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Cooling augmentation using microchannels with rotatable separating plates

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ABSTRACT

Cooling augmentation using double layered (DL) microchannels separated by rotatable plates is investigated in this work. The analyzed devices of the proposed configuration are (A) the flexible microheat exchanger, and (B) the DL-flexible microchannel device. The moment of the pressure forces on the separating plate is related to its rotational angle through its flexible supports. Energy equations for the flowing fluids are solved numerically using an iterative finite-difference method. Comparisons with obtained closed-form solutions under fully developed conditions are performed and excellent agreement is obtained. It is found that the effectiveness and the heat transfer rate per unit pumping power for the flexible microheat exchanger are always higher than that for the rigid one. Moreover, DL-flexible microchannels devices are found to provide more cooling effects per unit pumping power than rigid ones at flow Reynolds numbers below specific values, and at stiffness number and aspect ratio above certain values. These specific values are found to vary with the magnitude of the heating load. DL-microchannels with rotatable separating plates can be utilized in several applications such as electronic cooling.

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1. Introduction

Many electronic devices incorporate large integration density of chips in a small area such as VLSI components. These devices consume large amount of electrical energy which is dissipated as heat. The amount of dissipated heat is usually very large and can be more than 100 W/cm^2 [1]. As such, conventional cooling technologies may not work. Recent developments in microfabrication technologies have enabled readily accessible fabrication of microchannel heat sinks primarily for cooling of electronic components [2–8]. These devices can be arranged in a single layered (SL) micro-passages such as those described in the works of Lee and Vafai [9] and Fedorov and Viskanta [10]. In addition, they can be arranged in double layered (DL) microchannel passages which was invented and reported by Vafai and Zhu [11]. DL-microchannels are found to provide additional cooling capacity and they can decrease the coolant temperature gradients along the microchannel length. It should be mentioned that SL-microchannel heat sinks can be either single microchannel system [12] or multiple microchannel system [9]. Microchannels can have a wavy shape [13] in order to enhance heat transfer. The successive developments in microchannels technologies have revealed certain designs that are capable to increase fluid mixing within the fluid volume hence increasing the heat transfer passively [14].

The main disadvantage of conventional microchannel cooling devices is the increased coolant temperature as very large heating loads are dissipated by a relatively small coolant flow rates. As such, Vafai and Zhu [9] proposed the DL-microchannels heat sink devices. Another solution is to utilize flexible microchannels. These types of microchannels which were developed in the works of Khaled and Vafai [15–17] and Vafai and Khaled [18] reduce the coolant temperature because volumes of both the flow passage and the supporting seals are expandable. This effect causes an increase in the coolant flow rate. The volume expansion in flexible microchannels is due to pressure forces. These forces can be due to an increase in the pressure drop across the microchannel [18]. Also, it can be due to gas pressure if the supporting seals contain closed gas-cavities in contact with the heated surface. As such, any increase in the gas pressure due to excessive heating produces extra expansion in the volume [15,17]. As the expansion in the flow passage volume may result in slight reduction in the convection heat transfer coefficient [18], a new configuration of DL-flexible microchannels device is considered here.

In this work, a DL-microchannel cooling device with rotatable separating plate is proposed and analyzed for possible augmenting in the cooling effects. The separating plate is assumed to be supported via anti-leaking flexible seals. The only allowable motion for that plate is the rotational motion about a pivot rod. This rod is taken to be aligned along the microchannel center line normal to its sides boundaries. Two different devices based on the above configuration are considered. They are (A) the flexible micro heat exchanger and (B) the heated DL-flexible microchannel device.

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Nomenclature

A_d	maximum relative displacement of the separating plate, d/H_o
A_k	cold to hot fluids thermal conductivities ratio, k_c/k_h
$A\mu$	cold to hot fluids dynamic viscosities ratio, μ_c/μ_h
$A\rho$	cold to hot fluids densities ratio, ρ_c/ρ_h
C_c, C_h	cold and hot fluids thermal capacities per unit width [W m^{-1} K^{-1}]
d	maximum displacement of the separating plate [m]
E_o	dimensionless elastic parameter defined in Eq. (11)
H	microchannel height [m]
$\bar{H}$	microchannel dimensionless height defined in Eq. (1)
H_o	half main microchannel height [m]
h	convection heat transfer coefficient [W m^{-2} K^{-1}]
K	stiffness of the supporting seals per unit separating plate width [N]
Ka	stiffness number defined in Eq. (30)
k	thermal conductivity [W m^{-2} K^{-1}]
L	microchannel length [m]
Nu	local Nusselt number defined Eqs. (47), (48) and (62)
P_t	total ideal pumping power requirement [W m^{-1}]
p	mean pressure [N m^{-2}]
q'	heat transfer rate per unit width [W m^{-1}]
Pr	Prandtl number, $\mu c_p/k$
Re	Reynolds number, $\rho u_h H_o/\mu$
T	temperature field [K]
T_m	mean bulk temperature [K]
U	local overall heat transfer coefficient [W m^{-2} K^{-1}]
U_e	equivalent overall heat transfer coefficient [W m^{-2} K^{-1}]
u	velocity field [m s^{-1}]
$\bar{u}$	dimensionless velocity field defined in Eqs. (19) and (20)
x	axial micro-passage coordinate [m]
$\bar{x}$	dimensionless axial micro-passage coordinate defined in Eqs. 3(c, d)
y	transverse micro-passage coordinate [m]
$\bar{y}$	dimensionless transverse coordinates defined in Eqs. 18(a, b)

Greek symbols

ε	effectiveness of the heat exchanger defined in Eq. (43)
ε_c, ε_h	effectiveness of cold and hot fluids flows defined in Eqs. (35) and (36)
$\gamma_1\gamma_2$	first and second performance indicators defined in Eqs. (44) and (64)
λ_s	dimensionless maximum heated plate temperature defined in Eq. (63)
μ	fluid dynamic viscosity [kg m^{-1} s^{-1}]
θ	dimensionless temperature defined in Eqs. 18(c, d)
θ_m	mean bulk dimensionless temperature defined in Eqs. (41) and(42)
P	dimensionless ideal pumping power requirement defined in Eq. (33)
ρ	fluid density [kg m^{-3}]

Subscripts

1	inlet
2	exit
c	cold fluid
fd	thermally fully developed
h	hot fluid
m	mean value

The linear elasticity theory [19] is applied to flexible seals supporting the separating plate to relate the moment of the pressure forces on that plate to its rotational angle. The energy equations for both fluids are solved numerically for general conditions and analytically under special conditions. As such, the effectiveness of the flexible micro heat exchanger (device A) and other performance indicators for both devices (A) and (B) are calculated. The advantages of the proposed device in cooling attributes over the performance of the DL-rigid microchannel device are examined.

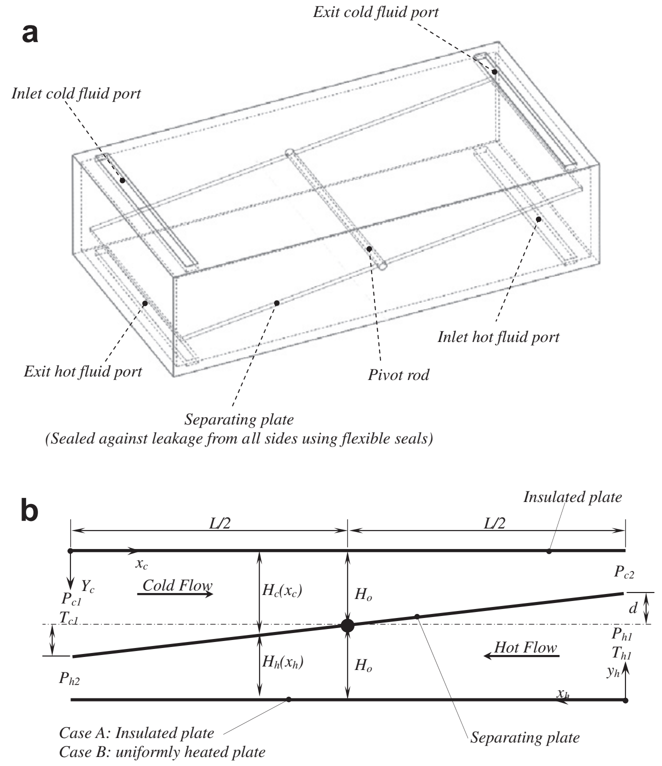

Fig. 1. (a) 3D view of the DL-microchannel device with rotatable separating plate, and (b) side view schematic of the device and the coordinate system.

2. Problem formulation

2.1. Modeling of the maximum relative displacement of the moving plate

Consider a wide microchannel of height $2H_o$ which is much smaller than its length L. Consider that this microchannel is divided into two identical microchannels by a highly conductive and inflexible separating plate mounted about a pivot axis (O). The pivot axis is taken to be a rod aligned along the normal centerline axis of the device as seen in (Fig. 1). Accordingly, the allowable motion of the separating plate is the rotational motion about that pivot axis. Two fluids at different temperatures are allowed to flow in counter-direction inside the lower and upper microchannels. The hot fluid which is at temperature T_{h1} enters the lower microchannel and flows towards the left direction along the x_h-axis as shown in Fig. 1. However, the cold fluid which is at temperature $T_{c1}(T_{c1} < T_{h1})$ is allowed to flow in the upper microchannel towards right direction along and the x_c-axis as shown in Fig. 1. The heights

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