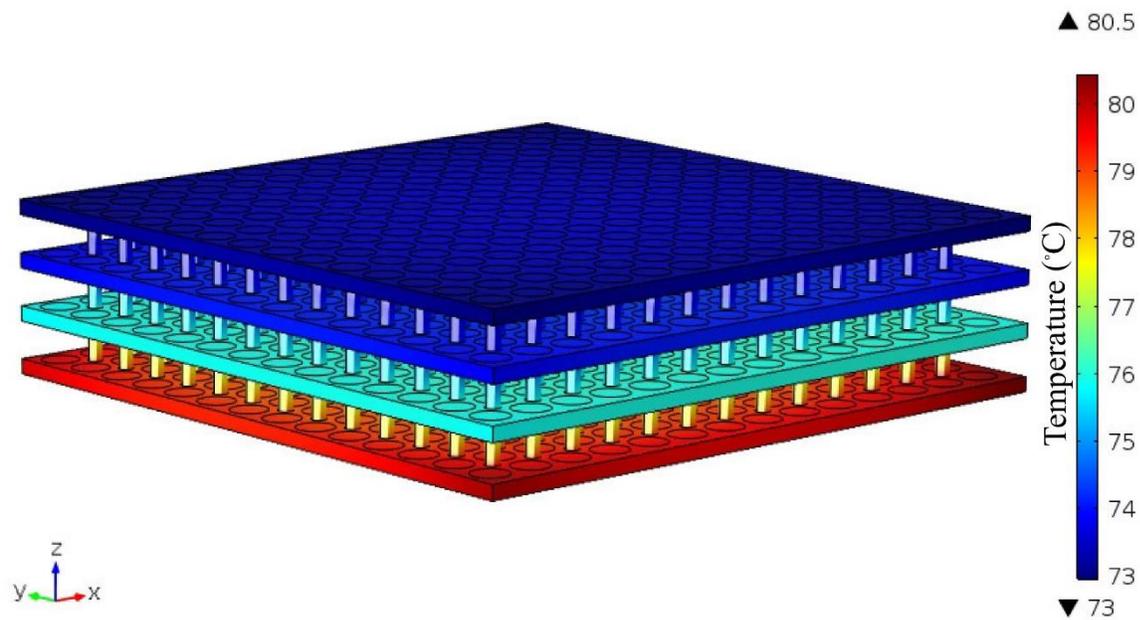


Figure12: Temperature distribution for tiered droplet evaporation cooling system using maximum number of posts and lowest number of tiers for the Intel Xenon Processor (130 W).

## 4.6 Evaporation flux of single droplet associated with thermal conduction

The evaporation flux with different angular position is determined by a numerical model for the two different microprocessors at 130 W thermal design power. Figures 13-14 show the variation of evaporation flux for the Xenon Processor and Core i7-900 Desktop Processor along the angular position. Figure 13 shows that the evaporation flux for Xenon Processor does not vary along the angular position with a uniform value of  $0.166 \mu\text{L}/\text{mm}^2\text{min}$ . The same trend is observed for the Core i7-900 Processor with a uniform flux of  $0.130 \mu\text{L}/\text{mm}^2\text{min}$ . The results agree with the predictions from Hu and Larson [13] for uniform evaporation flux along the angular position in hemispherical droplets.

The temperature distribution for the single droplet using thermal conduction based evaporation for  $r_d = 2.5 \text{ mm}$  is illustrated in Figure 15. It can be seen that the droplet has the maximum temperature at the bottom of the copper substrate while the top of the droplet has minimum temperature.

The variation of temperature distribution along the angular position is shown in Figure 16. It shows that temperature is lower at the apex ( $0^\circ$ ) and higher at the three phase contact line ( $90^\circ$ ) of the droplet. In order to determine whether the droplet temperature is feasible to maintain the evaporation or not, specifically if there is any risk of freezing, Figures 15-16 are analyzed. One of the interesting

situations that may occur is the one in which the temperature of the droplet may go below room temperature (25°C), which would result in a complex heat transfer situation with the warmer room air possibly providing energy to the droplet interface as well. Figure 16 confirms that there is no severe drop in temperature for the conduction limited droplet evaporation, and affirms that there is the possibility of improved evaporative cooling systems capable of removing more heat than the diffusion limited evaporation cases without the risk of freezing.

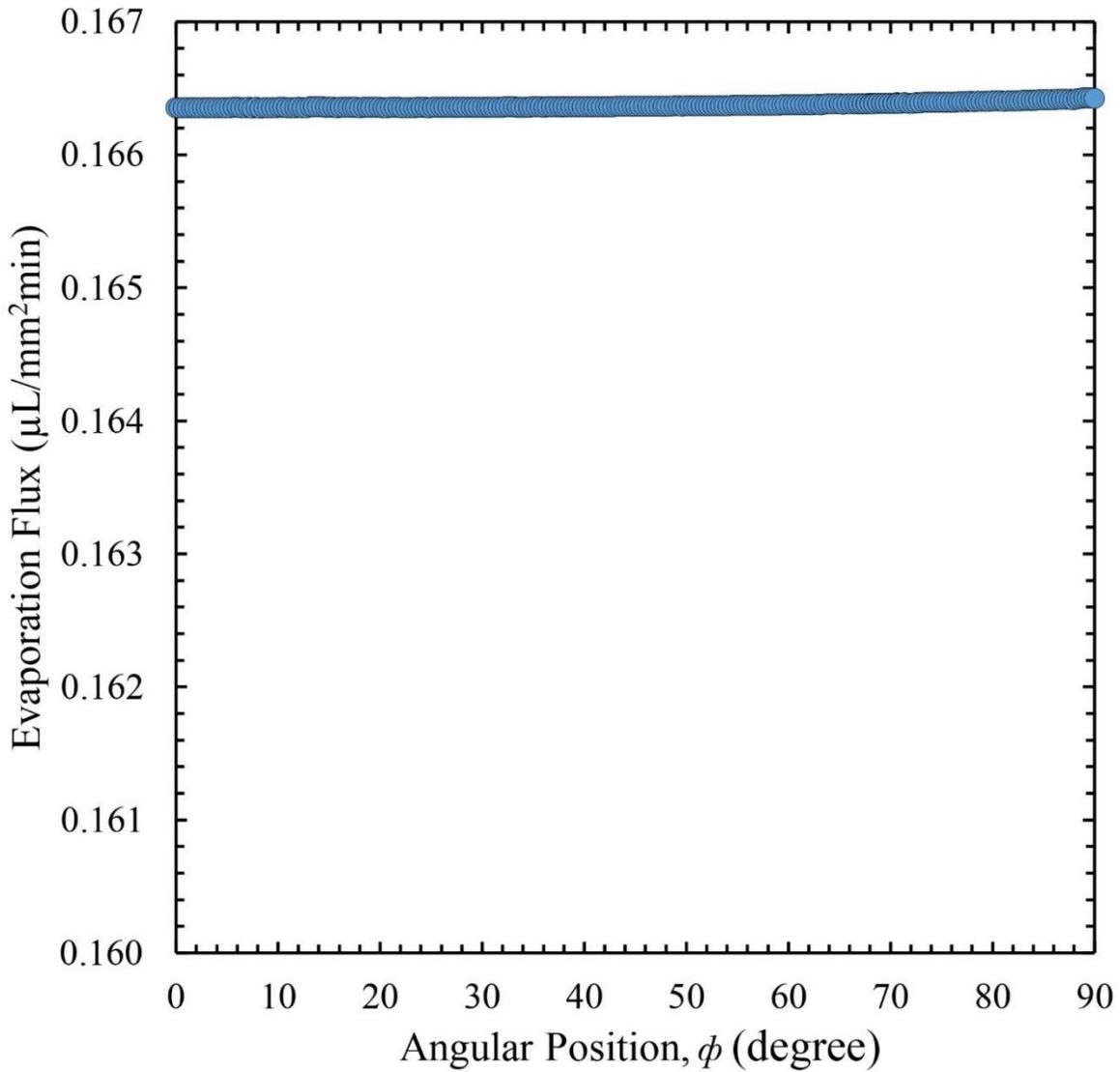


Figure 13: Distribution of the local evaporation flux associated with thermal conduction for the Xenon Processor.

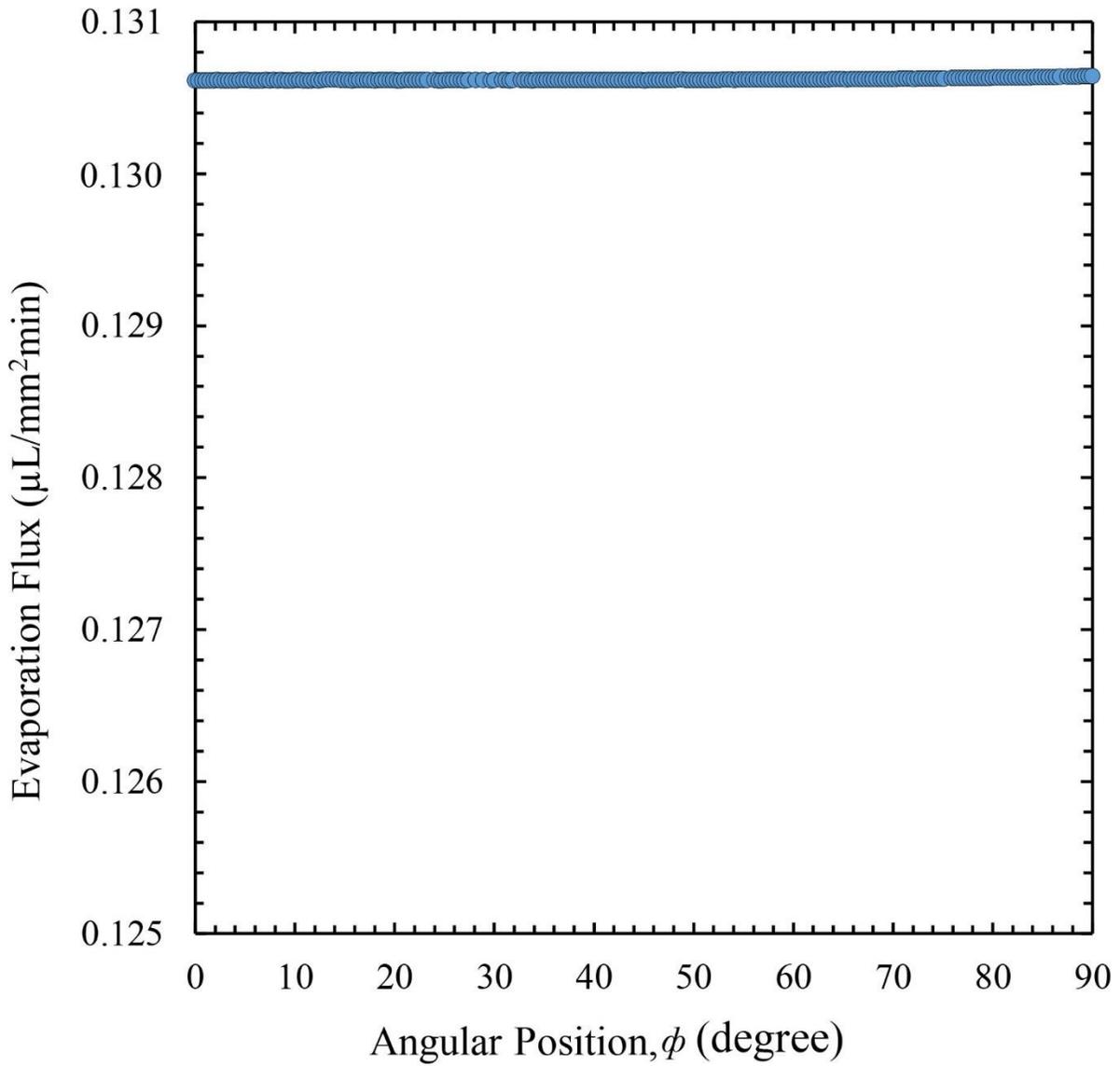


Figure 14: Distribution of the local evaporation flux associated with thermal conduction for core i7-900 Desktop Processor.

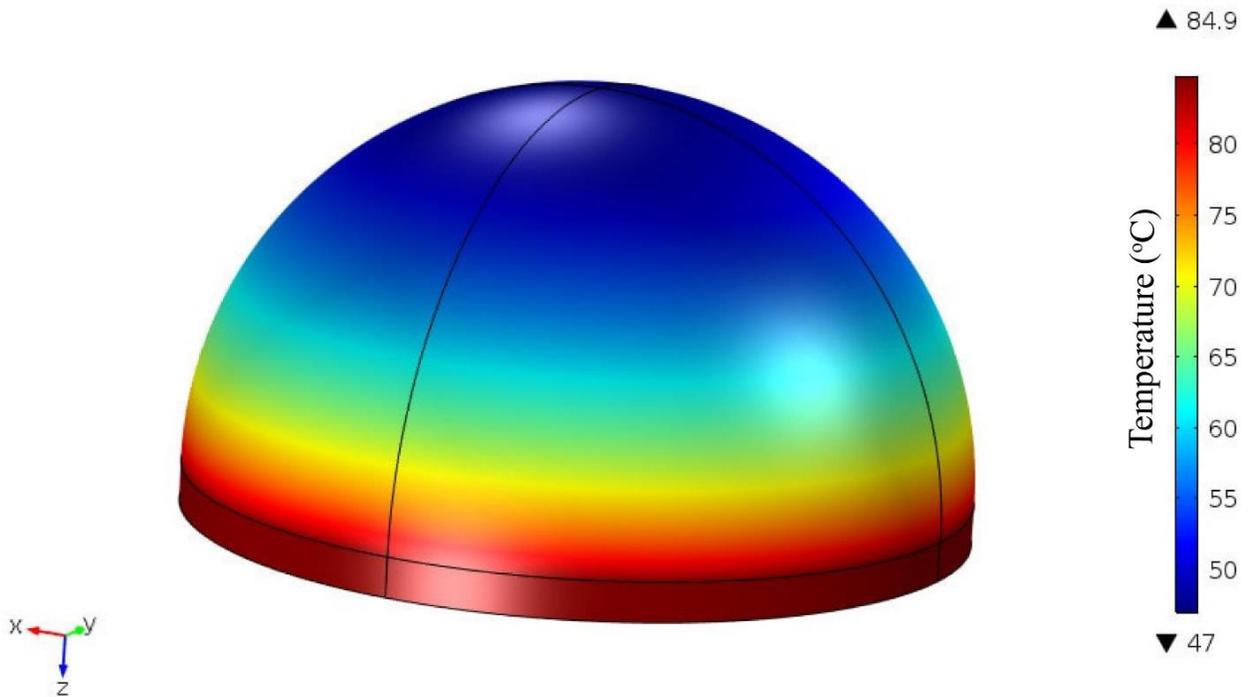


Figure 15: Temperature distribution for single droplet using thermal conduction based evaporation flux for Intel Xenon Processor (130 W).

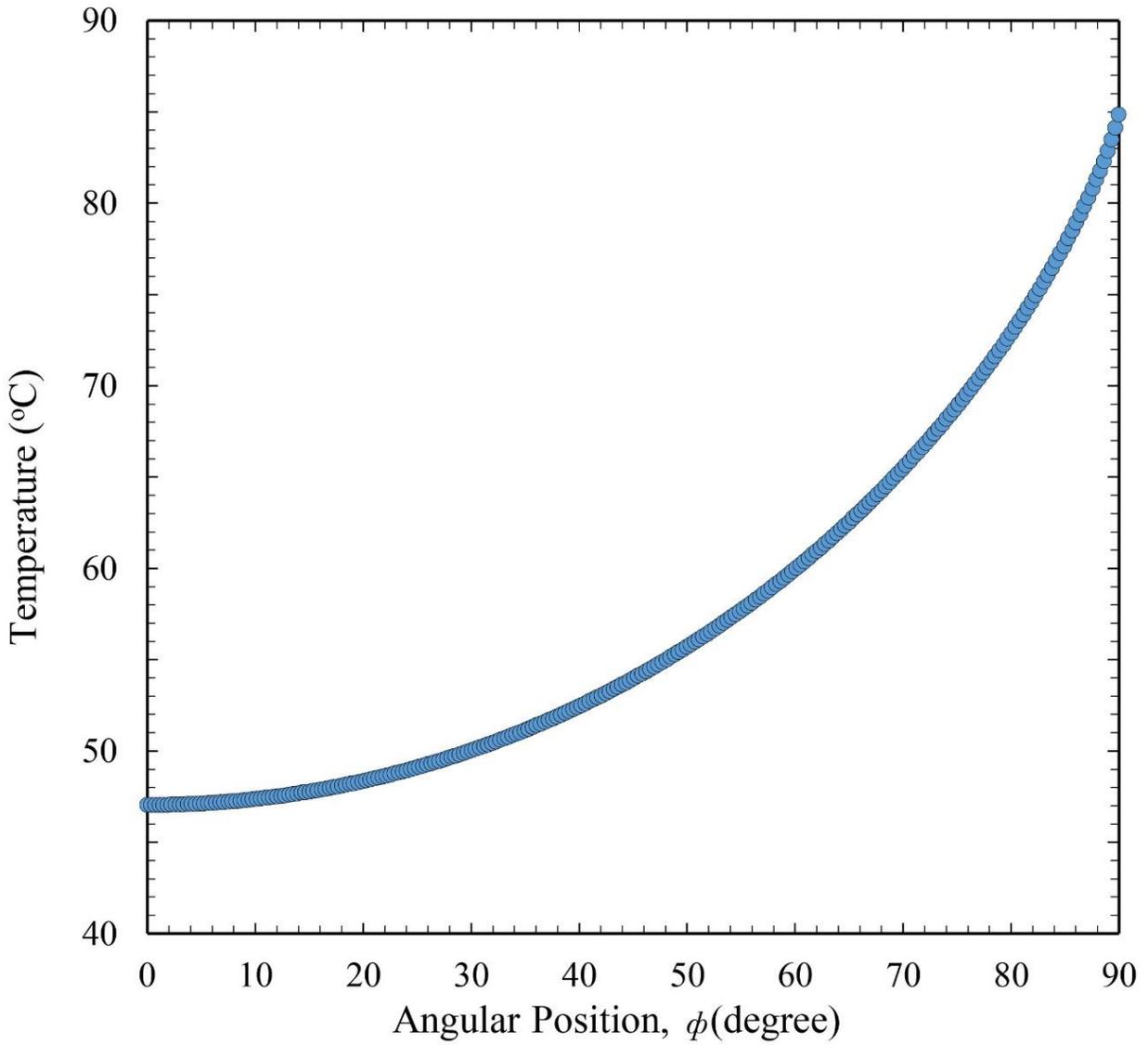


Figure 16: Distribution of the temperature associated with thermal conduction for Xenon Processor.

# Chapter 5

## Conclusions and Recommendations

The findings of the thesis are summarized in this chapter. The recommendations for future work are also included at the end of this chapter.

### 5.1 Conclusions

In this study, both an analytical model and a numerical model were developed to model an evaporative cooling system using arrays of evaporating sessile droplets driven by diffusion and assess the feasibility of providing heat removal for two processors, the Intel Xenon Processor and the Intel Core i7-900 Processor. The analytical model demonstrated that a single layer of evaporating sessile droplets is capable of providing sufficient heat removal for both

processors. A numerical model shows that tiered evaporative cooling system using evaporating sessile droplets driven by diffusion can effectively cool a microprocessor within the current space required for the heat sinks without using a fan. Another numerical model is also developed for sessile droplet to determine thermal properties along the interface for better implementation of evaporative cooling technology with forced air. The following conclusions can be made from this study:

1. It can be concluded that evaporative cooling with a single layer droplet array can remove heat from the microprocessors with tiny droplets and the results from analytical modelling showed that to provide cooling for the Xenon Processor, 5,184 droplets were required at  $r_d = 0.5$  mm and for the Core i7-900 Processor, 27,556 droplets were required at  $r_d = 0.25$  mm which is very large.
2. Results from the numerical model confirm that the developed tiered evaporative cooling system enables sufficient heat removal with larger droplets in a configuration that is easier to manufacture. For the Xenon Processor, at least 41 number of posts is needed to connect each tier for  $r_d = 2$  mm to reach required temperature  $85.0^\circ\text{C}$  whereas the Core i7 Desktop Processor is needed at least 42 number of posts is needed for  $r_d = 2$  mm to reach required temperature  $67.9^\circ\text{C}$  for 130 W.

3. The results from the numerical model indicate that the developed tiered evaporative cooling system can be fit into the conventional cooling system effectively and properly for the two different microprocessors, since the results shows that for Xenon processor, minimum 3 tiers are needed to reach required temperature  $85.0^{\circ}\text{C}$  whereas the Core i7 Desktop Processor is needed at least 4 tiers is needed for  $r_d = 2$  mm to reach required temperature  $67.9^{\circ}\text{C}$  for 130 W where tiers are less or equal to the same height of the conventional heat sinks.
4. Results of the numerical model suggests that that the tiered evaporative cooling systems required less droplets, which is easier to manufacture. It was found that a minimum of 3 tiers was required for the Xenon Processor, with a total of 867 droplets having a radius of 2 mm, and 4 tiers required for the Core i7-900 Processor, with a total of 1,296 droplets having a radius of 2 mm.
5. It can be concluded from the thermal conduction based evaporation that the temperature of the droplets is substantially above the freezing point and indicates the possibility of improved heat removal from droplets with forced air versus the diffusion limited droplets.

## 5.2 Recommendations

The challenges that have been discussed in the numerical model section can be addressed to improve the precision of the simulations. The following points are the recommendations for future work to develop a tiered droplet evaporative cooling system for microprocessors:

1. A study can be conducted to confirm that the vapor is sufficiently diffusing away from the droplets or not, and is there enough clearance space for the diffusion.
2. A study can be carried out to assess the effect of droplet interference, as the droplets are very close to each other.
3. A new study can be carried out to determine the economic feasibility of a tiered evaporative cooling system for other microprocessors with different thermal design power and different heat sink configuration to replace the conventional cooling systems.
4. Based on the study conducted, laboratory scale units can be built to provide experimental results so that the model developed in this study can be validated and used by the industry or other people for microprocessor cooling
5. A new study would be valuable for considering cyclical thermal design loads in microprocessors, to determine the transient response of an

evaporative cooling system with a time-dependent numerical model. Only steady state heat transfer is considered in this study.

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