

**A COMPUTATIONAL STUDY OF THERMAL
CHARACTERISTICS OF MICROCHANNEL HEAT SINK
WITH PASSIVE ENHANCEMENT METHODS**

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by

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DEPARTMENT OF APPLIED MECHANICS

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated to
The memory of my Grandparents

CERTIFICATE

This is to certify that the thesis entitled “**A Computational Study of Thermal Characteristics of Microchannel Heat Sink with Passive Enhancement Methods**” being submitted by **Pankaj Srivastava** is the report of bonafide research work carried by him under my supervision. This thesis has been prepared in conformity with the rules and regulations of Indian Institute of Technology Delhi. I further certify that the thesis has attained a standard required for the award of **Doctor of Philosophy** degree of the Institute. The research reported and the results presented in the thesis have not been submitted, in part or full to any other institute or university for the award of any other degree or diploma.

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Pankaj Srivastava

ABSTRACT

Advances in electronic industry and compactness of devices have significantly increased the heat flux density which can lead to the failure of electronic equipment. Therefore, heat flux removal has become increasingly important to maintain temperatures of such devices within the acceptable limits. Microchannel heat sink has a significant potential of large heat removal due to its high heat transfer area to fluid volume ratio, which leads to its high heat transfer coefficient.

A conventional microchannel generally employs rectangular shaped channels in which fluid flows nearly along a straight line. In such microchannels heat transfer performance deteriorates due to a poor fluid mixing as boundary-layers thicken along the flow direction. An improvement in heat transfer is possible by flow disturbance using obstacles in the fluid domain, change in channel shape, and multi-layering of the channel, etc. These passive methods lead to interruptions of boundary-layers and an increased fluid mixing and as a result an enhanced heat transfer. With the advancement in micromachining technology, it is possible to provide various channel shapes with different cross-sections. The present study deals with a computational investigation of flow and heat transfer aspects of microchannels with the combination of various passive enhancement methods. In this study, water is used as the working fluid and heat transfer and flow characteristics are determined under a constant surface heat flux in both laminar and turbulent flow regimes. Convective heat transfer analysis is performed on various configurations of the microchannel and the governing equations are solved using the finite-volume method.

In the present study, a convergent-divergent shaped microchannel has been considered for Re ranging from 120 to 900 and the effect of this shape on flow structures and temperature distributions have been studied using CFD solver ANSYS Fluent 15.0 to evaluate the cooling performance of the considered microchannel against a reported rectangular shaped channel. The primary motivation behind a change in the channel shape is to increase the effective area available for heat transfer and to reduce convective thermal resistance. It is observed that as the liquid flows through a convergent-divergent shape, it is accelerated and redirected towards the constant cross-section segment followed by the formation of vortex in the divergent segment depending on the value of Re and divergence angle. A good agreement is observed with the reported experimental results. The results showed that Nu increases and thermal resistance reduces up to 20% over the range of Re considered.

Further ribs and cavities have been used with the convergent-divergent shaped microchannel in laminar flow condition and thermal characteristics are studied in detail. When ribs and cavities are included, the streamlines deflect to the cavity causing a stagnation zone. Fluid is again accelerated when passing over the ribs and the maximum velocity occurs. A combined effect of ribs and cavities produces jetting and throttling effects. Besides this behaviour, an increase in heat transfer area owing to the presence of ribs and cavities leads to heat transfer enhancement. The present results show that the ribs and cavities can reduce the overall thermal resistance up to 40% and make the bottom surface temperature quite uniform. The results also show that increasing Re leads to an enhanced heat transfer in terms of an increased Nusselt number. In another study where convergent-divergent shaped microchannel with bifurcation is considered, the flow is split into multiple flow streams leading to interruption and restart of boundary-layer resulting in an enhanced fluid mixing. It is observed that the heated surface temperature follows a rising and then falling trend and the substrate temperature was quite uniform along the flow direction. Furthermore, it is shown that increasing Re leads to thinning of thermal boundary-layers resulting in an enhanced heat transfer in terms of an increased average Nusselt number from 38% to 74%.

Turbulent heat transfer characteristics in a microchannel have also been carried out to investigate the effect of higher flow rates on thermal characteristics. The study aims at highlighting the abilities of higher flow rates with flow disruption methods for a relatively high heat transfer while keeping the pressure drop within an acceptable range. Further the suitability of SST $k-\omega$ and standard $k-\epsilon$ turbulence models has been analysed based on the reported mathematical correlation and a suitable turbulence model has been used to compute the flow field, pressure and temperature distributions. In the present study on the effects of the convergent-divergent shape with ribs and cavities on turbulent thermal characteristics using the SST $k-\omega$ turbulence model, a quite low thermal resistance of $0.03 \text{ K.cm}^2/\text{W}$ has been achieved. It is further observed that when a convergent-divergent shape microchannel with bifurcation is used, the investigation shows that the average Nusselt number increases up to 1.41 times with an increase in the flow rate. Further in the case of the convergent-divergent shaped microchannel with bifurcation lower and smaller variations in the heated surface temperature are observed which are essential for an effective electronic cooling. However, such design of microchannel loses its heat transfer effectiveness due to a high pumping power for high values of Re .

In a single-layer microchannel, the coolant flows in one direction and therefore the coolant temperature increases along the channel length. This behaviour results in deterioration in the

temperature distribution uniformity leading to the development of thermal stresses and overheating. Multi-layering of microchannel reduces the undesired temperature variation along the channel length as the bottom channel is cooled by the top channel. In the present study, flow and thermal characteristics of a double-layered microchannel with bifurcation have been investigated using a FVM based open-source package OpenFOAM 3.0.0 for Re ranging from 50 to 900. The flow structures and temperature distributions are compared for parallel and counter-flow layouts and the effects of bifurcation plate on the overall thermal performance are also analyzed and compared with that of a single-layered microchannel with bifurcation reported in the literature. It is observed that the double-layer microchannel with bifurcation provides the best performance in terms of a low thermal resistance and it decreases up to 40% over the range of Re considered. The double-layer microchannel with bifurcation also provides the lowest substrate temperature along the channel length than the corresponding non-bifurcated microchannel. However, the counter-flow layout provides a more uniform bottom surface temperature which is essential to reduce thermal stresses in the substrate. Additionally, thermal enhancement factor which is defined as the ratio of the heat transfer coefficient of the designed configuration to that of rectangular channel is obtained for all the cases considered.

सारांश

विगत कुछ वर्षों में इलेक्ट्रॉनिक उद्योग में हुई प्रगति और उपकरणों के छोटे आकार के कारण ऊष्मीय फ्लक्स में अत्यधिक वृद्धि हुई है, जो कि इलेक्ट्रॉनिक उपकरणों की विफलता का प्रमुख कारण है। इसलिए ऐसे उपकरणों के तापमान को स्वीकार्य सीमा में बनाए रखने के लिए ऊष्मा का तेजी से संचरण अति आवश्यक हो गया है। माइक्रोचैनल हीट सिंक में उच्च ऊष्मीय संचरण की एक महत्वपूर्ण क्षमता होती है क्योंकि इसके ऊष्मीय संचरण क्षेत्रफल एवं द्रव मात्रा का अनुपात अधिक होता है, जिससे इसका ऊष्मीय संचरण गुणांक बढ़ जाता है।

एक पारंपरिक माइक्रोचैनल आम तौर पर आयताकार आकार के चैनलों को नियोजित करता है जिसमें द्रव लगभग एक सीधी रेखा में बहता है। ऐसे माइक्रोचैनल में गर्म और ठंडे द्रव के उचित मिश्रण न होने एवं प्रवाह की दिशा के साथ बाउंड्री लेयर के विकसित हो जाने के कारण ऊष्मीय संचरण की क्षमता का ह्रास होने लगता है। इन परिस्थितियों में चैनल के अंदर द्रव के प्रवाह को बाधित करके, चैनल के आकार में परिवर्तन करके और बहु स्तरीय माइक्रोचैनल का उपयोग करके ऊष्मीय संचरण में सुधार किया जा सकता है। आजकल माइक्रोमशीनिंग तकनीक में प्रगति के कारण विभिन्न क्रॉस-सेक्शन के साथ साथ चैनल के विभिन्न आकार को भी बनाना संभव हो सका है। इन निष्क्रिय विधियों से बाउंड्री लेयर के विकसित होने में रुकावट आती है और साथ ही गर्म और ठंडे द्रव के मिश्रण में भी वृद्धि होती है जिसके परिणामस्वरूप ऊष्मीय संचरण की क्षमता बढ़ जाती है।

वर्तमान अध्ययन, विभिन्न निष्क्रिय विधियों के संयोजन के साथ माइक्रोचैनल के प्रवाह और ऊष्मीय संचरण के पहलुओं की एक अभिकलनात्मक जांच से संबंधित है। इस अध्ययन में, विआयनीकृत आसुत जल का उपयोग कार्यशील तरल पदार्थ के रूप में किया गया है और ऊष्मीय संचरण और द्रव प्रवाह की विशेषताओं को लेमिनार और टर्बुलेंट प्रवाह व्यवस्था दोनों में एक निरंतर सतह ताप प्रवाह के तहत विश्लेषण किया गया है। इस अध्ययन में माइक्रोचैनल के विभिन्न विन्यासों के संवहनी ऊष्मीय संचरण का विश्लेषण किया गया है और गवर्निंग समीकरणों को परिमित मात्रा विधि (FVM) का उपयोग करके हल किया गया है।

वर्तमान अध्ययन में, रेनॉल्ड्स नम्बर 120 से 900 तक के विश्लेषण के लिए एक अभिसारी-अपसारी आकार के माइक्रोचैनल का उपयोग किया गया है और प्रवाह संरचना तथा तापमान वितरण पर इस आकार के प्रभाव का अध्ययन CFD सॉल्वर ANSYS Fluent 15.0 और OpenFOAM 3.0.0 का उपयोग करके किया गया है। इस माइक्रोचैनल के शीतलन का मूल्यांकन, लिटरेचर में रिपोर्टेड आयताकार आकार के चैनल के प्रयोगात्मक परिणाम से तुलना करके किया गया है। चैनल के आकार में बदलाव के पीछे प्राथमिक उद्देश्य ऊष्मीय संचरण के प्रभावी क्षेत्र को बढ़ाना और साथ ही साथ ऊष्मीय प्रतिरोध को कम करना है। अध्ययन में यह देखा गया है कि जैसे ही तरल पदार्थ एक अभिसारी-अपसारी आकार के चैनल से बहता है तो द्रव प्रवाह अभिसारी क्षेत्र में त्वरित गति से होता है और नियत क्रॉस-सेक्शन क्षेत्र में पुनर्निर्देशित हो जाता है। वर्तमान प्रवाह और ऊष्मीय संचरण के परिणाम एवं लिटरेचर में रिपोर्टेड प्रयोगात्मक परिणामों में एक अच्छी सहमति पाई गई है। वर्तमान परिणाम बताते हैं कि अभिसारी-अपसारी आकार के माइक्रोचैनल का नसल्ट नम्बर, रेनॉल्ड्स नम्बर के बढ़ने के साथ बढ़ता है और ऊष्मीय प्रतिरोध रेनॉल्ड्स नम्बर के बढ़ने के साथ लगभग 20% तक कम हो जाता है।

एक अन्य अध्ययन में अभिसारी-अपसारी आकार के माइक्रोचैनल के साथ रिब्स एवं केविटीज का उपयोग करके प्रवाह की स्थिति और तापीय विशेषताओं का लेमिनार प्रवाह में अध्ययन विस्तार से किया गया है। जैसे ही रिब्स एवं केविटीज को माइक्रोचैनल में सम्मिलित किया जाता है, तो द्रव प्रवाह केविटी की तरफ विक्षेपित हो जाता है जिससे केविटी में द्रव का ठहराव उत्पन्न होता है और रिब्स के ऊपर से गुजरने पर द्रव का प्रवाह फिर से तेज हो जाता है जहाँ पर इसका वेग अधिकतम होता है। रिब्स एवं केविटीज के संयुक्त प्रभाव से जेटिंग और थ्रॉटलिंग प्रभाव पैदा होता है। इस प्रभाव के अलावा, रिब्स एवं केविटीज के कारण ऊष्मीय संचरण क्षेत्र में भी वृद्धि होने से ऊष्मीय संचरण में और ज्यादा वृद्धि हो जाती है। वर्तमान परिणाम बताते हैं कि रिब्स एवं केविटीज, ऊष्मीय प्रतिरोध को लगभग 40% तक कम कर सकते हैं और सबस्ट्रेट के तापमान को काफी समान बना सकते हैं। परिणाम यह भी दिखाते हैं कि रेनॉल्ड्स नम्बर के बढ़ने से ऊष्मीय संचरण में वृद्धि होती है जो कि बड़ी हुई नसल्ट नम्बर के रूप में देखी जा सकती है।

एक अन्य अध्ययन में जहाँ पर अभिसारी-अपसारी माइक्रोचैनल के अंदर बाईफरकेसन (विभाजक) प्लेट का उपयोग किया गया है जिसके कारण प्रवाह कई धाराओं में विभाजित हो जाता है जिससे बाउंड्री लेयर के विकसित होने में रुकावट उत्पन्न होती है और फिर नई बाउंड्री लेयर बनने लगती है जिसके परिणामस्वरूप गर्म और ठंडे द्रव के मिश्रण में काफी वृद्धि हो जाती है। विश्लेषण में यह देखा गया है कि सबस्ट्रेट सतह का तापमान बढ़ने और गिरने की प्रवृत्ति का बारम्बार अनुसरण होता है और प्रवाह की दिशा के साथ सबस्ट्रेट के तापमान में भी काफी एकरूपता भी आ जाती है। परिणाम यह भी दिखाते हैं कि रेनॉल्ड्स नम्बर के बढ़ने से बाउंड्री लेयर पतली हो जाती है, जिसके परिणामस्वरूप नसल्ट नम्बर 38% से 74% तक बढ़ जाती है।

ऊष्मीय विशेषताओं पर उच्च प्रवाह दर के प्रभाव की जांच के लिए एक माइक्रोचैनल में टर्बुलेंट प्रवाह व्यवस्था के तहत ऊष्मीय संचरण के लक्षणों का भी अध्ययन किया गया है। इस अध्ययन का उद्देश्य एक स्वीकार्य सीमा के भीतर प्रेशर ड्रॉप को बनाए रखते हुए अपेक्षाकृत उच्च ऊष्मीय संचरण के लिए प्रवाह व्यवधान विधियों के साथ उच्च प्रवाह दर की क्षमताओं को उजागर करना है। इसके अलावा *SST k- ω* और *Standard k- ϵ* टर्बुलेंस मॉडल की उपयुक्तता का विश्लेषण गणितीय सहसंबंध के आधार पर किया गया है और प्रवाह क्षेत्र, दबाव और तापमान वितरण की गणना करने के लिए उपयुक्त टर्बुलेंस मॉडल का उपयोग किया गया है। *SST k- ω* टर्बुलेंस मॉडल का उपयोग करते हुए टर्बुलेंस ऊष्मीय विशेषताओं पर रिब्स एवं केविटीज के साथ अभिसारी-अपसारी आकार के प्रभावों पर अध्ययन किया गया है जिससे काफी कम ऊष्मीय प्रतिरोध लगभग $0.03 \text{ k.cm}^2/\text{W}$ हासिल किया गया है। आगे यह भी देखा गया है कि जब द्विभाजन के साथ एक अभिसारी-अपसारी आकार के माइक्रोचैनल का उपयोग किया जाता है, तो प्रवाह दर में वृद्धि के साथ नसल्ट नम्बर भी 1.41 गुना तक बढ़ जाती है। इसके अलावा, सबस्ट्रेट के तापमान में भी कमी आती है और साथ ही इसके तापमान वितरण में भी एकरूपता आती है जो एक प्रभावी इलेक्ट्रॉनिक शीतलन के लिए आवश्यक है। हालांकि, माइक्रोचैनल का ऐसा डिज़ाइन अपेक्षाकृत उच्च प्रवाह दर पर अपनी प्रभावशीलता खो देता है क्योंकि इसके लिए उच्च पंपिंग शक्ति की आवश्यकता होती है।

सिंगल-लेयर माइक्रोचैनल में, द्रव एक दिशा में बहता है और इसलिए द्रव का तापमान प्रवाह की दिशा के साथ बढ़ता है। इस व्यवहार के परिणामस्वरूप तापमान वितरण के एकरूपता में गिरावट आती है जिससे थर्मल स्ट्रेस और ओवरहीटिंग उत्पन्न हो जाता है। बहुस्तरीय माइक्रोचैनल प्रवाह की दिशा के साथ अवांछित तापमान भिन्नता को कम

करता है क्योंकि निचला चैनल शीर्ष चैनल द्वारा ठंडा किया जाता है। वर्तमान अध्ययन में, द्वि-स्तरीय माइक्रोचैनल के प्रवाह और ऊष्मीय विशेषताओं की जांच रेनॉल्ड्स नम्बर 50 से 900 तक के लिए एक FVM आधारित ओपन-सोर्स पैकेज *OpenFOAM 3.0.0* का उपयोग करके की गई है। प्रवाह संरचनाओं और तापमान वितरण की तुलना समानांतर और काउंटर फ्लो के लिए किया गया है। इन प्रवाह व्यवस्था और समग्र ऊष्मीय निष्पादन पर द्विभाजन प्लेट के प्रभावों का भी विश्लेषण किया गया है और साथ में लिटरेचर में रिपोर्ट किए गए द्विभाजन के साथ एकल-स्तरित माइक्रोचैनल के साथ तुलना भी की गई है। अध्ययन में, यह देखा गया है कि द्विभाजन के साथ द्वि-स्तरीय माइक्रोचैनल कम तापीय प्रतिरोध के मामले में सबसे अच्छा प्रदर्शन करता है और यह ऊष्मीय प्रतिरोध प्रयुक्त रेनॉल्ड्स नम्बर रेंज में लगभग 40% तक कम हो जाता है द्विभाजित द्वि-स्तरीय माइक्रोचैनल गैर- विभाजित माइक्रोचैनल की तुलना में सबसे कम सब्सट्रेट तापमान प्रदान करता है। हालांकि, काउंटर-फ्लो व्यवस्था में सब्सट्रेट के तापमान वितरण में अधिक एकरूपता होती है जो कि सब्सट्रेट में थर्मल तनाव को कम करने के लिए आवश्यक है। इसके अतिरिक्त, ऊष्मीय वृद्धि कारक जो कि डिज़ाइन किए गए माइक्रो चैनल और आयताकार चैनल के ऊष्मा संचरण गुणांक के अनुपात के रूप में परिभाषित किया जाता है, इसका भी विस्तृत अध्ययन इस थिसिस में किया गया है।

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NOMENCLATURE

L = length, mm

W = width, mm

H = height, mm

p = pressure, Pa

P = pumping power, W

q = wall heat flux, W/m^2

Q = total power generated by the chip, W

D_h = hydraulic diameter, mm

Kn = Knudsen number

M = Conduction number

Br = Brickman number

Po = Poiseuille number

f = fanning friction factor

k = turbulent kinetic energy

R = overall thermal resistance, $K.cm^2/W$

Re = Reynolds number

Pr = Prandtl number

Nu = Nusselt number

T = temperature, K

R = thermal resistance

C_p = specific heat capacity, $kJ/kg K$

h = heat transfer coefficient, W/m^2K

k = thermal conductivity, W/mK

Greek Symbols

Δp = pressure drop, Pa

ρ = density, kg/m^3

μ = dynamic viscosity, Ns/m^2

Δ = gradient

$\dot{\omega}$ = specific dissipation rate

ε = dissipation rate

η = Thermal enhancement factor

Subscripts

w = wall

in = inlet

out = outlet

max = maximum

s = solid

f = fluid