Two-phase thermal management of traction electronics in EVs/HEVs

M.Tech. Thesis

By

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Centre for Electric Vehicle and Intelligent Transportation System

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Two-phase thermal management of traction electronics in EVs/HEVs

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree
of
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by
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**Two-phase thermal management of traction electronics in EVs/HEVs"** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **Centre for Electric Vehicle and Intelligent Transportation System, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from August 2021 to June 2023 under the supervision of Dr. Pavan Kumar Kankar, Associate Professor, Department of Mechanical Engineering, Indian Institute of Technology Indore and Dr. Ankur Miglani, Assistant Professor, Department of Mechanical Engineering, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Gourav Manohar Sardar
15/06/2023

Signature of the student with date
Gourav Manohar Sardar

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

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DEDICATION

This thesis is dedicated to my parents, whose unwavering love, support, and encouragement have been the foundation of my academic journey. Their belief in me have inspired me to pursue excellence and overcome challenges. I am forever grateful for their presence in my life.

Abstract

In modern days the miniaturization of powerful electronic devices within electric vehicles has led to the requirement of better thermal management solutions. Regardless of the significant implications for heat transfer performance, the effect of axial-uneven heating on the flow distribution in parallel microchannels undergoing flow boiling has been understudied. In this current study, a model with two parallel microchannels subjected to flow boiling has been considered. The microchannels were subjected to axial non-uniform heating i.e., uneven heating along the length of the channel and the flow distribution characteristics within the microchannels were studied. It was found that compared to uniform heating, in the axial non-uniform heating the flow was severely more maldistributed and the range of flow over which the maldistribution occurred is also broader. It was also found that the flow maldistribution was better mitigated by using channel wall materials having higher thermal conductivity. These model predictions were generated with the help of MATLAB simulations.

Keywords: flow boiling, ledinegg instability, parallel microchannels, two-phase flow

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NOMENCLATURE

Δp	Pressure drop [Pa]
G	Mass flux [kg/s]
Te	Exit fluid temperature [K]
T_{in}	Inlet fluid temperature [K]
q''	Heat flux [W/m^2]
A_s	Total heated area [m^2]
$\dot{m}$	Mass flow rate [kg/s]
C_p	Specific heat at constant pressure [J/kgK]
W_{Total}	Total flow rate in the channels [kg/s]
W_i	Flow rate in individual channel having index i
Q_p (Total)	Total heat applied to the channel
Q_p (U.S)	Heat applied to the upstream part of the channel [W/m]
Q_p (D.S)	Heat applied to the downstream part of the channel [W/m]
ϕ	Axial non-uniform heating parameter
K	Thermal conductivity [W/mK]

Chapter 1: Introduction

1.1 Motivation

Modern electric vehicles (EVs) and hybrid electric vehicles (HEVs) are comprised of a variety of power electronic components, including IGBT modules and traction inverters. These elements are becoming more compact and potent, producing heat per unit volume comparable to that of a nuclear reactor. Therefore, more effective thermal management solutions are necessary, as single-phase cooling systems are insufficient for these devices. Extensive research has been conducted to investigate more efficient cooling methods to keep up with the rapid advancement of modern electronic devices. This is done with the aim of preventing electronic malfunctions and ensuring the dependability of electronic systems. Due to their high heat transfer coefficients resulting from boiling heat transfer and lesser caloric resistance resulting from the nearly isothermal nature of boiling and evaporation processes, two-phase thermal management systems offer a potential solution. Therefore, two-phase thermal management systems can provide a practical means of cooling contemporary electronics in electric vehicles. For electric vehicle application, a better thermal management system translates to better driving range, faster charging speeds, better reliability, passenger and component safety, lower maintenance and ownership cost. Also, a better thermal management system can simplify and reduce the size of the components thereby allowing more space in the vehicle for other applications.

However, the vast majority of practical engineering systems with two-phase flow are prone to a variety of instabilities. These instabilities lead to the flow within the parallel microchannels being maldistributed, which in turn leads to a significant and sudden change in the flow rate within the parallel microchannels, which in turn causes the channel surface temperature to rise. This completely undermines the system's intended function for cooling the microchip as the heat transfer performance of the system is significantly reduced.

Prior studies have been extensively carried out on microchannel heat sinks to study the heat transfer performance under non-uniform lateral heating conditions. The objective of this study is to examine and improve the heat transfer performance of a heatsink that incorporates parallel microchannels exposed to axial non-uniform heating. The heat transfer input to the microchannels and the channel wall material was varied and the flow maldistribution characteristics within the channel were investigated.

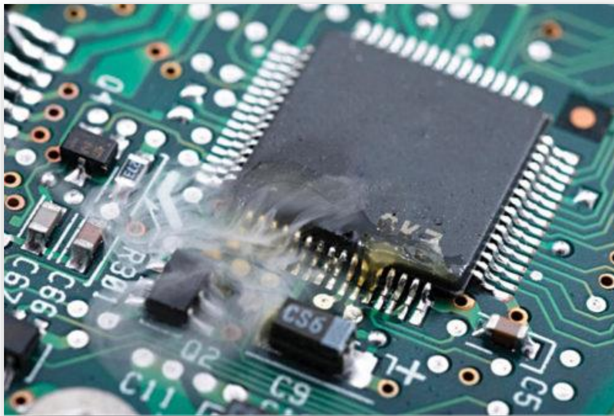

Fig 1: Figure showing overheating in a micro-chip

1.2 Organization of the Thesis

Chapter 1 provides a concise overview highlighting the significance of electronics cooling. Additionally, the importance, limitations, and challenges associated with using two-phase cooling systems for cooling traction inverters in electric vehicles and hybrid electric vehicles are also described. Objectives of the study have also been stated in this chapter.

Chapter 2 describes the previous works that have been done on this topic. The first part of the chapter describes the flow instability (Ledinegg instability/flow excursion) involved with two-phase thermal management systems. The second part describes the previous works that have been done on this topic involving lateral non-uniform heating and various method used to mitigate flow maldistribution in parallel microchannels.

Chapter 3 presents the model utilized for the simulation and outlines the specific cases examined in this research study.

Chapter 4 details the outcomes obtained from the conducted simulation.

Chapter 5 thoroughly examines and discusses the derived conclusions from the results.

Chapter 6 looks into the future prospects and potential areas for further exploration within this field of research.

Chapter 2: Literature Review

2.1 Literature Review on Flow Boiling and Ledinegg Instability

In two-phase heat transfer, boiling heat transfer is advantageous because it can provide a much higher heat transfer rate than single-phase heat transfer. This is due to the fact that the phase change from liquid to vapour during boiling can absorb a great deal of heat, which can then be transferred away from the heated surface. In addition, the formation and collapse of bubbles during boiling can contribute to an increase in heat transfer by promoting fluid mixing and disrupting the boundary layer near the heated surface. In contrast to single-phase heat transfer, boiling heat transfer can occur under a variety of operating conditions, including high heat fluxes and low flow rates. Lastly, boiling heat transfer can be utilized to control the temperature of a system by regulating the heat flux, which is useful for electronics cooling.[1]

Ledinegg instability, also referred to as the Flow excursion instability, is a widely recognized phenomenon that is a common occurrence in conventional and several micro-scale channels. This occurs when the slope of the pressure-drop–mass flux, Δp-G, demand curve becomes smaller than the Δp-G supply curve. Mathematically it can be described as,

$$\frac{\partial(\Delta p)}{\partial G}\Big|_D \leq \frac{\partial(\Delta p)}{\partial G}\Big|_S,$$

This instability can result in a significant and abrupt change in flow rate, which can increase the surface temperature of the channel. It is common in flow boiling systems because the pressure drop tends to increase with decreasing mass flow rate. Therefore, it is important to understand the mechanism controlling the existence of the slope and its trend to prevent the system from becoming unstable. Proper measures, such as inlet restrictors, pressure drop elements, and fabricated nucleation sites, can be taken to suppress boiling flow oscillations and stabilize flow boiling in microchannels. Understanding the conditions in which a system is susceptible to Ledinegg instability is crucial for designing efficient and reliable two-phase thermal management systems. Let us understand Ledinegg instability with the help of the following curve,

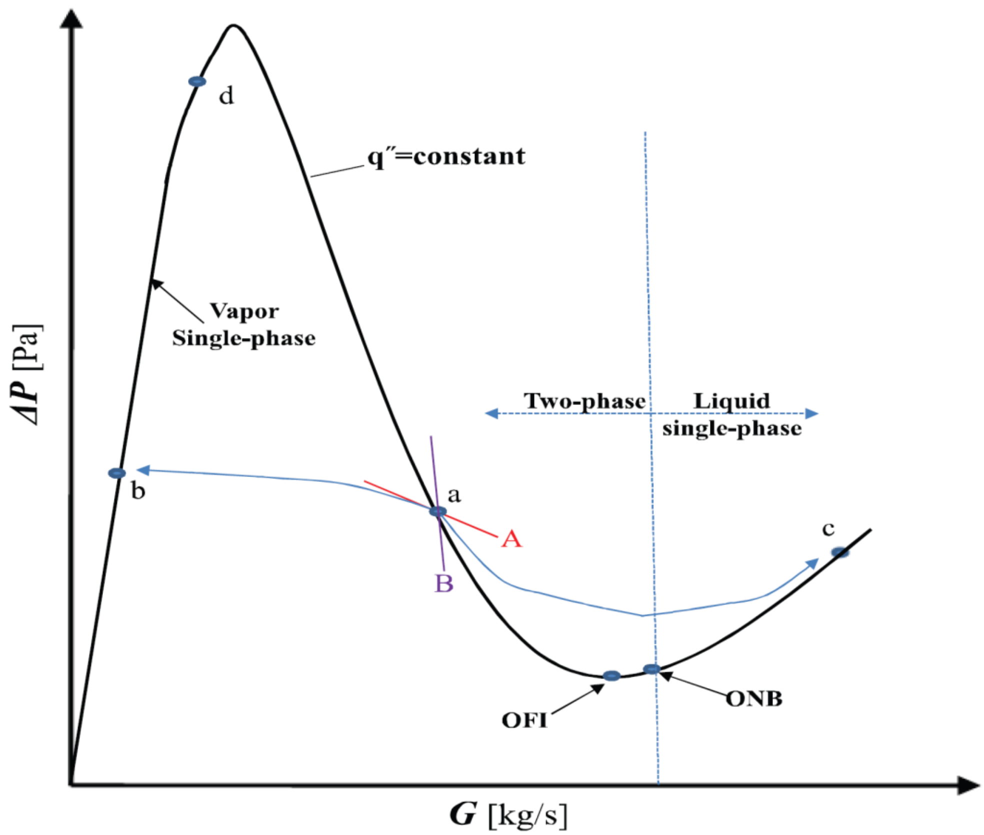

Fig 2: Pressure drop-Mass flux curve for a uniformly heated channel

Fig 2 represents the pressure drop-mass flux demand curve of a heated channel subjected to a constant heat flux q''. Subcooled liquid with a temperature of T_{in} enters a heated channel through an inlet plenum and heats up as it travels downstream due to convection heat transfer from the channel walls to the fluid. At sufficient flow rates, the fluid will depart as a single-phase liquid in Fig 2 at point 'c'. According to the principle of conservation of energy for single-phase flow, if the mass flux, G, is decreased progressively, the exit fluid (and surface) temperature, T_e, will rise,

$$Te = Tin + \frac{q'' * A_s}{\dot{m} * C_p}$$

Here, A_s=total heated area

C_p=Specific heat at constant pressure

ONB (Onset of nucleate boiling) takes place at the channel exit at a particular mass flux. However, ONB can start before the average fluid temperature reaches saturation temperature (subcooled boiling). Consistently decreasing the flow rate will ultimately give rise to the onset of significant void (OSV) phenomenon in the context of subcooled boiling. The phenomenon known as OSV involves the scenario wherein bubbles become detached from the high-temperature wall and subsequently blend with the subcooled liquid inside the channel core, without undergoing complete condensation. This results in a substantial increase of the void fraction. From this point, a minor reduction in flow rate will initiate the onset of flow instability (OFI) which is a local minimum on the ΔP-G demand curve (shown in Fig 2) which results in Ledinegg instability within the channel. However, it also must be noted that instability will only occur beyond this point provided that proper measures are not taken. As the boiling becomes more vigorous, there is an increase in vapour introduced to the flow. Due to the fact that vapour has a lower density than liquid, and in accordance with the principle of mass conservation in a steady flow, the flow rate increases as the mass quality increases. This phenomenon is observed when the mass flux rate decreases while the heat flux remains constant. Furthermore, it is to be noted that the kinematic viscosity of vapour is generally significantly higher compared to that of its liquid counterpart. This will result in a notable rise in the pressure drop required to meet the channel demand.

Due to the above-mentioned reasons, the demand curve for the pressure-drop-mass flux(ΔP-G) rate exhibits a negative slope when the mass flux rate is less than the value associated with OFI conditions. Mathematically, it can be expressed as,

$$\frac{\partial(\Delta p)}{\partial G}\Big|_{D} \leq 0$$

In instances where the negative value of the pump supply curve slope of the (as shown in Fig 2, Curve A) is comparatively smaller than that of the demand curve i.e.

$$\frac{\partial(\Delta p)}{\partial G}\Big|_{D} \leq \frac{\partial(\Delta p)}{\partial G}\Big|_{S}$$

It can be observed that Ledinegg instability occurs and the system becomes unstable. [2]

2.2 Literature review on two-phase flow in parallel microchannel

(Miglani, Weibel, et al., 2021b),conducted experiments and revealed that the Ledinegg instability-induced flow maldistribution becomes progressively more severe as heat input increases. In their experimental configuration, two parallel microchannels were employed to facilitate the flow of coolant while the heat was applied to both channels simultaneously. At lower heat transfer rates, the flow within the parallel channels remained evenly distributed, as the coolant remained in a liquid phase. However, as the heat transfer rate increased, boiling initiated in one of the channels, subsequently introducing the Ledinegg instability. This instability resulted in flow maldistribution, creating a temperature disparity between the channels. Consequently, one of the channels experienced a higher flow rate, while the other channel became deprived of adequate flow. Moreover, the study established a direct correlation between the degree of maldistribution and the heat transfer rate, with an increase in the latter leading to a higher magnitude of flow maldistribution.[3]

(Miglani, Weibel, et al., 2021a) , in their research, the authors conducted similar experiments involving parallel microchannels exposed to heat input, aiming to compare the heat transfer performance between thermally isolated channels and thermally coupled channels, particularly under lateral non-uniform heating conditions. The results indicated that when lateral thermal coupling was employed, the flow maldistribution across the parallel channels could be effectively mitigated, resulting in a comparatively improved heat transfer performance of the system.[4]

(Miglani, Soto, et al., 2021)studied the effect of lateral irregular heating conditions on the flow distribution behaviour between boiling parallel microchannels is studied, along with a comparison to the known characteristic behaviour under even heating conditions. The severity of flow misdistribution under such unequal heating conditions is quantified and it was concluded that the flow misdistribution under conditions of lateral irregular heating is typically more severe than under conditions of even heating. It was also found that the degree of lateral uneven heating was found to directly impact the severity of flow maldistribution based on the following three metrics, (a) the flow rate range in which the maldistribution takes place (b) The maximal disparity in the fraction of flow rate among the channels. (c) the total flow rate range in which the most severe flow maldistribution occurs. [5]

(AKAGAWA K et al., 1971) studied the flow rate and flow instabilities within long parallel evapourators with the help of experiments. The experiments were conducted with R-113 refrigerant as the coolant and the pressure was varied between the range of atmospheric pressure and supercritical pressure. It was found from the experiments that in parallel flow systems the flow rates in the individual tubes can be derived from the characteristic curves of the individual tubes. It was also found that the phenomenon of excursions is observed at the points of operation where the tangent of the characteristic curves for the parallel system is equivalent to that of the pumping system. [6]

(Patankar & Salamon, 2018) studied the maldistribution of flow rate in parallel channel heat sinks and the effect of thermal coupling between them. In this study, a new method was found for determining the flow rate distribution in a heat sink with thermally coupled parallel channels. The thermal interconnectivity between them is considered through thermal transport in the heat sink walls and base. A resistance network method was used to model the thermal transport in the heat sink wall and base. This approach for modelling the thermal interconnection among channels in a parallel channel heat sink enabled an examination of the influence of the number of channels within the heat sink while keeping the channel and wall geometry fixed, on the threshold base and wall thermal conductivity necessary to achieve uniform flow distribution. This suggests that enhancing the thermal connection between the channels in a two-phase parallel channel heat sink is crucial for reducing flow maldistribution. [7]

(Van Oevelen et al., 2017) carried out a study to predict the stability and flow distribution in a two-phase system with several parallel channels. The stability of the steady-state flow distributions within parallel channels is influenced by the characteristics of the pump curve. It was also found that specifically, in the case of a constant pressure-drop pump curve, the stability of each individual channel is not affected by the behaviour or conditions in the other channels [8]

(Van Oevelen et al., 2018) studied the impact of lateral thermal coupling between parallel microchannels on the distribution of two-phase flow. The study concluded that the occurrence and severity of flow maldistribution are dependent on the magnitude of the heat input to the microchannel array. [9]

From the above discussion, we can conclude that in order to mitigate the flow maldistribution in parallel microchannels it is important to minimize and ideally eliminate the Ledinegg instability in parallel microchannels for the best heat transfer performance of two-phase heat transfer systems.

Chapter 3: Model Description and Cases for Simulation

The flow model used for this study is shown below:

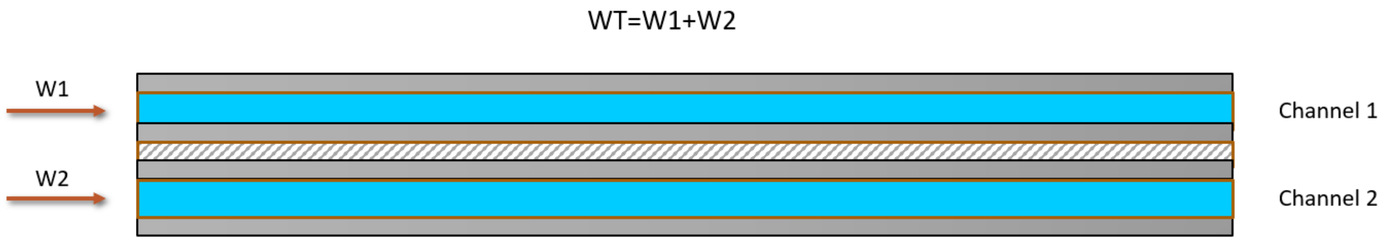

Fig 3: Figure showing the flow network architecture of the system with flow through two parallel channels

The simulation is conducted on an ideal, open-loop flow network architecture with flow through two parallel channels, as depicted in Figure 3, in which a pump delivers subcooled liquid to two parallel heated microchannels connected hydraulically through a common inlet and outlet. This configuration ensures that the channels experience similar pressure drop boundary conditions and thereby simulating the conditions found in heat sinks where microchannels are connected to a common header.

By the principle of conservation of mass, we can say that,

$$W_{Total} = \sum_{i=1}^{2} W_i$$

Where, W_{Total}=Total flow rate in the channels

W_i=Flow rate in individual channel having index i

For this simulation, two parallel microchannels were considered as shown in Figure 3. The channel was divided into two parts along the length and different values of heat is applied to the upstream and downstream parts of the channel. This is known as axial non-uniform heating. The axial non-unform heating of the parallel microchannels is shown with the help of the following figure.

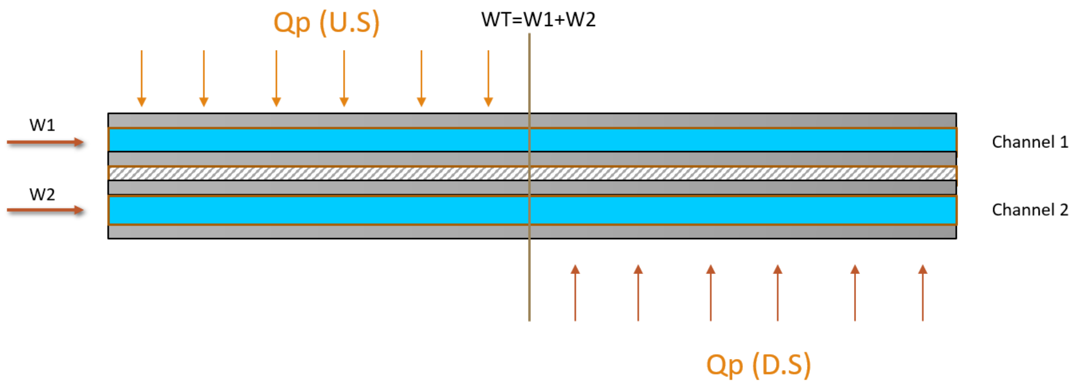

Fig 4: Figure showing axial non-uniform heating in parallel microchannels

The heat applied to the upstream part of the microchannel is denoted as Q_p (U.S) and the heat applied to the downstream part of the microchannel is denoted as Q_p (D.S).

It is important to quantify the degree of axial non-uniform heating taking place within the microchannels. This is done with the help of relative heat input to the upstream and downstream parts of the channel and the parameter is known as the axial non-uniform heating parameter. It is denoted by 'ϕ'.

$$\phi = \frac{Qp(US) - Qp(DS)}{Qp(US) + Qp(DS)} \qquad \text{Where, } -1 \leq \phi \leq 1$$

$\phi=1$ is an extreme case where all the heat is applied to the upstream part of the microchannel

$\phi=0$ is the case of uniform heat application to the upstream and downstream part of the microchannel

$\phi=-1$ is an extreme case where all the heat is applied to the downstream part of the microchannel

Parameters	Magnitude
Number of channels	2
Channel dimensions [Channel width (Wc), Channel height (Hc), Channel length (Lc)]	Wc=200 μm Hc=200 μm Lc=10 mm
Channel wall dimensions [Wall Width (Ww), Wall height (Hw)]	Ww=300 μm Hw=300 μm
Degree of axial non-uniform heating (ϕ)	-1 to 1
Wall thermal conductivity(k) (W/mK)	K=148 (Silicon), K=237(Aluminium), K=385(Copper), K=2200(Diamond)
Qp (Total)	200 W/m, 100W/m, 50 W/m
Fluid inlet temperature	353.15 K
Inlet pressure	10^5 Pascal
Fluid selected as coolant	Water
Ambient temperature	300K

Table1: Different operational variables and boundary conditions used for the simulation

Simulations were carried out on MATLAB by varying the following variables:

1. Total heat input to the channel. [Qp (Total)]
2. Heat applied to different parts of the channel along the length. [Qp (U.S), Qp (D.S)]
3. Channel wall material (thermal conductivity). [k]

The following cases as shown in the table were simulated,

When k = 148W/mk

Q_p(Total)(W/m)	Q_p (U.S) (W/m)	Q_p (D.S) (W/m)	ϕ
200	200	0	1
	100	100	0
	0	200	-1
100	100	0	1
	50	50	0
	0	50	-1
50	50	0	1
	25	25	0
	0	50	-1

Table 2: Simulation cases when silicon (K=148 W/mk) is taken as the wall material

When k = 237 W/mk

Q_p(Total)(W/m)	Q_p (U.S) (W/m)	Q_p (D.S) (W/m)	ϕ
200	200	0	1
	100	100	0
	0	200	-1
100	100	0	1
	50	50	0
	0	50	-1
50	50	0	1
	25	25	0
	0	50	-1

Table 3: Simulation cases when aluminium (K=237 W/mk) is taken as the wall material

When k = 385 W/mk

Q_p(Total)(W/m)	Q_p (U.S) (W/m)	Q_p (D.S) (W/m)	ϕ
200	200	0	1
	100	100	0
	0	200	-1
100	100	0	1
	50	50	0
	0	50	-1
50	50	0	1
	25	25	0
	0	50	-1

Table 4: Simulation cases when copper (K=385 W/mk) is taken as the wall material

When k = 2200 W/mk

Q_p(Total)(W/m)	Q_p (U.S) (W/m)	Q_p (D.S) (W/m)	ϕ
200	200	0	1
	100	100	0
	0	200	-1
100	100	0	1
	50	50	0
	0	50	-1
50	50	0	1
	25	25	0
	0	50	-1

Table 5: Simulation cases when diamond (K=2200 W/mk) is taken as the wall material

From the simulations the flow maldistribution was recorded under each case was recorded and compared to see in which case the flow maldistribution was least severe and the case in which the range of flow maldistribution was the least.

Chapter 4: Simulation Results and Discussion

Before discussing the simulation results, it is essential to understand the characteristic flow distribution curve. The characteristic flow distribution curve shows the relative flow rate fraction as a function of the total flow rate for the two characteristic flow distribution within the parallel microchannels.

We can understand the simulation results with the help of a particular case in which,

- Channel Wall thermal conductivity k=148W/mk (Silicon)
- Qp (Total) =200W/m
- Qp (U.S) = 200, Qp (D.S) =0

The characteristic flow distribution curve obtained from the above case is shown in the figure below,

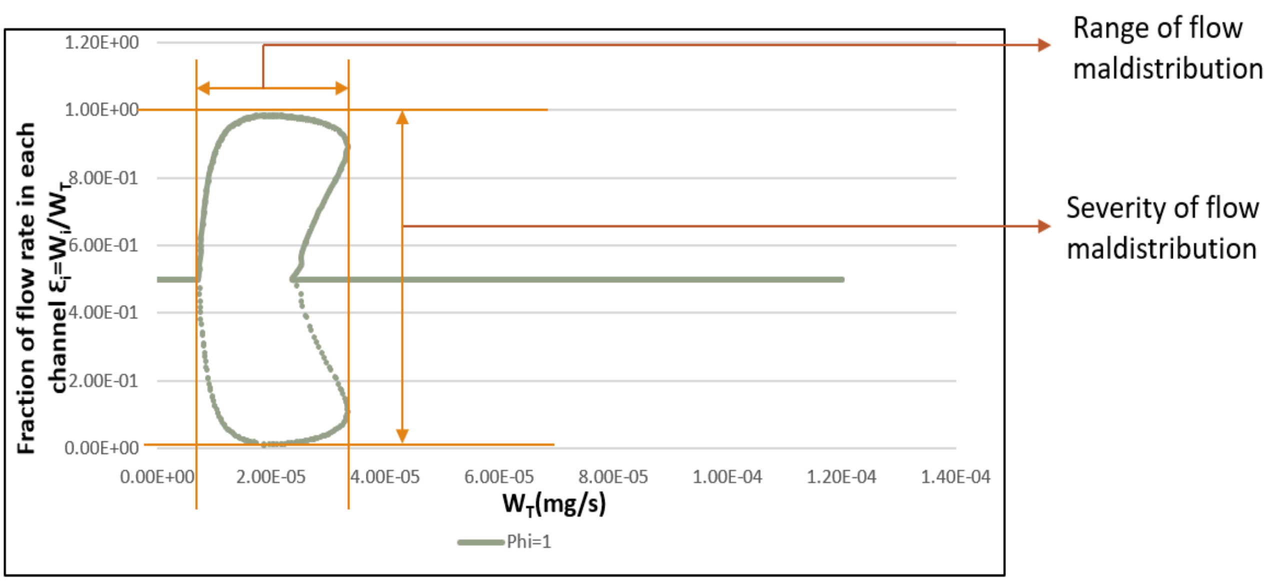

Fig 5: Flow distribution diagrams showing the relative flow rate fraction as a function of the total flow rate for the two characteristic flow distribution behaviours

From the characteristic curve, we can see that, from the width of the curve we can determine the flow maldistribution and from the length of the curve we can determine the severity of flow maldistribution in the parallel microchannels. The solid line in the top half of the curve represents the flow fraction in the channel which receives the excess flow whereas the dotted line in the bottom half represents the flow fraction in the channel which is starved of flow.

As previously discussed in the chapter on the literature review, in order to make a two-phase thermal management system more practical and efficient, it is crucial to reduce flow instabilities (Ledinegg instability) within parallel microchannels. This can be accomplished by minimising flow misdistribution in parallel microchannels.

Consequently, the lesser the length of the characteristic curve, the less severe the flow maldistribution, and the narrower the width of the characteristic curve, the smaller the flow maldistribution range in parallel microchannels.

For a particular channel wall material, the total heat input to the channel was varied and the flow maldistribution was studied for different degrees of axial non-uniform heating.

Case 1,

K=148 W/mk

Q_p (Total)=200 W/m

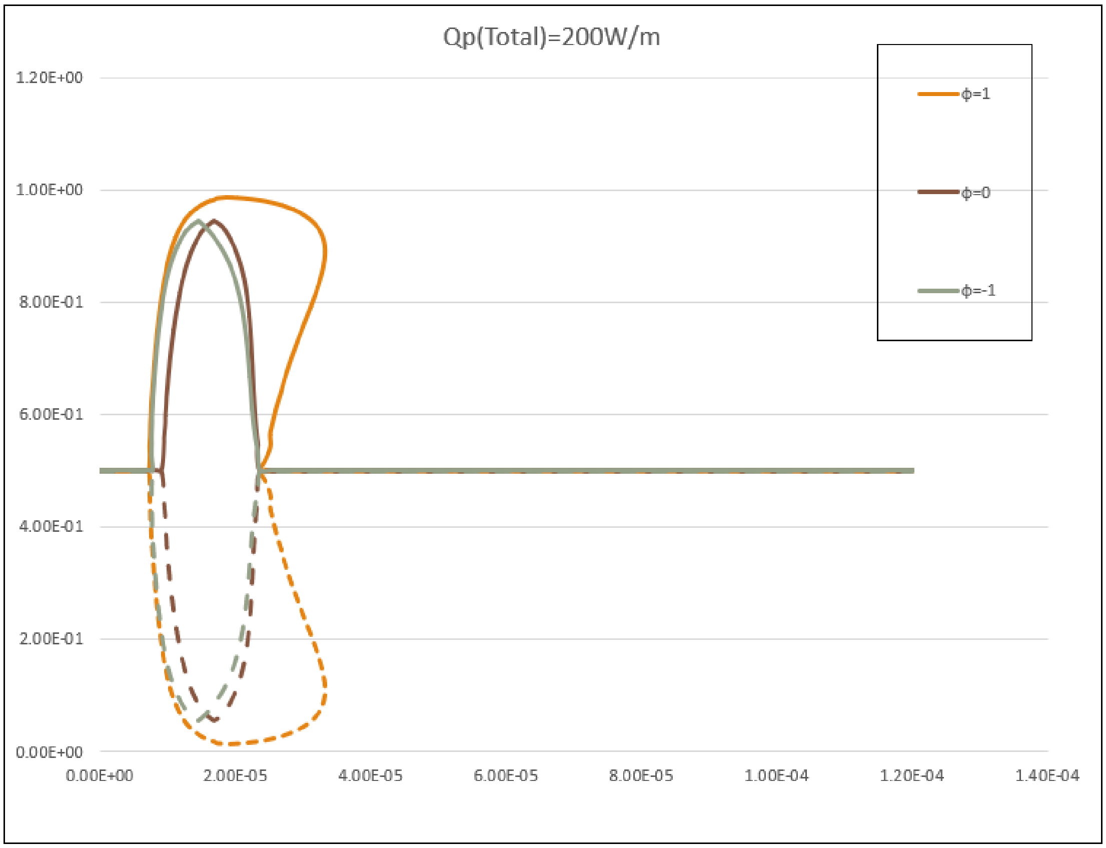

Fig 6: Flow distribution curve of two parallel microchannels with silicon channel walls(k=148W/mk) receiving a total heat input of 200W/m.

The above flow distribution curve shows a notable observation regarding the flow maldistribution. Specifically, it demonstrates that at the extreme upstream condition (ϕ=1), the flow maldistribution is the most severe and also the range of flow maldistribution is greater. It should also be noted that the flow maldistribution at the extreme downstream case (ϕ=-1) is significantly less compared to the extreme upstream case suggesting that the flow maldistribution can be better controlled by applying the heat in the downstream part of the channel. Conversely, when the heat input is uniformly distributed along the channel's length (ϕ=0), there is a significant reduction in both the severity and range of flow maldistribution. This finding suggests that a uniform division of heat input along the length of the channel leads to the best flow distribution characteristics within the channel.

Case 2,

K=148 W/mk

Q_p (Total)=100 W/m

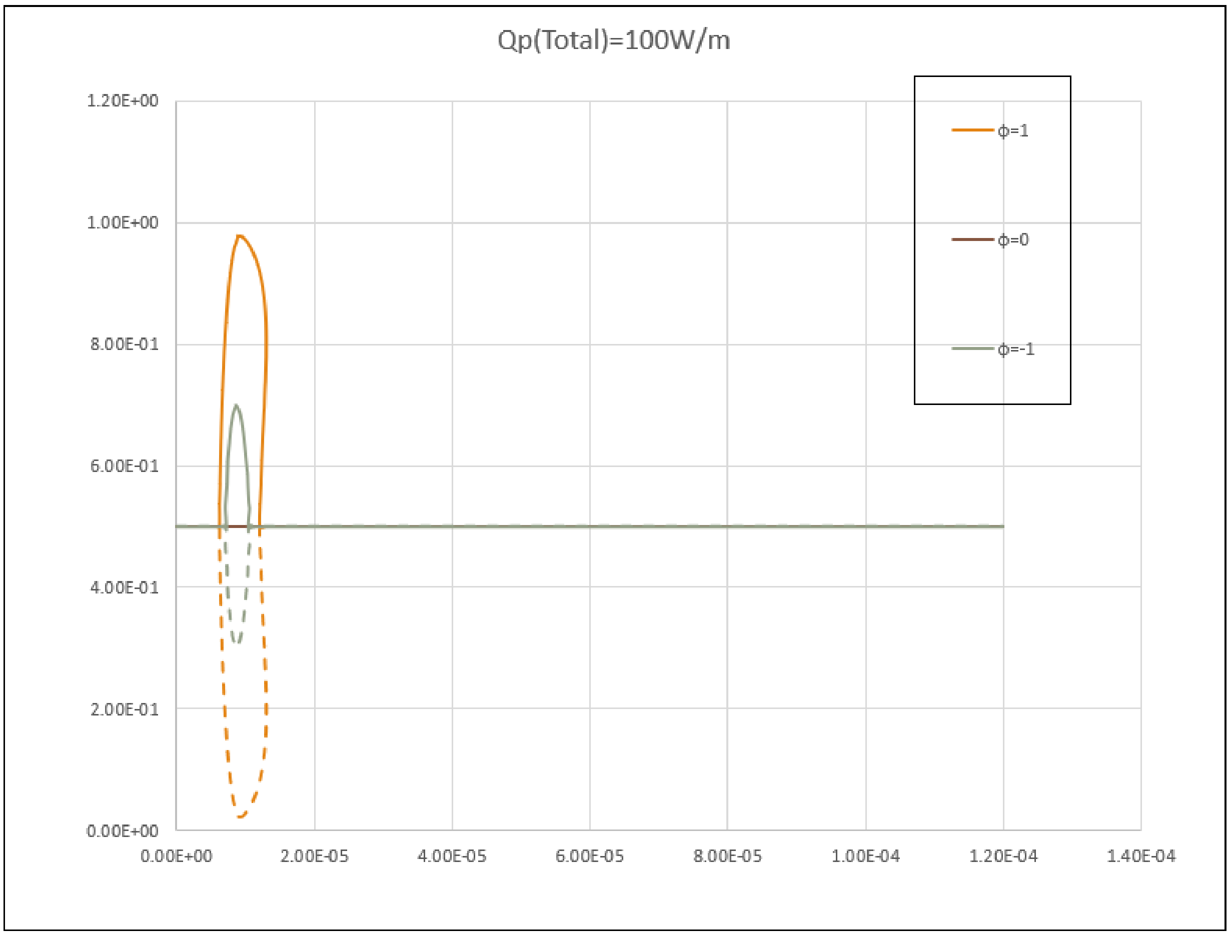

Fig 7: Flow distribution curve of two parallel microchannels with silicon channel walls(k=148W/mk) receiving a total heat input of 100W/m.

Identical patterns can also be observed in this case. At the extreme upstream condition (ϕ=1), the flow maldistribution is the most severe and also the range of flow maldistribution is greater. In the extreme downstream case (ϕ=-1) is significantly less compared to the extreme upstream case. When the heat input to the channel is uniformly distributed along the length of the channel the flow maldistribution is non-existent.

Case 3,

K=148 W/mk

Q_p (Total)=50 W/m

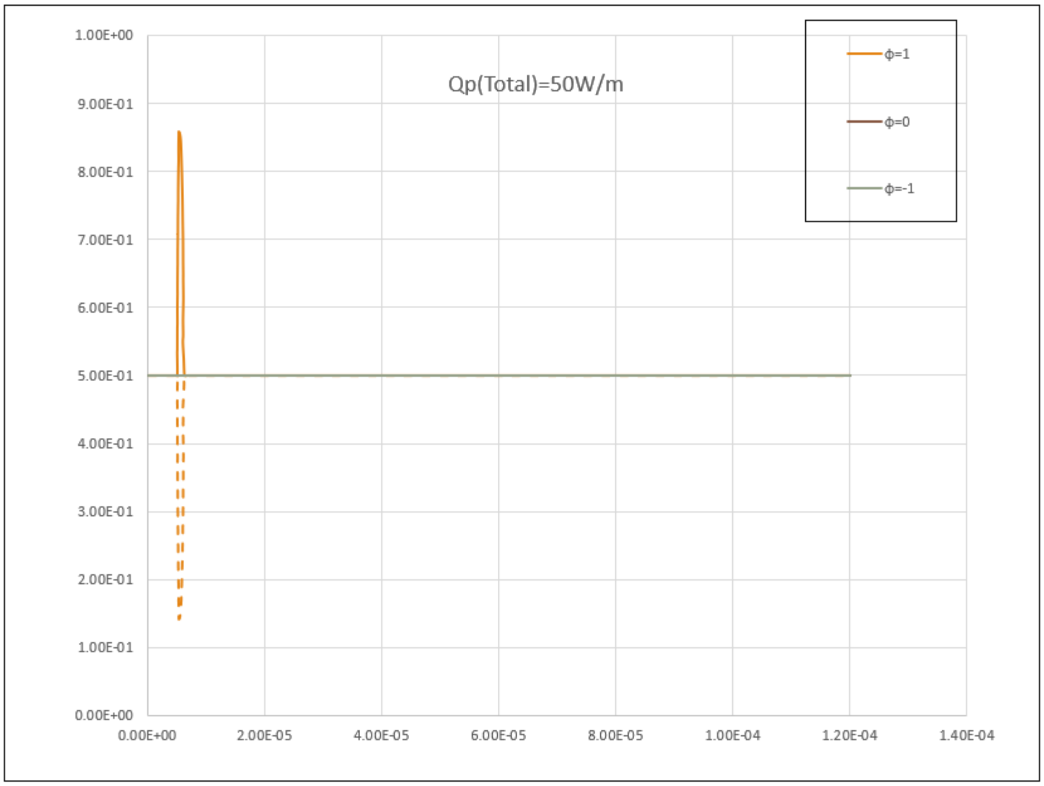

Fig 8: Flow distribution curve of two parallel microchannels with silicon channel walls(k=148W/mk) receiving a total heat input of 50W/m.

Similarly, we can see that in this case as well the flow maldistribution at the extreme upstream case (ϕ=1) is the maximum whereas for the extreme downstream condition (ϕ=-1) and the equal heat distribution case (ϕ=0) the flow maldistribution is completely non-existent.

Choosing K=237Wmk (Aluminium) as the channel wall material and varying the total heat input to the channels the following flow distribution curves were obtained:

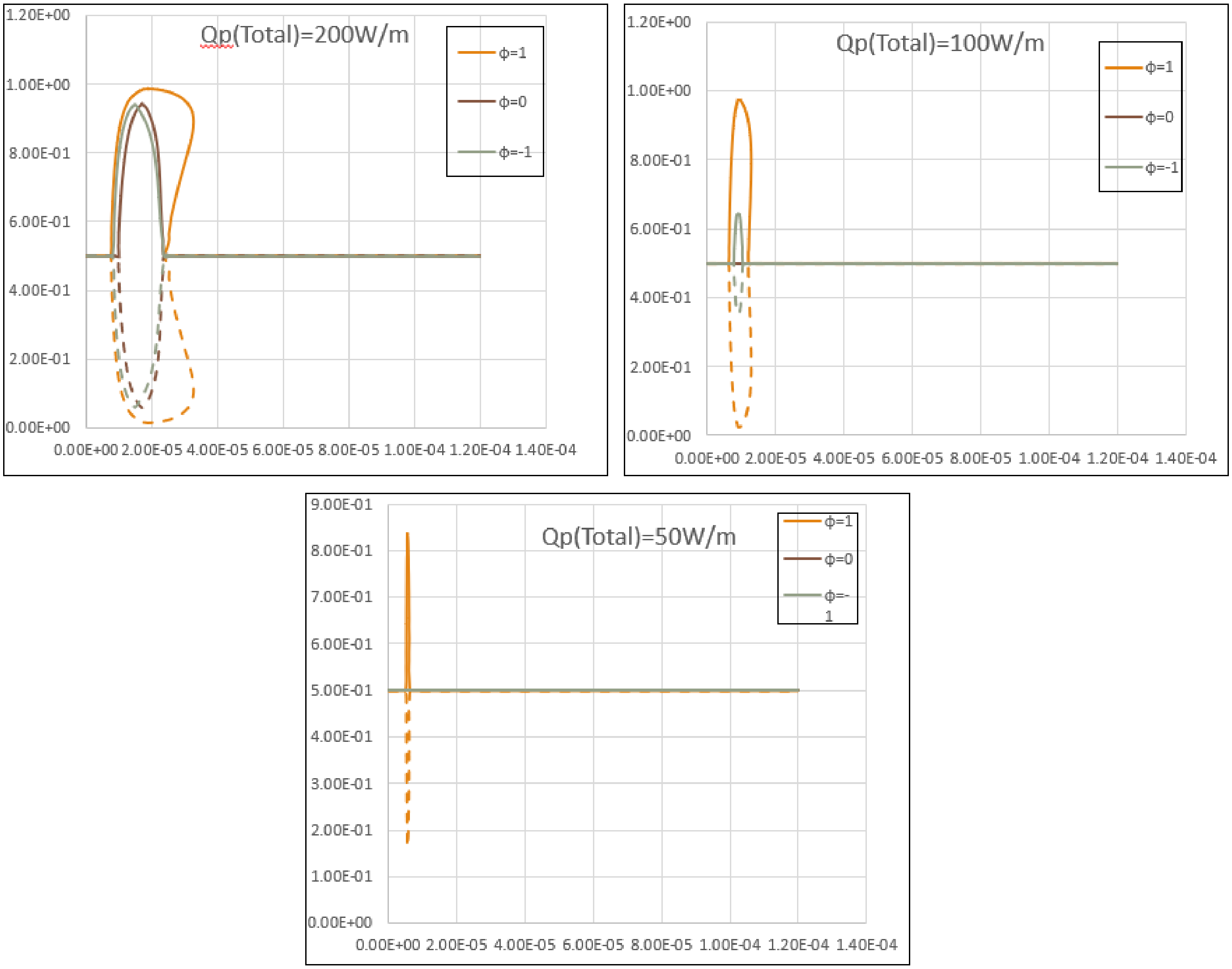

Fig 9: Flow distribution curves of two parallel microchannels with aluminium channel walls (k=237W/mk) receiving different values of total heat input

As seen from the flow distribution curves above the patterns are identical. The flow maldistribution at the extreme upstream case (ϕ=1) is the maximum whereas for the extreme downstream condition (ϕ=-1) it is comparatively less and for the equal heat distribution case (ϕ=0) the flow maldistribution is the least.

Similarly, choosing K=385W/m (copper) as the channel wall material and varying the total heat input to the channels the following flow distribution curves were obtained:

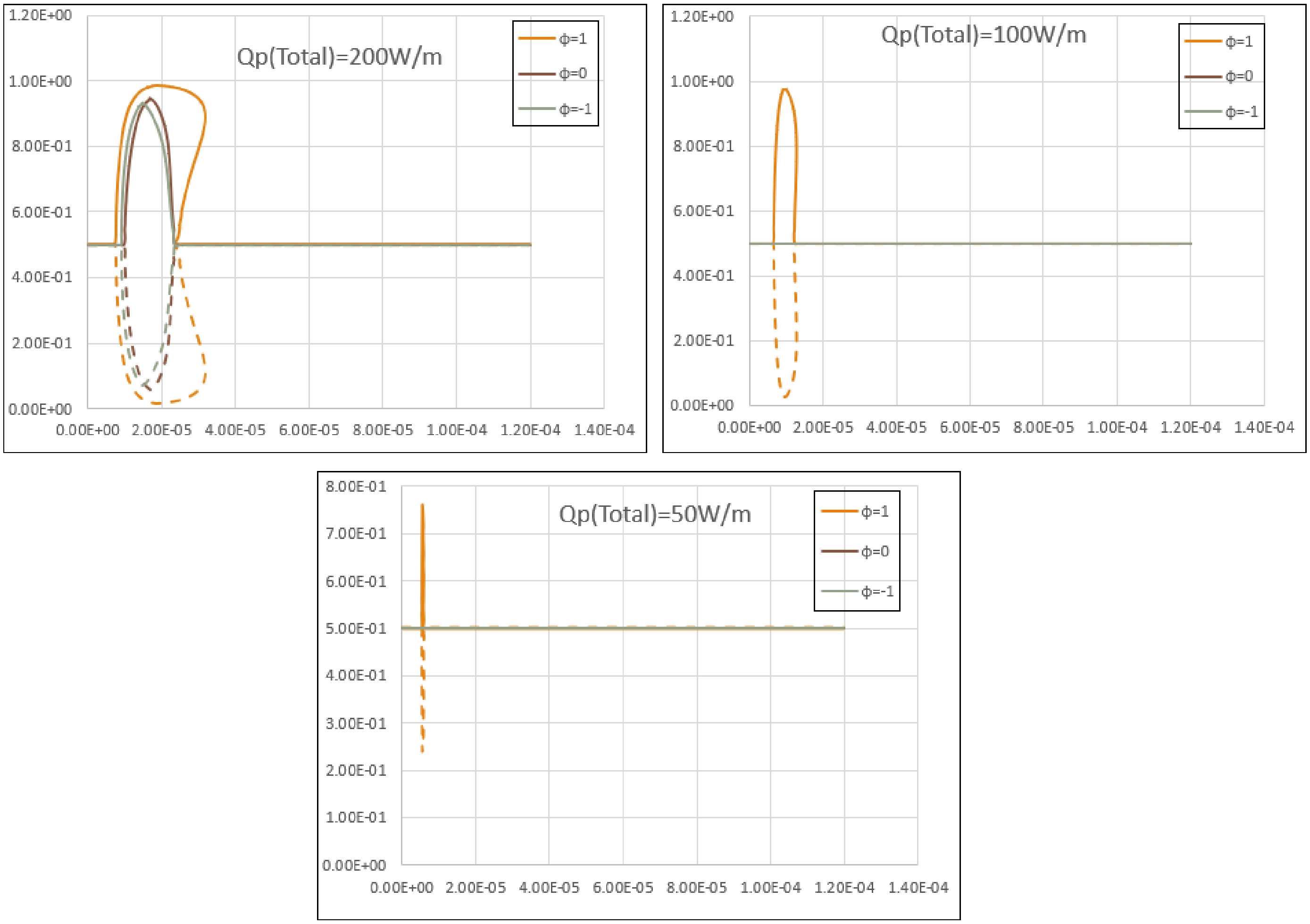

Fig 10: Flow distribution curves of two parallel microchannels with copper channel walls (k=385 W/mk) receiving different values of total heat input

In case of copper channel walls as well the flow distribution curves display identical patterns. The flow maldistribution at the extreme upstream case (ϕ=1) is the maximum whereas for the extreme downstream condition (ϕ=-1) it is comparatively less and for the equal heat distribution case (ϕ=0) the flow maldistribution is the least.

Finally selecting K=2200W/mk (Diamond) as the channel wall material and varying the total heat input to the channels the following flow distribution curves were obtained:

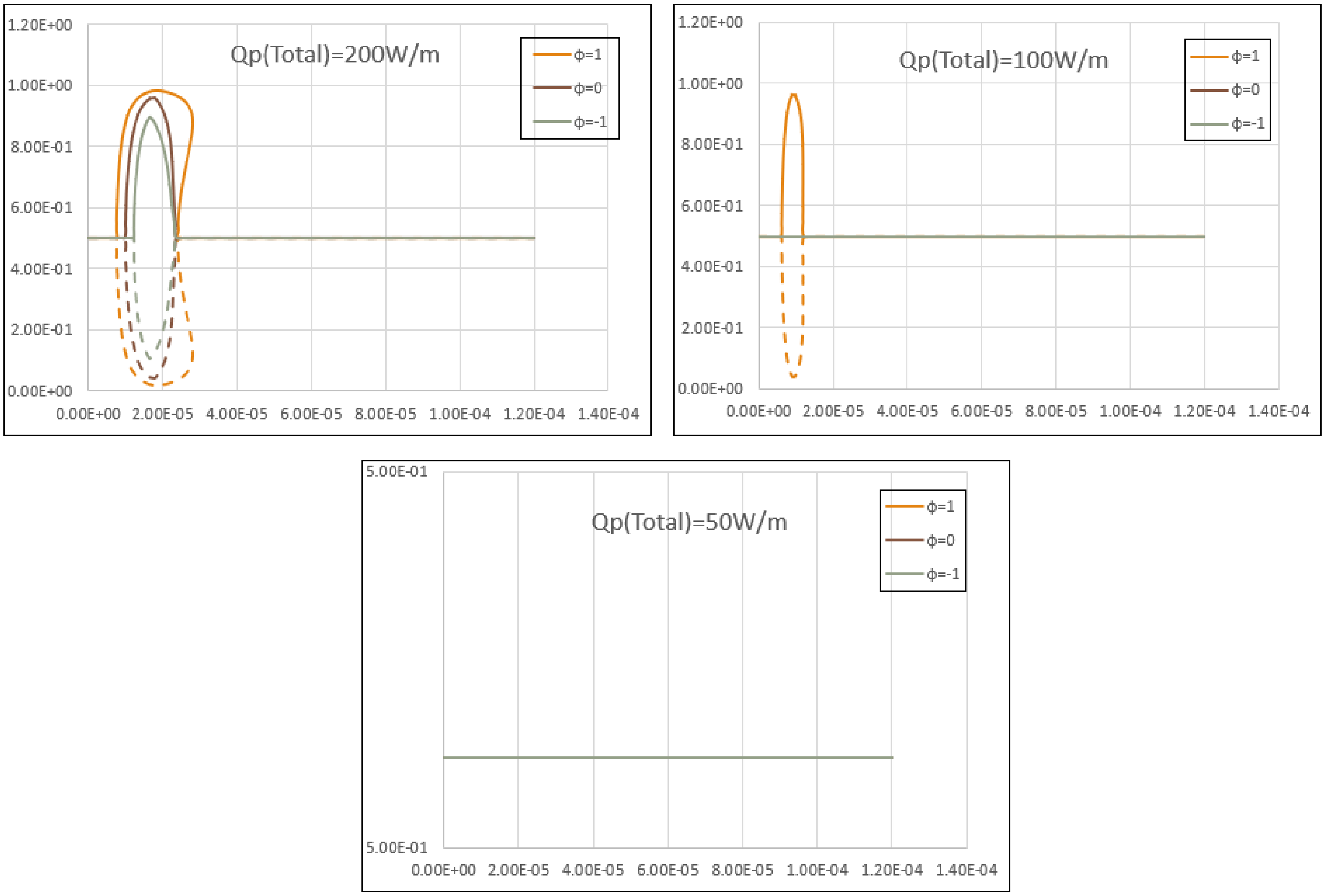

Fig 11: Flow distribution curves of two parallel microchannels with diamond channel walls (k=2200 W/mk) receiving different values of total heat input

As seen in the above flow distribution curves, there is an exception case. When the total heat input is maintained at 200W/m, the extreme downstream flow maldistribution (ϕ =-1) is less severe and has a smaller range compared to the uniform distribution case (ϕ = 0). It must be noted, however, that the use of diamond channel walls for thermal management of electronics in electric vehicles is not a practical engineering solution as diamond microchannels are very expensive for mass manufacturing.

Qp(Total)=50W/m

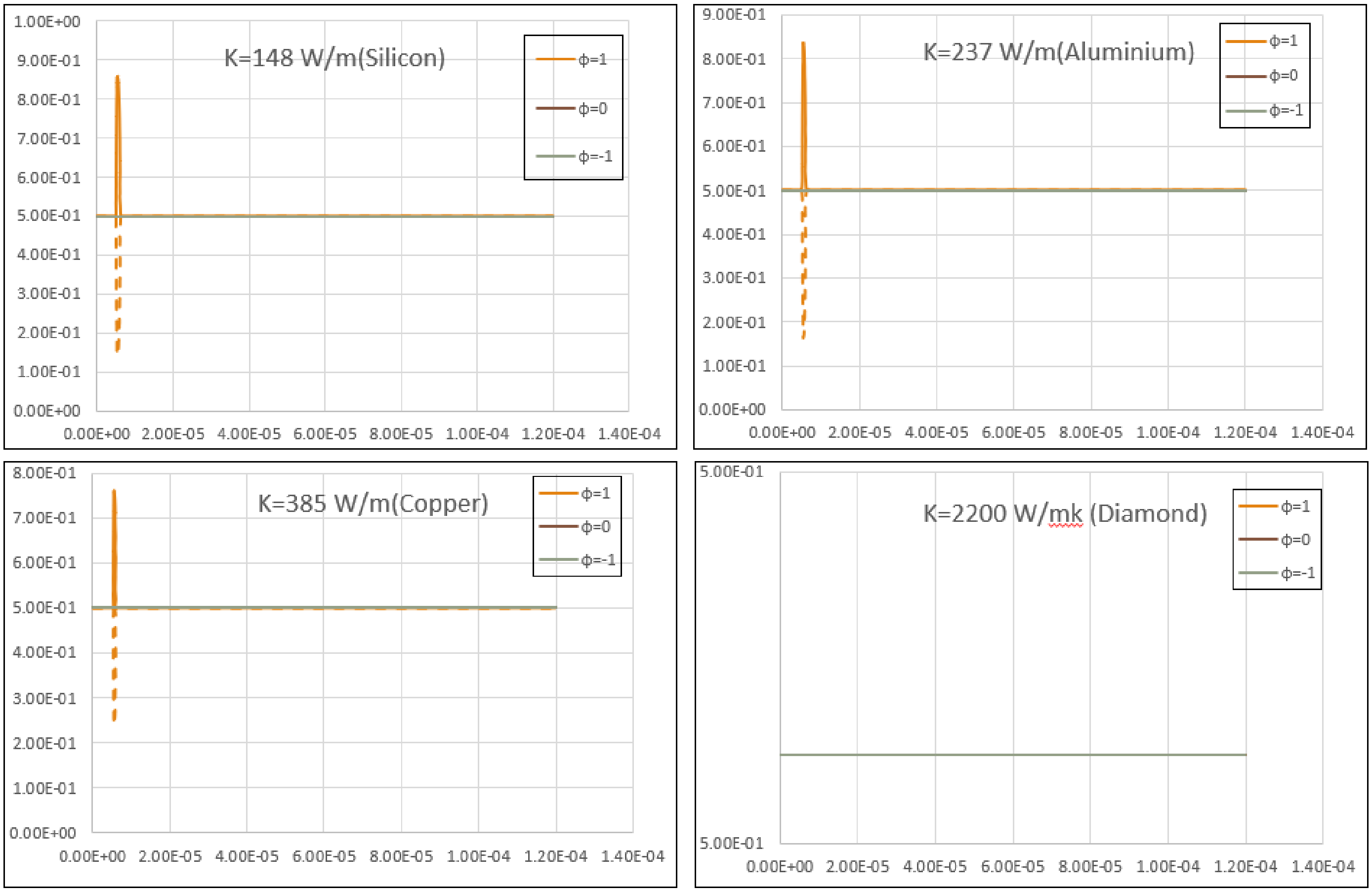

Fig 12: Flow distribution curves of two parallel microchannels with different channel wall material receiving a total heat input of 50 W/m

Based on the flow distribution curves presented above, it can be concluded that the degree of flow maldistribution is comparatively lower for aluminium channel walls as opposed to silicon channel walls. Conversely, copper channel walls exhibit a significantly lower severity of flow maldistribution. In the case of diamond channel wall material, which represents an extreme case, the flow maldistribution is absent. Therefore, it is justifiable to deduce that an increase in channel wall thermal conductivity at a specific heat input value results in a notable reduction in flow maldistribution within the channel as it ensures better heat redistribution within the channel.

In summary, the results of the simulations are given in the figure below:

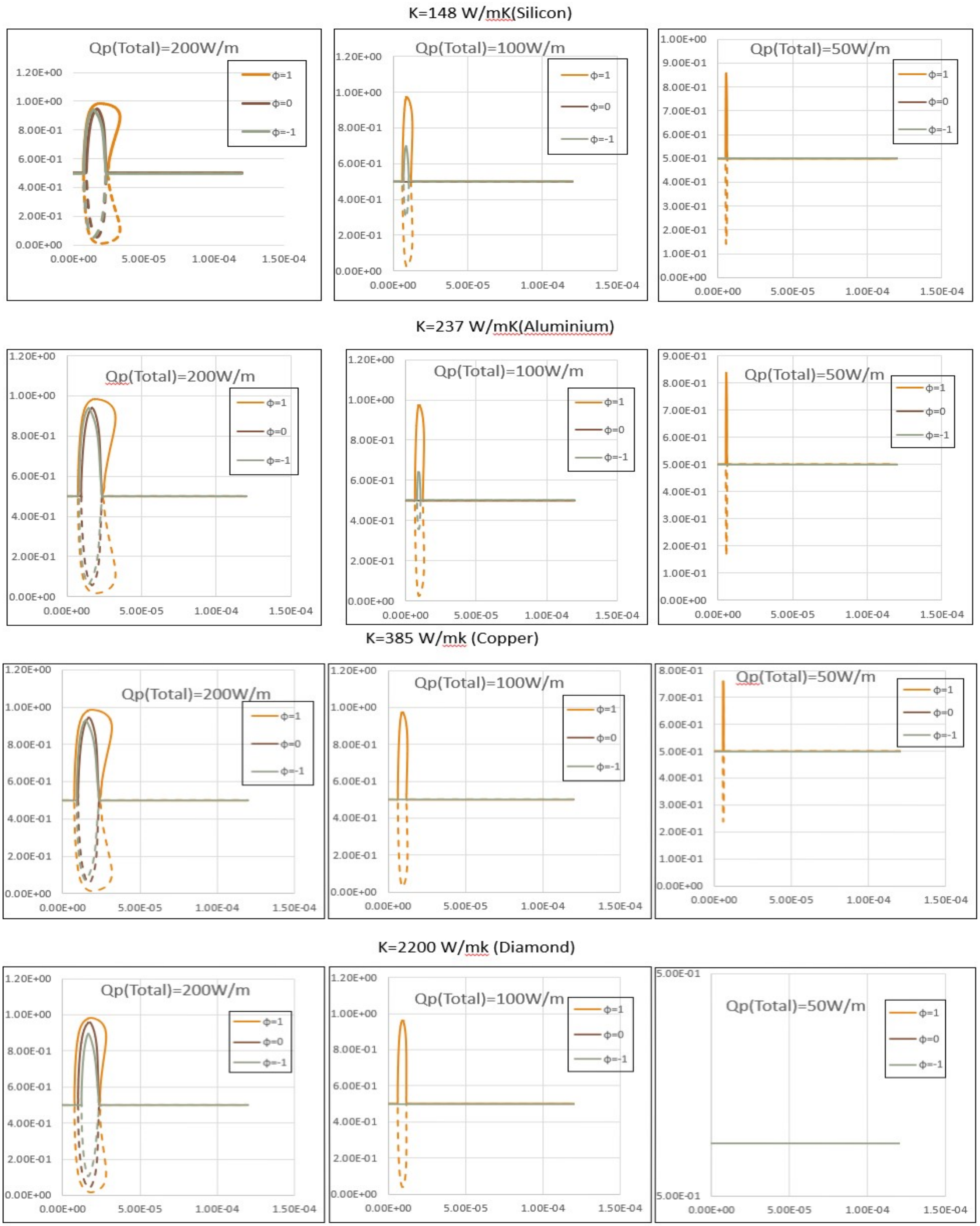

Fig 13: Flow distribution curves of two parallel microchannels with different channel walls receiving different values of total heat input

Chapter 5: Conclusions

The current study aims to analyze the flow distribution characteristics of parallel microchannels subjected to axial non-uniform heating. The quantitative assessment of flow maldistribution in parallel microchannels yielded the following conclusions:

1. The axial non-uniform heating of parallel microchannels typically results in a more severe flow maldistribution in comparison to uniform heating conditions along the length of the channel.
2. The severity of flow maldistribution is higher when the degree of axial non-uniform heating is greater. The flow maldistribution at the extreme upstream case (ϕ=1) is the maximum whereas for the extreme downstream condition (ϕ=-1) it is comparatively less and for the equal heat distribution case (ϕ=0) the flow maldistribution is the least.
3. An increase in channel wall thermal conductivity at a specific heat input value results in a notable reduction in flow maldistribution within the channel as it ensures better heat redistribution within the channel.

Hence, with axial non-uniform heating, we can determine the position of the heat sink with respect to the microchannel and select appropriate channel wall material for better cooling performance thereby ensuring better safety and reliability of the electronic devices present within modern-day electric vehicles.

Chapter 6: Future Scope

The future scope of research in this field is immense, with abundant opportunities for innovation. Following is a list of additional cases that can be simulated for future research in the field of two-phase thermal management of electronics using parallel microchannels.

- Simulations with different channel dimensions having different length width height and thickness.
- Simulations with multiple parallel channels (greater than 2 channels).
- Simulations with different channel profiles.
- Simulations with different boundary conditions with different pressure and temperature.

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