Enhancing controllability of forced convection cooling with minichannel heatsinks using pulsating flow of variable frequency

Galina Kennedy
Dept. Mechanical, Manufacturing & Biomedical Engineering
Trinity College Dublin
Dublin, Ireland
kennedga@tcd.ie

Tim Persoons
Dept. Mechanical, Manufacturing & Biomedical Engineering
Trinity College Dublin
Dublin, Ireland
persoont@tcd.ie

***Abstract*—This study investigates the effect of the introduction of sinusoidal pulsatile waveforms of varying frequency to laminar flow on heat transfer. Experimental investigations were conducted with a constant pulsation amplitude of 1 mm across a range of flow rates and pulsation frequencies. Results demonstrate a significant enhancement in heat transfer,ranging from 5% to 51%, increasing with both pulsation frequency and flow rate, relative to steady state conditions at equivalent flow rates. The maximum enhancement was observed at a flow rate equivalent to a steady state Reynolds number Re = 50 and a pulsation frequency of 2.0Hz (Wo = 8.2). A predictive correlation was developed to estimate heat transfer enhancement based on steady-state and pulsating Reynolds numbers. The model yielded a strong correlation (R^2 = 0.93) with experimental data, confirming its predictive capability. Beyond heat transfer performance, the study also revealed the potential of pulsatile flow as a cooling control strategy. For a certain defined power dissipation and flow rate, junction temperature rise (ΔT_j) decreased with increasing pulsation frequency, while coolant temperature rise (ΔT_c) remained largely unaffected. This indicates improved cooling efficiency through pulsatile flow. Notably, cooling performance achieved under high steady-state flow conditions could be replicated at lower flow rates by introducing pulsation, with further efficiency gains observed at higher pulsation frequencies. The findings of this study indicate a clear possibility as to all for more effective extraction of high grade waste heat from systems with varying heat load.**

NOMENCLATURE

Acronyms

DC	Data Centre	
Greek Symbols		
α	Aspect ratio	$-$
μ	Dynamic viscosity	Ns/m^2
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
τ	Shear stress	N/m^2
Roman Letters		
A	Area	m^2
a	Amplitude	m
A_{piston}	Piston cross-sectional area	m^2
D	Diameter	m
d_h	Minichannel hydraulic diameter	m
f	Frequency	Hz
H	Minichannel height	m
k	Thermal conductivity	W/mK
L	Minichannel length	m
N	Number of fins	$-$
Nu	Nusselt number	$-$
q	Heat flux	W/m^2
Re	Reynolds number	$-$
T	Temperature	K
U	Velocity	m/s
V	Volumetric flow rate	m^3/s
w	Minichannel width	m
Wo	Womersley number	$-$
x_{pp}	Peak-to-Peak amplitude	m

I. INTRODUCTION

In the hyper-connected world of today, data, information, and knowledge have become a crucial asset in almost every enterprise, with high-quality data being essential to the prosperity of some of the world's most valued business. In the contemporary digital era, vital business decisions made based on insights derived from data can significantly affect the value and success of a business. Therefore, as a result, data centres are now at the epicentre of modern digital infrastructure, allowing for the processing, storage, and distribution of large volumes of information and data [1]–[3]. However, the increased reliance on data centres in recent years has led to a significant increase in the proportional contribution of data centres to global emissions, with DCs contribution to approximately 1% of global emissions in 2023, primarily due to the significant amount of water usage, as well as the substantial amount of waste heat produced during cooling. The surge in the global dependency on data centres has also led to a significant strain on the global electricity supply, with data centre contributing to approximately 1.5% of the global electricity usage in 2023. This is predicted to increase to 4% by 2030 due to the explosive interest in AI leading to more high-density DCs [4]–[7].

The escalating energy demands and environmental impact of data centres have led to a growing imperative for innovative strategies to mitigate their contribution to climate change. One proposed approach involves the utilisation of waste heat generated by data centre operations as a low-cost heat source for adjacent residential and industrial sectors. However, current thermal management technologies for high-performance computing systems are not adequately equipped to support efficient and sustainable waste heat recovery. As a result, the development of advanced cooling solutions has become a central focus of modern research in the field, with increasing attention directed towards enhancing reliability, thermal efficiency, and energy reuse potential [8].

Therefore, this paper aims to address the growing pressure on energy infrastructure and supply, as well as the negative environmental impact associated with data centres, by enhancing the potential for chip-level control of cooling efficiency within these facilities. The long-term objective of this study is to improve the controllability of direct-to-chip minichannel heat sink cooling systems in order to adapt to varying heat loads and maintain elevated outlet coolant temperatures. This, in turn, facilitates more effective waste heat recouperation from data centre operations.

When considering advancements in cooling technologies, and the improvement of thermal performance, the primary challenge is the augmentation of heat transfer within single-phase liquid flow. Therefore, in recent years there has been significant research done to attempt to improve heat transfer through the use of various techniques, with the primary methods being focused in two primary categories, being passive and active methods. The primary passive methods that have seen significant improvements in heat transfer are the introduction of baffles to channels containing laminar flow [9] [10], as well as the use of serpentine channels [11]–[13]. However, though significant improvements were seen with the use of passive methods, it is the active methods that have seem far superior improvements in heat transfer, with the active method of the introduction of pulsating waveforms showing the most substantial promise [14]–[18].

This study expands upon a previous study which investigates the effect of the introduction of pulsatile flow with sinusoidal waveforms to a commercially available rectangular parallel minichannel heatsink [19]. The experimental study outlined in this paper examines the effect of sinusoidal waveforms of variable frequency on heat transfer performance within the minichannel heat sink by way of investigating changes in the temperature delta between the average wall temperature and inlet temperature of the microchannel heat sink when a sinusoidal waveform is superimposed on a steady developing laminar flow using a pulsation actuator.

II. Methodology

A. Minichannel heat sink and flow loop

The reference minichannel heatsink contains N = 28 channels of rectangular cross-section with dimensions of H = 2.5mm, w = 1.77mm, and heatsink length of l = 17.5mm , corresponding to a hydraulic diameter of approx. 2mm, and a nickel electroplated high purity copper base. The inlet and outlet orifices are located perpendicular to the channels. The heatsink is bonded by means of Artic Silver ®5 thermal paste to a copper block with two embedded cartridge heaters which achieve a maximum heating power of 45W.

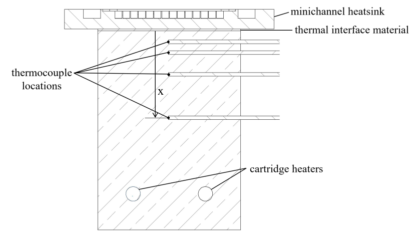

Fig. 1. Experimental test section including the heated copper block with thermocouple locations

The copper block temperature is measured using four sheathed T-type thermocouples placed at defined distances from the heated surface of the block and inserted 20mm into the block. A 0.55mm bond line thickness between the heat sink base and copper heater block is maintained through the use of a clamp with spacers around the circumference of the heated copper block which provides even pressure to each edge of the heatsink, thus forming a rigid structure.

The experimental facility used to conduct the experiments within this study consisted of a closed-loop system in which a Micropump GA-T23-DB380B DC magnetic drive motor was set up in series with the flow providing the working fluid, deionised water at atmospheric pressure, throughout the system. The working fluid is maintained at room temperature

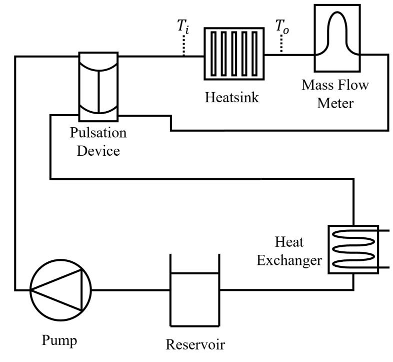

Fig. 2. Minichannel heat sink experimental facility with inline pulsating flow device

within a reservoir by means of a fan-cooled liquid-to-air heat exchanger. A vacuum pump was also integrated into the system as to remove air bubbles and dissolved gas from the working fluid. The flow is characterised by the dimensionless Reynolds number ($Re_s = \frac{\rho U_s d_h}{\mu}$), which in turn is dependant on the steady state velocity component U_s ($U_s = \frac{V}{wHN}$), and the hydraulic diameter $d_h = \frac{2wH}{w+H}$.

The closed-loop flow system contains a Bronkhorst M15 mini CORI-FLOW mass flow meter which has a maximum allowed flow rate of 300 kg/h with an accuracy of ±0.2% for liquid. Two T-type thermocouples located in series with the flow before and after the test section to measure the respective inlet and outlet temperatures. All thermocouples are calibrated using an isothermal bath across a range of 20-60°C with an ASL F100 precision thermometer temperature probe, with an accuracy of ±0.02°C across its full range, used for a reference temperature.

B. Pulsation device

The pulsating velocity components of the experiments within this study are generated using an inline pulsator device with adjustable frequency and amplitude as seen in figure 3. The pulsator consists of a miniature membrane pump with two pumping chambers generating pulsations of opposite phase (b), with the flow entering each chamber (a) from the gear pump and mass flow meter respectively, as seen in figure 2. The pulsations are generated by a piston with an area of 38mm, which is driven by a central DC motor (c). The frequency of the pulsations is defined by the voltage supplied to the DC motor and recorded using an encoder. The operating range of the pulsation device covers 0.5 and 2Hz. The peak-to-peak amplitude of the pulsations is adjusted using two opposing set screws, with the maximum range being between 0.2 and 1.5mm.

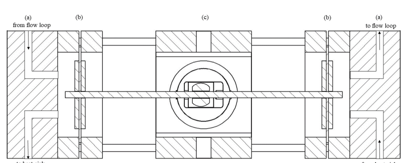

Fig. 3. Pulsation Device for generating pulsating flow component with adjustable amplitude and frequency

The pulsating channel flow is characterised by a dimensionless pulsating Reynolds number ($Re_p = \frac{\rho U_p d_h}{\mu}$), where U_p is the peak fluctuating velocity ($U_p = \frac{\pi f A_{piston} x_{app}}{wHN}$) which is dependant on the piston area, and the pulsation amplitude and frequency, and the Womersley number as the dimensionless frequency, which describes the relationship between transient pulsatile forces and viscous forces and is defined by the equation $Wo = \frac{d_h}{2}\sqrt{\frac{2\pi f}{\nu}}$, where f is the frequency, and ν is the kinematic viscosity.
The Nusselt number $Nu = \frac{h d_h}{k}$, where h is the thermal coefficient, is calculated using the log mean temperature difference (LMTD) which is the eqivalent average temperature difference to describe convective heat transfer from an isothermal wall and is defined by the equation

$$LMTD = \frac{T_o - T_i}{ln(\frac{T_w - T_i}{T_w - T_o})} \qquad (1)$$

which in turn, is dependant on the wall temperature calculated from the total thermal resistance ($R_{\theta_T} = \frac{LMTD}{Q}$), which is calculated using an extrapolation of the 4 temperatures recorded at defined points within the heated copper block.
A number of permutations for pulsator amplitude (within the range of 0.5 – 1.0mm peak-to-peak), frequency (within the range of 0.5-2.0Hz), corresponding to a Womersley number between approx. 4.1 and 8.2 for a channel aspect ratio of approx. 1.5.

C. Experimental Procedure

For all experiments conducted in this investigation, a labview program was created to allow for the simulation of different stages consisting of defined parameters which would switch automatically between stages depending on a defined time limit. Therefore, for each experimental investigation, the power dissipation, flow rate, and frequency was defined for each stage, which were then recorded, along with all other desired parameters for the entire experiment, showing clearly when each stage reached thermal equilibrium.

1) Steady State: The experiments in the steady state stage of the study were conducted in the flow loop without operating the pulsation device. For each experiment, the flow rate is set to the desired flow rate measurement to be investigated, which in this study, were a low, mid, mid-high, and high flow rate corresponding to an equivalent steady state reynolds number of Re = 10, 30, 35, and 50 respectively, with the power dissipation of the copper block being defined, which in the case of this study was an idle, mid, and high power value corresponding to 10, 25, and 50W respectively. For each stage of a certain experiment, the flow rate and power dissipation was defined and the stage was ran, with all significant data being recorded, for approximately 60mins as to allow the system to reach a state of thermal equilibrium. The Nusselt number is then calculated using the log mean temperature difference, which in turn, is dependant on the wall temperature calculated from the total thermal resistance, which is calculated using an extrapolation of the 4 temperatures recorded at defined points within the heated copper block. The resulting plot as seen in figure can then be used to create a power law correlation which can be used to calculate the predicted enhancement for the respective steady state Reynolds number investigated.

2) Pulsation State: The pulsating velocity component of the experiments within this study are generated using an inline pulsator device with adjustable frequency and amplitude. The pulsator consists of a miniature membrane pump with two pumping chambers generating pulsations of opposite phase. The pulsations are generated by a piston which is driven by a DC motor. The operating range of the pulsator covers frequencies between 0 and 100Hz, with a maximum peak-to-peak pulsation amplitude of 5mm per stroke. The pulsating channel flow is characterised by a dimensionless pulsating

Reynolds number (Re_p). A number of permutations for frequency (within the range of 0.5 - 2.0 Hz), corresponding to a Womersley number between approx. 4.1 and 8.2 for a channel aspect ratio of approx. 1.5.

The repeatability of these experimental investigations has been verified by retesting a number of permutations for flow rate, and amplitude a number of days apart and achieving almost identical results. For all experimental investigations the 95% uncertainty for δNu was calculated, with the uncertainty for δNu being calculated to be 6.5-12.5% for all permutations investigated.

III. Results

A. Heat Transfer Enhancement

The experimental results for the pulsating flow state of each investigation are presented as a percentage enhancement of heat transfer, defined as an enhancement in Nusselt number with pulsating flow in comparison with the predicted Nusselt number enhancement for steady state at the same steady state Reynolds number, defined by the equation

$$\delta Nu = \frac{Nu_p - Nu_s}{Nu_s} \tag{2}$$

Where Nu_s is the steady state Nusselt number of the steady state experiment with the equivalent conditions for flow rate and power dissipation.

Figure 4 below shows the percentage enhancement as a function of pulsation frequency, for a range of frequency of $0.5Hz < f < 2.0Hz$ in intervals of 0.5Hz.

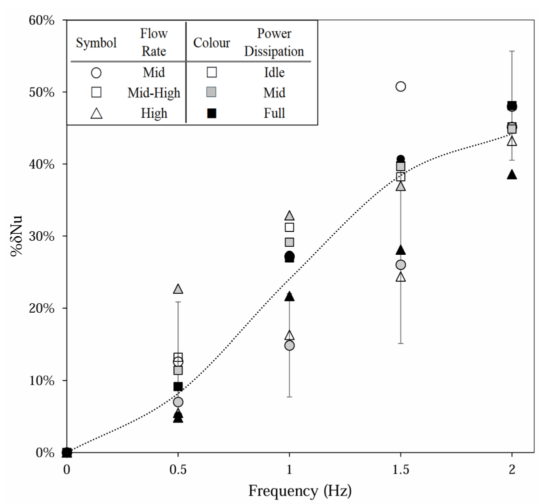

Fig. 4. Nusselt number enhancement δNu expressed as a percentage (δNu x 100%) as a function of pulsation frequency (Hz). Each marker represents the respective flow rate and power dissipation for each data point

As seen from figure 4 above, the results of the experimental study showed that for all flow rate and power dissipation values investigated, there is a clear trend showing an increase in Nusselt number enhancement with an increase in frequency.

B. Correlation

Following from the heat transfer results as seen in section III-A, a prediction correlation was developed as to predict the heat transfer enhancement from known values for Steady State Reynolds number (Re_s) & Pulsating Reynolds number (Re_p), in the form of a correlation equation as seen below:

$$\Delta Nu_p = aRe_p^{m1} Re_s^{m2}$$

A GRG Nonlinear solving model was used to solve for the most optimum values for a, m1, and m2. The resulting correlation is shown as:

$$\Delta Nu_p = 0.017 Re_p^{0.804} Re_s^{-0.439} \tag{3}$$

This correlation results in an R^2 value of 0.93 showing an almost perfectly linear correlation between the real and the predicted heat transfer enhancement values. This is demonstrated in the graph in figure 5.

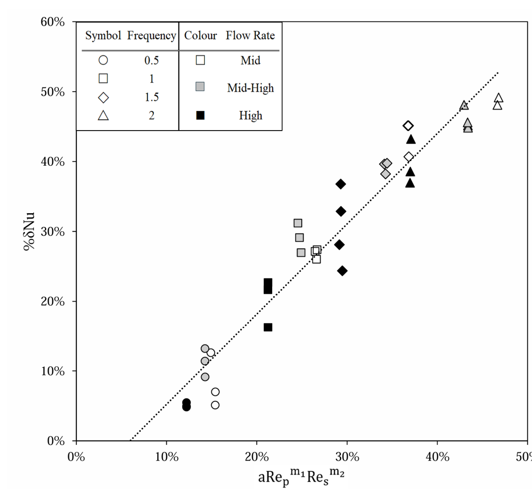

Fig. 5. Nusselt number enhancement δNu expressed as a percentage (δNu x 100%) as a function of the prediction correlation formula in terms of Re_p & Re_s as seen in equation 3. Each marker represents the respective frequency and flow rate for each data point

The graph shown in figure 5 above shows the strong positive linear correlation between the predicted values for the actual measured Nusselt number enhancement values and the Nusselt number enhancement using the correlation equation, where a = 0.017, m_1 = 0.804 & m_2 = -0.439.

C. Control Method

As mentioned previously, the primary goal of this study was to assess the potential of the introduction of sinusoidal waveforms to laminar flow as a method of controlling the cooling effectiveness of a parallel rectangular minichannel heatsink. In order to achieve this, different permutations for flow rate, power dissipation, and pulsation frequency were tested as to attempt to see an improvement in cooling efficiency. The Table I below shows the results for Junction temperature rise (ΔT_j), which is calculated as the difference between the wall temperature and coolant inlet temperature $\Delta T_j = T_w - T_i$, for each permuation of flow rate, power dissipation, and pulsation frequency investigated.

TABLE I
JUNCTION TEMPERATURE RISE RESULTS FOR 1 OF THE 3 POWER DISSIPATION VALUES INVESTIGATED, AND 3 FLOW RATE VALUES (MID, MID-HIGH, & HIGH REPRESENTS RE = 30, 35, & 50 OR 0.085, 0.099, & 0.142 L/MIN, RESPECTIVELY) INVESTIGATED.

Power Dissipation (W)	Pulsation Frequency (Hz)	Junction temperature rise (ºC) ΔT_j		
		Mid	Mid-High	High
25	0	9.13	8.59	7.01
	0.5	8.47	7.79	6.65
	1	7.48	7.04	5.95
	1.5	7.10	6.74	5.65
	2	7.04	6.69	5.51

Table I shows the junction temperature rise ΔT_j for a certain power dissipation, and for all values of pulsation frequency investigated. The results show a clear decrease in ΔT_j with an increase in both pulsation frequency and flow rate. However, the results also demonstrate how the introduction of pulsatile flow can be utilised as a method of control of cooling of computational components.

The results demonstrate that for a certain power dissipation value, the value of ΔT_j that is achieved with stable laminar flow of a certain flow rate, thus with no pulsations, can be achieved at a lower flow rate, with the introduction of a sinusoidal waveform of a defined frequency to the flow. In the case of the Mid power dissipation value, as seen highlighted in the table, the value of ΔT_j seen in the steady state case at the High flow rate can be achieved at the Mid-High flow rate, with the introduction of pulsations of a frequency of 1Hz, and at the Mid flow rate with pulsation of a frequency of 2Hz.

The overall goal of this study was to improve the efficiency of cooling of computational components. When correlating this to the experimental investigation results, this was characterised by improved cooling without a reduction of outlet temperature. This can be seen in the results for coolant temperature rise (ΔT_c) as seen in Table II below.

TABLE II
COOLANT TEMPERATURE RISE RESULTS FOR 1 OF THE 3 POWER DISSIPATION VALUES INVESTIGATED, AND 3 FLOW RATE VALUES (MID, MID-HIGH, & HIGH REPRESENTS RE = 30, 35, & 50 OR 0.085, 0.099, & 0.142 L/MIN, RESPECTIVELY) INVESTIGATED.

Power Dissipation (W)	Pulsation Frequency (Hz)	Coolant temperature rise (ºC) ΔT_c		
		Mid	Mid-High	High
25	0	3.68	3.16	2.22
	0.5	3.36	2.86	2.04
	1	3.25	2.79	2.04
	1.5	3.52	3.01	2.12
	2	3.84	3.21	2.20

The results shown in Table II show that for a certain power dissipation and flow rate investigated, the values for ΔT_c do not change drastically with a chance in pulsation frequency. When comparing these values to those as seen in table I, this clearly shows that for a certain power dissipation and flow rate, though there is a clear decrease in ΔT_j with an increase in pulsation frequency, there is no clear change in ΔT_c, thus showing a clear increase in efficiency of cooling with the introduction of pulsatile flow.

IV. DISCUSSION

The results of this study show the effect of the introduction of pulsatile waveforms of varying frequency to a steady state laminar flow on heat transfer. The pulsatile state results outlined the heat transfer enhancement with the introduction of a sinusoidal waveform of a range of frequencies in comparison with the equivalent steady state case with the same flow rate, with a pulsation of a defined constant amplitude.

For the investigations outlined in this study, the effect of the introduction of pulsations of varying frequency to a laminar flow were investigated, thus a constant pulsation amplitude of 1mm was maintained for all experiments undertaken during this study.

The experiments conducted in this study investigated the effect of varying pulsation frequency on heat transfer enhancement. The results showed clear enhancement with the introduction of pulsation of 5-51%, dependent on the flow rate and pulsation frequency investigated. The results show a clear trend in increasing enhancement with an increase in flow rate for a defined constant pulsation frequency, and an increase in pulsation frequency for a certain constant flow rate. The trend follows through with the greatest enhancement being seen with a flow rate of Re = 50 and a pulsation frequency of 2.0Hz.

Deriving from the heat transfer enhancement results, a prediction correlation was developed to predict a value for heat transfer enhancement from know values for steady state and pulsating Reynolds number. The resulting correlation, solved using a GRG Nonlinear solving model, as seen in equation (3), resulted in an accurate prediction equation which, when plotted against the actual heat trasnfer enhancement values, resulted in an R^2 of 0.93, showing a strong positive correlation, further proving the accuracy of the resulting predicted heat transfer enhancement values calculated using the prediction correlation equation.

As previously mentioned, the primary goal of the study was to investigate the effect of introducing sinusoidal pulsations of varying frequency to laminar steady flow on heat transfer. The results showed that pulsatile flow can also act as a cooling control method, with a clear reduction in junction temperature rise (ΔT_j) as both flow rate and pulsation frequency increase. For example, at a power dissipation of 40W, the same ΔT_j observed at a steady flow rate of Re = 50 was achieved with a lower flow rate of Re = 35 using a 1.0Hz pulsation, and even at Re = 30 with a 2.0Hz pulsation. This demonstrates that similar cooling capacity can be achieved with reduced flow rates by increasing pulsation frequency. While coolant temperature rise (ΔT_c) showed no clear trend with pulsation frequency, the consistent drop in ΔT_j indicates an overall improvement in cooling efficiency. These findings highlight the potential of pulsatile flow to optimize cooling in computational components, reducing energy usage and environmental impact in applications such as in data centers.

V. Conclusion

This study examines the influence of introducing variable-frequency pulsatile flow into a laminar flow regime on heat transfer performance. The primary objective of this study was to explore the potential for enhancing heat transfer, and thereby improving the controllability of forced convection liquid cooling in minichannel heat sinks, through the superposition of sinusoidal flow waveforms onto a steady-state laminar flow. The results show a clear enhancement in heat transfer with an increase in both flow rate and pulsation frequency with a constant pulsation amplitude of 1mm. Therefore, as expected, the greatest heat transfer enhancement was seen at the highest flow rate and largest pulsation frequency investigated with a flow rate of Re = 50 and pulsation frequency of 2.0Hz resulting in an enhancement of 51%. A prediction correlation equation was developed from these results which resulted in a strong positive correlation between the predicted heat transfer enhancement values calculated using the prediction equation, which uses known values for steady state and pulsation Reynolds number values, and the actual enhancement values, proving the accuracy of the predicted values resulting from this equation. The results of this study show clear controllability of cooling with the introduction of pulsatile flow to laminar flow. The results of the study show that for a defined power dissipation value, the value for ΔT_j that is achieved at a certain flow rate can be achieved at a lower flow rate with the introduction of sinusoidal waveforms with a certain pulsation frequency. The same value can be achieved at an even lower frequency with an increase in pulsation frequency. This finding proves clear controllability of cooling of computational components with pulsatile flow.

Following this study, further alterations will be made to the experimental facility to investigate further variations in heat sink geometries to see if the findings of this study follow through to microchannel heatsinks of smaller and larger geometries. This will allow for a more accurate conclusion to be formed as to the improvement of efficiency of cooling of computational components.

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