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Thermal-hydraulic performance of a tapered microchannel

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ABSTRACT

Tapered microchannel is a channel configuration design (CCD) which has gained attention owing to the superior performance in promoting uniform temperature distribution in a microchannel. In this study, the thermal-hydraulic performance of four different tapered channels is evaluated against a straight microchannel. The average hydraulic diameter, conductive heat transfer in the substrate material and convective heat transfer area are kept constant for the microchannels. The experiment is conducted for steady-state convective heat transfer using distilled water as the working fluid for Reynolds number range of 1300–3400 and a constant heat flux of 53.0 W/cm^2. Results show that highly-tapered microchannels promote early turbulence at lower Reynolds numbers with better heat transfer and much greater pressure drop. All the tapered microchannels possess a thermal-hydraulic performance index which is less than 1, implying that a tapered microchannel yields a lower heat transfer capability given the same pumping power as a straight microchannel.

1. Introduction

Microchannel heat sink (MCHS) was introduced by Tuckerman and Pease [1] in an attempt to achieve a compact liquid cooling of integrated circuits with high thermal performance. This initial design of MCHS, which is capable of achieving a power density of 790 W/cm^2 with a maximum increment of 71 °C in the substrate temperature above the inlet water temperature, consists of parallel rectangular channels in a silicon substrate.

MCHS is compact and thermally efficient owing to the high surface area to volume ratio and it requires less working fluid. It has been commonly applied in high power electronic cooling and other highly specialized areas such as aerospace, biomedical processes, automotive industries and photovoltaic cells [2,3]. The increased heat flux in microelectronic devices and the emergence of microscale devices that require superior cooling spur the development of microchannels [4].

One of the key areas of thermal performance optimization is channel configuration design (CCD). These include single-layer parallel channels, double-layer parallel channels, wavy channels and tapered channels. Initial works on CCD involve single-layer parallel channels. Various geometrical shapes [5–7] and aspect ratio [8–10] of the channel have been studied or optimized in terms of heat transfer and hydrodynamic characteristics. One of the drawbacks of the single-layer channel configuration is the huge temperature variation within the heat sink between the inlet and outlet mainly due to the small amount of coolant [11]. This high-temperature rise is undesirable as the resultant thermal stresses lead to thermal instability as well as reduced reliability and lifetime of the microelectronic devices. Although a single-layer MCHS with high depth-to-width ratio can mitigate this issue, it comes with a cost in terms of pumping power and fabrication complexity [12].

Double-layer parallel channels with counter flow configuration were first introduced by Vafai and Zhu [13] to address the issue of temperature nonuniformity of the heat sink. An extensive amount of work has also been done to optimize the performance of this channel configuration [14–20]. The parameters which are being studied include channel number, aspect ratios, channel-to-pitch width ratio and operating conditions [15]. These works reveal that a double-layer channel configuration enhances the cooling performance, temperature uniformity and hydrodynamic performance as compared to a single-layer MCHS.

Similarly, different configurations of wavy passage have also been studied extensively to enhance the heat transfer performance of MCHS. A wavy channel promotes heat transfer through the formation of Dean vortices due to the centrifugal force and chaotic advection at the troughs and crests. Both the aforementioned mechanisms promote fluid mixing [21]. The improved thermal performance with affordable pressure drop as compared to straight channels spawned studies in this field, mainly focus on the parametric studies on amplitude, wavelength as well as the aspect ratio of the channel [22–28].

Another emerging study area of CCD is a converging flow channel along the stream-wise direction. A converging channel increases the fluid velocity along the stream-wise direction and thereby increasing the convective heat transfer coefficient. The ensued reduction in the local wall temperature improves the overall temperature distribution

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Nomenclature

A	surface area (m^2)
A_c	cross-sectional area (m^2)
c_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
D	diameter (m)
E	enhancement or increment factor (−)
h	mean heat transfer coefficient ($kW\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
Nu	Nusselt number (−)
p	pressure (Pa)
$\dot{Q}$	heat flow rate (W)
r	radius (m)
r^*	radius ratio (−)
Re	Reynolds number
T	temperature (K)
$\mathbf{u}$	velocity vector ($m\,s^{-1}$)
$\dot{V}$	volumetric flow rate ($m^3\,s^{-1}$)

Greek symbols

ε	surface roughness (m)
ε^*	dimensionless surface roughness (−)
υ	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
τ	stress tensor (Pa)
μ	dynamic viscosity (Pa·s)
η	performance index (−)

Subscript

c	copper
f	fluid
h	hydraulic
i	inlet
m	mean
o	outlet
r	radial
s	reference
w	wall

and thermal resistance of the MCHS. The effect of converging flow channel on the thermal resistance in both single and double-layer MCHS have been investigated.

Hung and Yan [11] studied numerically the effect of tapering ratio on the thermal resistance and temperature distribution of MCHS under a fixed pumping power condition. Their results show that there is an optimum tapering ratio which yields the lowest overall thermal resistance. In another numerical study, Hung et al. [29] predicted that a tapered-channel outperforms parallel, single-layered and double-layered MCHS in terms of the overall thermal resistance and temperature uniformity, subjected to a fixed pumping power.

Dehghan et al. [30] proved that converging flow channels increase the convective heat transfer coefficient downstream of the microchannel, where the value remains constant for a parallel channel as the entrance effect diminishes. The average hydraulic diameter of the MCHS varies with the tapering ratio. Osanloo et al. [12] predicted numerically that the thermal performance improves with a higher convergence angle, at the expense of a higher pressure drop. Nevertheless, there is no assessment on whether the additional pumping power required is justifiable by the enhanced thermal performance. Wong and Ang [31] further studied the thermal hydraulic performance of a converging double-layered MCHS. The numerical results predicted a minimal increment in the heat transfer performance with a significant rise in the pumping power requirement. Therefore, it was concluded

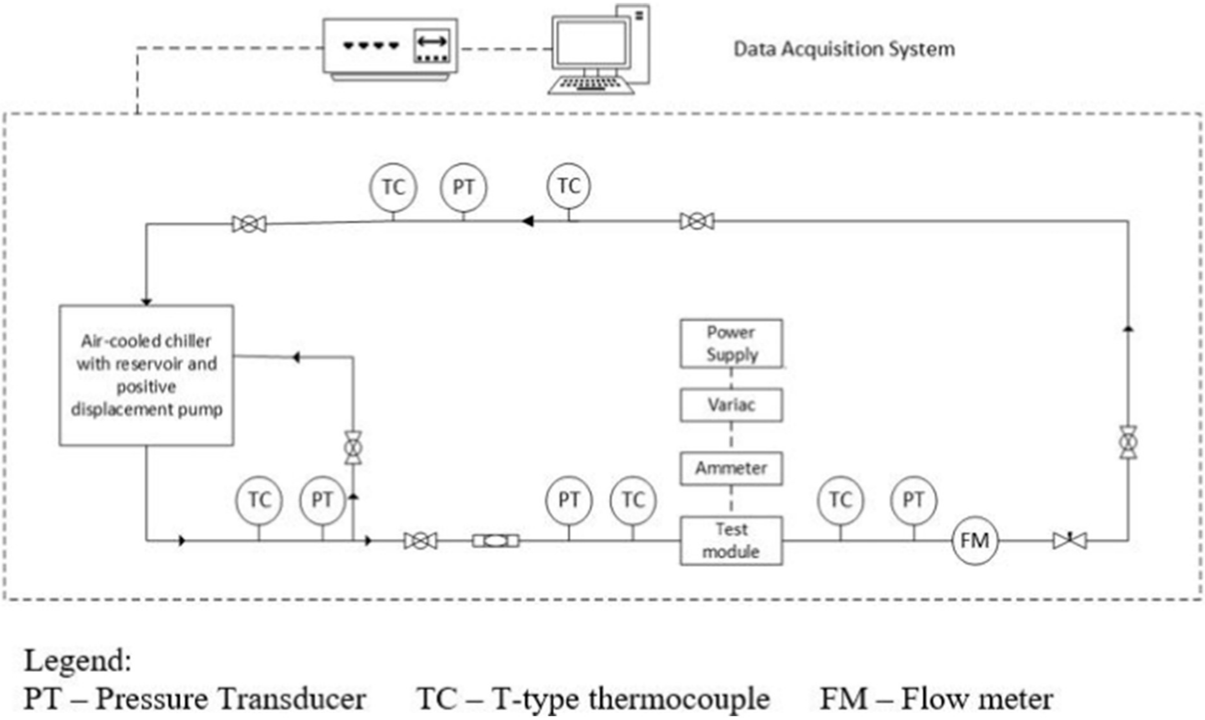

Fig. 1. Experimental setup [34].