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Exergy analysis and performance evaluation of flow and heat transfer in different micro heat sinks with complex structure

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ABSTRACT

Simulations are conducted to investigate flow and heat transfer performance of de-ionized water flowing through different micro heat sinks with complex structure under uniform heat flux. Six new micro heat sinks with different types of cavities and ribs are proposed. Moreover, they are compared involving friction factor and Nusselt number relative to other micro heat sinks in the existed literature. Exergy analysis is also applied to investigate the physical mechanism of heat transfer enhancement. Different performance evaluation criteria, based on first and second law of thermodynamics, are proposed to assess the overall performance of micro heat sinks. The results clearly show that the micro heat sink with triangular cavities and triangular ribs (Tri.C–Tri.R for short) presents the best heat transfer performance over a Reynolds number range of 300–600. The performance of heat transfer can be enhanced by decreasing the net temperature gradient of fluid in micro heat sinks. New correlations of friction factor and Nusselt number are proposed based on numerical data, which relate with Reynolds number and relative cavity height and relative ribs height.

1. Introduction

Liquid flow in micro heat sinks is manifested itself as one of the promising methods to remove high heat flux for microelectronic devices, which has been concerned by many authors. However, micro heat sinks with simple structure have been unable to meet the cooling demand with the increment of heat flux in the microelectronic devices, thus resulting in peak temperature maintain in the electronic chips [1].

Therefore, the roughness, ribs, grooves, and cavities inside the micro heat sinks with complex structure play a significant role in the rate of heat transfer, which can be enhanced by interrupting the hydrodynamic and thermal boundary layer, causing the secondary flow in the grooves or cavities, and providing more surface areas by roughness or prominence [2,3]. Haimohammadi et al. [4] proposed "N-branch" cavities intruding into the equal divisions of a rectangular/trapezoidal heat generating body, the peak temperature of the body could be reduced. In order to minimize the peak temperature, the thickness of conductive thick plate placed between a heat source and a cold fluid was optimized by detailed numerical simulation [5]. The results show that the temperature of heat source influenced by Reynolds number and material thermal conductivity. Moreover, they did lots of similar works to reduce hot spot temperature of heat source [6–9].

A great deal of the research have also been done to understand the mechanism of flow and heat transfer in micro heat sinks, which are generally focused on the pressure drop, Nusselt number, or thermal enhanced factor [10–12]. According to the first law of thermodynamics, the heat exchange between the bottom of heat sink and fluid is in balance, which reveals the quantity of energy in the heat transfer process. However, the forced convective heat transfer is a typical irreversibly process in the microchannel, which can also cause entropy generation and exergy destructive. Besides the analysis based on the energy conservation law, the second-law analysis is also important in understanding the portions of irreversibility attributed to the thermodynamic systems.

Oztop et al. [13] presented that the energy analysis in terms of Nusselt number or heat transfer coefficient had been used in a number of studies while exergy analysis had been applied to the relatively low numbers of systems. As known, thermal energy is a kind of low grade energy and only part of it is effectively transferred in the process, when compared to mechanical, electric or chemical energy. Therefore, exergy analysis (a qualitative analysis of energy) based on the second law of thermodynamics seems to be essential. In the aspect of flow and heat transfer in micro heat

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Nomenclature

A	contact area between fluid and silicon mm^2
c_p	special heat capacity kJ/(kg K)
D_h	hydrodynamic diameter mm
e_1	cavity height mm
e_2	rib height mm
f	friction factor
h	heat transfer coefficient $\mathrm{W/(m^2\,K)}$
L	length of channel mm
$\dot{m}$	mass flow rate kg/s
N	number of microchannels
Nu	Nusselt number
N_s	augmentation entropy generation number
Δp	pressure drop Pa
q''	Heat flux $\mathrm{W/m^2}$
$\dot{Q}$	input power W
$\dot{Q}_d$	irreversible heat loss W
$\dot{S}'''_{\Delta p}$	entropy generation rate of fluid friction $\mathrm{W/(m^3\,K)}$
$\dot{S}'''_{\Delta T}$	entropy generation rate of heat transfer irreversibility $\mathrm{W/(m^3\,K)}$
$\dot{S}'''_{\mathrm{gen}}$	total entropy generation rate $\mathrm{W/(m^3\,K)}$

Re	Reynolds number
T_f	average temperature of fluid K
T_in	inlet temperature K
T_out	outlet temperature K
ΔT	temperature different K
u_m	mean velocity m/s

Greek symbols

η	thermal enhancement factor
η_t	transport efficiency of thermal energy
ρ	density $\mathrm{kg/m^3}$
λ_f, λ_s	thermal conductivity W/(m K)
μ	dynamic viscosity $\mathrm{kg/(m\,s^2)}$

Subscript

f	fluid
s	solid
in	inlet
out	outlet
m	mean

sinks, most of the studies focused mainly on the effect of modified structure on the irreversibility caused by flow and heat transfer in micro heat sinks. The irreversibility in terms of entropy generation was firstly proposed by Bejan [14], which caused by flow and heat transfer. Thus, the thermodynamic performance of micro heat sinks increases with decreasing the entropy generation rate. From the view point of it, the method of entropy generation minimization (EGM) has become a robust and useful optimization tool for a wide range of thermal application.

A significant number of studies related to the thermodynamic optimization of various thermal systems with entropy generation [15–21] or exergy method [22–24] have been conducted. Li et al. [15] used the method of entropy generation minimization to optimize ground heat exchanger with single U-tube. The characteristic of three different types of heat exchangers was investigated by Leong et al. [19]. The study indicated that shell and tube heat exchanger with 50° helical baffles exhibited the lowest entropy generation. Kosar [22] used unit cost per product exergy, relative cost difference, and exergo-economic factor to evaluate the thermoeconomic performance over four micro pin fin heat sinks. Zimmermann et al. [23] experimentally studied the exegetically efficient electronics cooling using hot water. New metrics of heat recovery efficiency and an application specific utility function were introduced to investigate the benefits of hot water cooling.

From the above literature review, there has been considerable studies on the structural optimization in micro devices, but less available work is lost in exploring the essence of heat transfer enhancement. To the best of authors' knowledge, none of studies in the open literature explicitly explores the physical mechanism of heat transfer enhancement in micro heat sinks from the view point of thermodynamics. A physical understanding of this impact is a fundamental issue in designing the energetic efficiency of micro heat sinks.

To bridge this information gap, the main concern of the present study is to investigate the essence of heat transfer enhancement in micro heat sinks with complex structure. This study is organized into three parts. In the first part, based on our previous work [25–27], six different configurations of micro heat sinks are presented to investigate the characteristic of flow and heat transfer. In the second part, the augment entropy generation number and transport efficiency of thermal energy have been derived from the second law of thermodynamics, with the purpose of applying them to reveal the essence of heat transfer enhancement. In the third part, new correlations of friction factor and Nusselt number of micro heat sinks are proposed, then the relationship among thermal enhancement factor, entropy generation number and transport efficiency of thermal energy is also analyzed in detail.

2. Theoretical analysis

2.1. Entropy generation

Entropy generation can be used to evaluate the irreversibility of flow and heat transfer process, which was proposed by Bejan [14]. The expression of volume entropy generation rate is defined as follow:

$$\dot{S}'''_{\mathrm{gen}} = \dot{S}'''_{\Delta p} + \dot{S}'''_{\Delta T} = \frac{\mu\Phi}{T_\mathrm{f}} + \frac{\lambda_\mathrm{f}(|\nabla T_\mathrm{f}|)^2}{T_\mathrm{f}^2} \tag{1}$$

where, $\dot{S}'''_{\mathrm{gen}}$, $\dot{S}'''_{\Delta p}$ and $\dot{S}'''_{\Delta T}$ are total volume entropy generation rate, entropy generation rate of fluid friction and entropy generation rate of heat transfer irreversibility, respectively. Φ, λ_f, μ and T_f are the viscous dissipation, thermal conductivity, dynamic viscosity and average temperature of fluid, respectively.

From Eq. (1), the volume entropy generation rate is generated by the fluid friction and by the heat transfer due to the wall-to-fluid temperature difference, which is related to velocity gradient and temperature gradient. $\dot{S}'''_{\Delta T}$ decreases and $\dot{S}'''_{\Delta p}$ increases with increasing mass flow rate. Therefore, the total volume entropy generation rate is affected by many factors, which does not clearly and intuitively reflect the essence in the process of flow and heat transfer.

By integrating Eq. (1) over the domain Ω,

$$\dot{S}_{\mathrm{gen}} = \int\int\int_\Omega \dot{S}'''_{\mathrm{gen}} dV \tag{2}$$

Then, the augmentation entropy generation number [14], $N_{\mathrm{s,a}}$, is introducing to evaluate the merit of augmentation,

$$N_{\mathrm{s,a}} = \dot{S}_{\mathrm{gen}}/\dot{S}_{\mathrm{gen,0}} \tag{3}$$