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A new double-pass parallel-plate heat exchanger with better wall temperature uniformity under uniform heat flux

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ABSTRACT

A new flow passage arrangement is introduced for parallel-plate heat exchanger for cooling channel walls under uniform heat flux. Heat transfer performance of the new double-pass heat exchanger is compared with those of the corresponding single-pass and original double-pass heat exchangers from wall temperature uniformity viewpoint, because total heat transfer is the same for three types of the parallel-plate heat exchangers. Computed results show that wall temperature in the new double-pass heat exchanger has better uniformity compared to the usual one. Despite the advantage of better uniformity in wall temperature, power consumption for handling the specified volumetric flow rate within the new double-pass heat exchanger is greater than those are required within the two others.

1. Introduction

Heat transfer in laminar flow within two parallel plates has been frequently studied [1]. Both uniform temperature and uniform heat flux thermal boundary conditions have been widely investigated [1] for flow with negligible axial conduction, which is known as Graetz problem [2,3]. Other researchers considered extended Graetz problem with axial conduction for fluids with low Prandtl number in parallel-plate channel [4–7]. Classical and extended Graetz problems are the basic heat transfer problems with thermal characteristics used for designing flat plate heat exchangers. Therefore, many researchers consider this particular flow as the simplest heat exchanger absorbing heat from channel walls.

Relevant researches have usually attempted to improve heat transfer performance of parallel-plate heat exchanger. They have generally concerned with increasing the convective heat transfer coefficient, especially when a prescribed temperature distribution was exerted on the channel walls [8–10]. Convective heat transfer coefficient depends on flow pattern through the channel. Therefore, when the channel occupation is unchangeable, heat transfer surface is also fixed. Hence, the only way for increasing the convective heat transfer coefficient is to change the flow pattern within the enhanced internal channel space. There are several solutions for this purpose. Finned walls [11,12] have been already used to improve heat transfer performance of the flow within the parallel-plate heat exchanger. Another solution is to use wavy plate instead of usual flat plate for channel walls [13–15]. Fins and wavy walls generate secondary flows along the flow direction. Secondary flows increase the local convective heat transfer coefficient, but they increase the power consumption to handle the required mass flow rate at the same time.

Among the different practical solutions for improving heat transfer performance of a parallel-plate heat exchanger, doubling the flow passage through the channel to make two counter-flow streams is the simplest and more practical one. This particular flow passage can be constructed by inserting a flat plate between the two channel walls of the original single-pass parallel-plate heat exchanger. It provides simpler fabrication and maintenance for engineering applications. Ho et al. [16–19] have frequently reported that a double-pass arrangement of a heated parallel-plate heat exchanger has greater heat transfer performance compared to the corresponding single-pass one. Ho et al. [20,21] also studied multi-pass arrangement of a heated parallel-plate heat exchanger and concluded that heat transfer performance of the multi-pass heat exchanger was better than the corresponding single-pass one.

Separating plate in the double-pass heat exchanger was generally a flat plate with negligible thickness and conductive resistance. Goodarzi and Mazharmanesh [22] studied a double-pass heat

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Nomenclature

A	cross section area, m^2
B	channel depth, m
Gz	Graetz number
I_P	power consumption increment
K	thermal conductivity, W/mK
L	channel length, m
Nu	Nusselt number
P	power, W
P	pressure, Pa
Q	volumetric flow rate, m^3/s
$\ddot{q}$	heat flux, W/m^2
T	temperature, K
V	velocity, m/s
W	channel width, m
X	longitudinal coordinate, m

Symbols

A	thermal diffusivity, m^2/s
B	uniformity index
M	viscosity, kg/m.s
Ξ	dimensionless longitudinal coordinate
P	density, kg/m^3
Ψ	dimensionless temperature

Subscriptions

I	Inlet
O	outlet
Total	total values
W	wall

exchanger with sinusoidal separating plate. They showed that sinusoidal separating plate increased heat transfer performance compared to the flat one.

Literature shows that local and/or overall convective heat transfer coefficient are improved with double-pass arrangement of a parallel-plate heat exchanger. All previous studies focused on this coefficient in term of Nusselt number. A particular thermal boundary condition is the uniform heat flux on the channel walls. It is more practical thermal boundary condition in many engineering applications. Note that total heat absorption by flow is fixed with the surface area of the channel walls and mass flow rate regardless of the flow passage arrangement within the parallel-plate heat exchanger.

In many practical applications with uniform heat flux over the channel walls, engineers want to cool the walls down to a desired wall temperature. In these cases, more uniform wall temperature provides more advantage for device that is cooling by the parallel-plate heat exchanger. In fact, uniformity of the wall temperature rather than total heat absorption is desirable for these particular applications. For example, an electronic processor generating uniform heat flux should be cooled with a cooling stream. In addition to the lower processor wall temperature, uniform temperature distribution within this special electronic device synchronizes processing rates between internal sub-processors, which decreases waiting time for transferring data among sub-processors.

Single-pass heat exchanger cools walls down symmetrically. Symmetric cooling may be important in some cooling applications. Original double-pass heat exchanger cools channel walls down asymmetrically. A new double-pass heat exchanger is proposed in this article, which can cool the channel walls down symmetrically as the simple-pass arrangement does.

This article concerns with comparative heat transfer analysis of a parallel-plate heat exchanger with three flow passage arrangements under uniform heat flux. Single-pass and previously introduced double-pass arrangements are compared with a new double-pass arrangement from wall temperature uniformity viewpoint.

2. Problem definition

Heat transfer in a parallel-plate flow is the simplest thermo-flow problem, which is frequently studied by engineers. Fig. 1(a) schematically shows the single-pass arrangement of this particular heat exchanger. Cold flow enters the heat exchanger with inlet temperature denoted by T_i, and absorbs the heat from channel walls on which a particular heat source exerts a uniform heat flux. W denotes the width between the channel walls, and heat exchanger length is denoted by L. Q denotes the volumetric flow rate within the heat exchanger, and T_o is the outflow temperature.

Double-pass arrangement could be constructed by inserting an impermeable flat plate with negligible thickness and conductive resistance between the channel walls. A rounded return channel should be included at the end of the parallel-plate heat exchanger for returning the flow exiting the incoming channel into the entrance of the outgoing channel. For correct comparing, total heat transfer surface should be fixed in different arrangements. Therefore, returning channel is thermally insulated. Fig. 1(b) schematically shows double-pass arrangement with flow passage inside the sub-channels. Note that the same volumetric flow rate enters the incoming sub-channel so that averaged inlet velocity increases compared to the single-pass arrangement.

New double-pass arrangement is constructed by inserting two separating plates between the channel walls. Cold flow enters the heat exchanger via the central sub-channel constructed by two separating plates, and exits the heat exchanger via the two outer sub-channels as shown in Fig. 1(c). The width of the central sub-channel is equal to the width of each double-pass heat exchanger sub-channel described in the previous paragraph. It is worth to mention that counter-flow streams within the double-pass arrangements can exchange the heat with each other across the separating plates.

3. Governing equations and boundary conditions

Flow regimes through the presented parallel-plate heat exchangers are laminar and incompressible. All molecular fluid properties are uniform and constant throughout the flow field. Heat flux makes no change in the flow phase. Therefore, governing equations for such a steady thermo-flow field are continuity, momentum, and energy equations, which are presented by the following vector notation:

$$\vec{\nabla}\cdot\vec{V} = 0 \tag{1}$$

$$\rho(\vec{V}\cdot\vec{\nabla})\vec{V} + \vec{\nabla}p - \mu\nabla^2\vec{V} = 0 \tag{2}$$

$$(\vec{V}\cdot\vec{\nabla})T - \alpha\nabla^2 T = 0 \tag{3}$$