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Exergy transfer in a porous rectangular channel

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ABSTRACT

Present paper is performed to investigate the heat and exergy transfer characteristics of forced convection flow through a horizontal rectangular channel where open-cell metal foams of different pore densities such as 10, 20 and 30 *PPI* (per pore inches) were situated. All of the bounding walls of the channel are subjected to various uniform heat fluxes. The pressure drop and heat transfer characteristics are presented by two important parametric values, Nusselt number (Nu_{H}) and friction factor (f), as functions of Reynolds number (Re_{H}) and the wall heat flux (q). The Reynolds number (Re_{H}) based on the channel height of the rectangular channel is varied from 600 to 33 000, while the Grashof number (Gr_{Dh}) ranged from approximately 10^5–10^7 depending on q. Based on the experimental data, new empirical correlations are constructed to link the Nu_{H}. The results of all cases are compared to that of the empty channel and the literature. It is found that the results are in good agreement with those cited in the references. The mean exergy transfer Nusselt number (Nu_e) based on the Re_{H}, Nu_{H}, Pr and q for a rectangular channel with constant heat flux is presented and discussed.

1. Introduction

The porous medium with high thermal conductivity has emerged as an effective method of heat transfer enhancement due to its large surface area to volume ratio and intense mixing of flow. Using metal foams in heat transfer applications is quite new subject; hence many researches have been carried out since the year 2000. Leong and Jin [1], for instance, performed an experimental work including oscillating flow through a rectangular channel filled with open-cell metal foam of 10, 20 and 40 *PPI* (per pore inch) for porous medium. Moreover, Leong and Jin used the same materials to obtain heat transfer performance of metal foam heat sinks subjected to oscillating flow of various oscillatory frequencies [2].

A review of the current literature showed that, the metal foams were generally used in heat exchangers because of its high heat transfer behavior. For example, Boomsma et al. [3] used open-cell metal foams as compact heat exchangers. Lu et al. [4,5] did some analytical studies including forced convection heat transfer characteristics in pipes [4] and in heat exchangers [5], both filled with high porosity open-cell metal foam. Dukhan et al. [6] analyzed one-dimensional heat transfer in open-cell metal foam numerically.

Recently, Tzeng and Cheng [7] have investigated the convective heat transfer and pressure drop in porous channels with 90-deg turned flow. Tzeng et al. [8] also examined air flow passing through a rotating serpentine channel inside aluminum foam material.

As mentioned above, the current literature is lacks papers dealing with the heat transfer and pressure drop analyses of porous channel flow, reflecting the absence of second law analysis studies. The present work endeavors on shedding some light on the topic of second law analysis of the channel flow filled with porous foam material. In general, in the papers including second law analysis of a channel flow, non-dimensional entropy generation number is employed in the irreversibility examination of convective heat transfer [9–11]. Thus, the present paper consists of non-dimensional entropy generation (or exergy destruction) of channel flow with porous medium.

In fact, this work is a second step of a continued project, of which first part is recently published in an archival journal [12]. In the former work, heat transfer analysis of the flow passing through a rectangular channel which contains various pore sizes of aluminum foam plates was investigated by means of Nusselt numbers. However, in this later one, the thermodynamic performance has been studied by introducing mean exergy transfer based Nusselt number (Nu_e), entropy generation number (Ns), and merit function (MF). Some empirical correlations for heat transfer and

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Nomenclature

A	cross sectional area of channel, m^2
C	heat capacity, W/K
c_p	specific heat, J/kg K
Da	Darcy number
Dh	channel hydraulic diameter, m
e'	specific exergy J/kg
f	friction factor
g	gravitational acceleration, m/s^2
Gr	Grashof number
h	heat transfer coefficient, W/m^2 K
h'	specific enthalpy J/kg
H	height of the channel, m
I	current, A
$\dot{I}$	irreversibility, W
k	thermal conductivity, W/mK
L	length of the channel, m
$\dot{m}$	mass flow rate of air, kg/s
Ns	entropy generation number
Nu_i	local Nusselt number
Nu_H	average Nusselt number based the channel height
Nu_{D_h}	average Nusselt number based the channel hydraulic diameter
p	pressure, N/m^2
Pr	Prandtl number
Q	heat transfer rate, W
$\dot{Q}$	exergy transfer rate, W
R^2	regression coefficient
Re_H	Reynolds number based the channel height
Re_{Dh}	Reynolds number based the channel hydraulic diameter
s	specific entropy J/kg K
St	Stanton number
$\dot{S}$	entropy rate, W/K
T	temperature, K
U	velocity, m/s
U'	overall heat transfer coefficient, W/m^2 K
V	voltage, V
W	width of the channel, m

Greek symbols

β	thermal expansion coefficient, 1/K
ε	porosity
χ	correlation coefficients
κ	permeability
μ	dynamic viscosity, kg/m s
ν	kinematic viscosity, m^2/s
θ	dimensionless temperature
ρ	density, kg/m^3
Δx	spacing between thermocouples, m
ΔT	temperature difference, K

Subscripts

c	conduction
env	environment
ex	exergy
ex,m	mean exergy
f	fluid
F	forced convection
h	heating surface
i	surface column index ($i = 1,2,\ldots,6$)
in	inlet
ins	insulation
gen	generated
l	laminar
lc	laminar flow at critical Re number
r	radiation
t	total
tu	turbulence
w	wall of channel

pressure drop in a channel with porous medium are presented. Also, exergy transfer and exergy loss caused by forced convective heat transfer through a rectangular channel filled with open-cell aluminum foam are investigated in detail.

The open-cell aluminum foams situated in flow area increase the heat transfer coefficient and outlet temperature of air. Accordingly, the efficiency of the heat exchanger increases too. However, an increase is observed in pressure loss. It would be misleading to consider only the capital costs of heat exchangers in their design because high operation and maintenance costs during their maintenance life may also greatly increase total costs. Therefore, energy saving aspects is very important in the design, construction and operation of the heat exchangers. The key requirement is to address why exergy analysis is valuable from the scientific points of view to be introduced? The exergy method is an alternative technique based on the concept of exergy (availability), vaguely defined as a universal measure of the work potential or quality of different forms of energy in relation to a given environment [13]. The exergy analysis is also useful to engineering for operating and design decisions, including design optimization. As known, heat exchanger effectiveness does not indicate the effect of pressure losses on performance. In heat exchangers, pressure loss can contribute significantly to the overall irreversibility rate and cannot be neglected in an analysis of the process. Because of this, in this paper, in addition to energy analysis is needed to perform an exergy analysis.

2. Experimental set-up

The experimental set-up is the same set-up used in the authors' previously published paper (see Ref. [12] for further details). We have been focusing on forced and mixed convection heat transfer in the previous study. In this second part; exergy transfer analysis in a porous rectangular channel is performed in detail. Fig. 1(a) presents the schematic view of whole set-up with a picture beside each element. The set-up is divided into three main parts; namely (i) air supply system, (ii) test section and test specimens, and (iii) data acquisition system. Air from the quiescent laboratory room is driven into the operators by means of a downstream-positioned blower. The air enters along hydrodynamic development length ($L/D_h \sim 100$) in order to establish a well-defined velocity profile at its downstream end. The downstream end of the development section is mated to the inlet of the test section. The test section proper is a rectangular duct filled with a metallic porous medium. The length of the test section in the flow direction was held fixed at 62 mm. The downstream end of the test section was, in turn, mated to an extension of the test section walls, but without the porous medium. At the far end of the downstream section, an isolation device was installed to decouple any possible blower-motor vibration.

Heating of test section was accomplished on all of its bounding surfaces by means of a very tightly wrapped silicon-rubber-sheathed heating element. The heating element was backed by