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Heat transfer enhancement on a microchannel heat sink with impinging jets and dimples

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ABSTRACT

The introduction of dimples to heat transfer surface can effectively improve the heat transfer performance of a microchannel heat sink with impinging jets (MIJ). MIJs with different dimple structures, including convex, concave, and mixed dimples, are compared with MIJs without dimples by numerical simulation and the application of the field synergy principle. Results indicate that (1) MIJs with convex dimples exhibited the best cooling performance, followed those without dimples, with mixed dimples, and with concave dimples; (2) the application of convex dimples could decrease flow resistance in MIJs; and (3) among all tested cases, MIJs with convex dimples exhibited the best overall performance, followed by MIJs without dimples, with mixed dimples, and with concave dimples.

1. Introduction

The number of transistors in a dense integrated circuit grows exponentially, according to Moore's law. With an increase in the number of transistors, heat flux in electronic devices can reach 100 W/cm^2 [1]. High-energy density presents challenges to thermal management in electronic devices. Cooling electronic devices with transient high heat flux by microchannels has attracted considerable interest from researchers worldwide. In 1981, Tuckerman and Pease [2] introduced the concept of a microchannel heat sink (MHS), which can significantly enhance heat transfer. The shape and size of the MHS affect its performance [3]. For a rectangular MHS, a higher aspect ratio can decrease its thermal resistance [4]. With consideration of the effect of shape on the microchannel, a triangular microchannel has a higher cooling efficiency than a rectangular or trapezoidal channel [5].

The heat transfer performance of an MHS can be enhanced. Theoretical breakthroughs in heat transfer enhancement can provide guidance. The performance of MHS is determined by the convective heat transfer coefficient, Nusselt number, average temperature, and temperature uniformity on the cooling surface, pressure drop in the flow, overall efficiency, and so on [6–9]. Optimization of the MHS usually targets the minimum power consumption [10] and the maximum heat transfer coefficient [11], which cannot be achieved simultaneously [12]. An optimization technique can be implemented by minimizing exergy destruction [13] or entransy dissipation [14,15]. Another approach to heat transfer enhancement is based on the field synergy principle [16,17], which indicates that single-phase heat convection can be enhanced by improving the synergetic relation between physical quantities, such as the velocity field and the heat flux field [14,18,19]. These theories can significantly help in the assessment and design of an MHS with high overall performance.

Meanwhile, technical improvement by the combination of MHS with other configurations has also drawn significant interest. Studies found that impinging jets [20] and various inserts, such as dimples [21,22], tapes [23,24], and porous medium[25,26] in microchannels can help enhance heat exchange relative to that of traditional fluid cooling devices because they can cause vortexes, decrease the boundary layer thickness, and/or increase the temperature gradient near the target walls. Thermal performance can be optimized by creating more disturbances in the flow of the cooling medium [23,24,27–33]. From the aspect of technical improvement mentioned earlier, impinging jets play an important role in cooling technology. For confined circular air jets vertically impinging on a flat surface, the Nusselt number is linearly associated with the

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Nomenclature

A	area of the jet cross-section (mm^2)
c_p	isobaric specific heat (J/K kg)
D	hydraulic diameter of the micro channel (mm)
H	heat sink height (mm)
H_1	jet height (mm)
H_2	channel height (mm)
G	acceleration of gravity (m/s^2)
H	convective heat transfer coefficient (W/m^2 K)
K	thermal conductivity of water (W/m K)
k_f	thermal conductivity of the fluid (W/m K)
k_s	thermal conductivity of the solid (W/m K)
L	heat sink length (mm)
L_1	length of jet in cross section (mm)
L_2	spacing between jets (mm)
$\dot{m}$	total mass flow rate of jet inlets (g/s)
N	number of jets (–)
Nu	Nusselt number (–)
P	static pressure (Pa)
P_{in}	static pressure of a jet inlet (Pa)
P_{out}	static pressure of channel outlet (Pa)
$\dot{q}$	heat flux (W/mm^2)
R	radius of dimple (mm)
T	temperature (K)
$\bar{T}_f$	average temperature of the fluid between the inlet and outlet (K)
T_s	temperature of the heat sink (K)
T_w	average temperature of the cooling wall (K)
u, v, w	velocity components in x, y and z directions (–)
W	heat sink width (mm)
W_1	channel width (mm)
x, y, z	Cartesian coordinates (–)

Greek symbols

μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
β	field synergy angle (°)
ΔP	pressure drop (Pa)

Subscripts

f	fluid
in	impinging jet inlet
out	channel outlet
s	solid heat sink
w	cooling surface wall

jet–jet spacing to the jet diameter ratio [8]. Moreover, compared with free-surface jets, confined submerged jets generally exhibit higher heat transfer for a given water pumping power [34]. Analysis indicates that single mean jet velocity, nozzles of different diameters, and 2 multiple-nozzle arrays markedly influence heat sink exchangers [35]. An MIJ has a more efficient cooling performance compared with other technologies [6,7]. Zhuang et al. [36] analyzed a MIJ with different cooling media and found that the impingement flow exhibits excellent heat transfer relative to the conventional parallel flow in channels.

Inserts, such as dimples, can positively affect heat transfer by causing a turbulence [22]. Lee et al. [11,37] demonstrated that the small-angle diagonal ribs and small fins spacing in the channel contribute to heat transfer in the MHS. Suresh et al. [38] conducted an experimental study of convective heat transfer and friction factor in a nanofluid tube with dimples. The experimental results indicated that the Nusselt numbers obtained with the dimpled tube and nanofluids under a turbulent flow are about 19%, 27%, and 39% higher than the Nusselt numbers obtained with the plain tube and water.

Several studies have been conducted on combining microchannels with dimples [21,22,38–41], microchannels subject to an impinging jet [6,7], and impinging jets with dimples [42–45]. However, studies on the combination of the 3 technologies—dimples, microchannels, and impinging jets—in a single device have rarely been reported. The combination of any 2 technologies can lead to better performance, compared with the single technology; with 3 technologies combined, an improvement to a greater extent is expected. In the present study, a new structure consisting of a MIJ and dimples was proposed. The heat transfer between the working fluid and the heated surface could be enhanced by introducing the flow disturbance via impinging jets and dimples. The heat exchange, flow resistance, and overall performance of 4 different structures (convex dimples, concave dimples, mixed dimples, and non-dimple) were numerically evaluated, indicating that the MIJ with convex dimples can lead to enhanced heat transfer and reduced pressure drop relative to those of the MIJ without dimples.

2. Introduction of the model

2.1. Principle of impinging jets

The flow field in a single nozzle with a dimple is illustrated in Fig. 1. At the nozzle outlet, the jet expands continuously owing to the momentum exchange among the surrounding stationary medium, and the potential core velocity remains constant. With the fluid moving forward, the core continues to shrink. When the jet reaches the convex dimples, the fluid spreads apart toward the surrounding surface. Owing to the presence of the dimple structure, a disturbance [22] occurs between the fluid and the surface, the effect of which varies from that of a smooth surface.

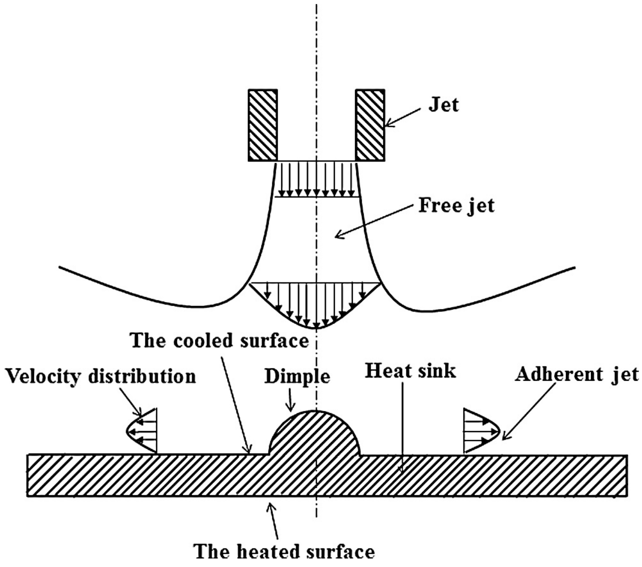

Fig. 1. Single-nozzle flow field with convex dimples.