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Experimental investigation on hydrodynamics and heat transfer of fluid flow into channel for cooling of rectangular ribs by passive and EHD active enhancement methods

A. Alamgholilou [a,*], E. Esmaeilzadeh [b]

[a] Department of Mechanical Engineering, Azarbaijan University of Tarbiat Moallem, Tabriz, 53751-71379, Iran
[b] Department of Mechanical Engineering, University of Tabriz, Tabriz, 51666-14766, Iran

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ABSTRACT

In the present study, the heat transfer enhancement on ribs established on the floor of a rectangular duct was investigated. These ribs were used as heat sources and means of cooling of them has been carried out with air flow by experimental procedure. The flow was two dimensional, steady, viscous and incompressible with regimes of either laminar ($500 \leqslant Re_{D_h} < 2000$) and turbulent ($2000 \leqslant Re_{D_h} \leqslant 4500$). The hydrodynamics and heat transfer behavior of this flow was studied by passive, active and compound methods with application of corona wind. The state of the art of this work is its experimental investigations of a compound method including EHD[1] active method and passive method of perforated surface between ribs and enhancement of heat transfer from their surfaces. For conducting the experiment, a special apparatus has been designed. The comparison of the results for various boundary conditions of problem was fairly agreement.

1. Introduction

All of the electronic boards are constructed from small and tiny elements which generate considerable amount of heat. Cooling of hot electronic board surfaces and other local heat sources with air flow is an essential part of the boards. The main cooling systems for these equipments are flow of air over them through channels, thus reducing heat generation through forced convection. Nowadays, due to using various elements in boards and size reduction (i.e., board compaction), the cooling element has become a vital part of the system. Optimum active and/or passive cooling systems are preferred approaches for performance evaluation criteria (PEC) of the boards [1,2]. Active and passive methods are well known for their ability to work with and without any external sources of energy. Corona is a visible luminous emission caused by the creation of photons. This occurs in the vicinity of sharp edges where the intensity of the electric field is high. An important aspect of corona discharge is the generation of corona wind, which is a gas flow induced by corona discharge. This phenomenon is caused by the ionization of gas molecules and formation of electrons that accelerate in strong electric fields and collide with neutral molecules, resulting in more ionization. The ions are heavier than electrons; they accelerate and drag the neighboring gas molecules. This generates a secondary flow, known as corona wind.

The present work examines both passive and active methods of the cooling system including a combined cooling system. The combined cooling system, which is the interaction of EHD active site of positive corona wind with the passive site of perforated surfaces, is a new cooling method, which has been developed in our lab. This is a novel cooling approach, and based on the authors' knowledge, it has not been introduced earlier.

Many researchers have studied corona wind for their application to heat transfer enhancement [3–7]. In some of the studies, perforated surfaces over and between ribs have been applied for as a passive method of heat transfer enhancement [8,9].

Ohadi et al. [3] used the wire-plate electrodes for forced convection enhancement in pipe flow. They showed that the Two-wire electrode design provided a modestly higher enhancement than did the single wire electrode design. With two electrodes, they showed that for Reynolds numbers up to 10,000, it is possible to use this technique for enhancement.

Kasayapanand and Kiatsiriroat [4,5] investigated the heat transfer enhancement with electrohydrodynamics (EHDs) technique in laminar forced convection inside a wavy channel with different wire electrode arrangements. The numerical and mathematical modeling has been achieved for this work. The electric field is generated by the wire electrodes charged with DC high voltage. The mathematical

* Corresponding author. Tel.: +98 914 4035212.
E-mail addresses: alamgholilou@tabrizu.ac.ir (Amin Alamgholilou), esmzadeh@tabrizu.ac.ir (Esmaeil Esmaeilzadeh).

[1] Electrohydrodynamics.

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Nomenclature

A	area of orifice hole (m^2), coefficient in Eq. (6)
B	coefficient in Eq. (6)
b	rib height (m), mobility of ions ($m^2\ V^{-1}\ s^{-1}$)
C	distance between wire and ground electrodes (m)
D	diameter, diameter of pipe (m)
d	diameter of orifice (m)
D_h	hydraulic diameter (m)
E_t	rate of heat transfer enhancement
E_{lost}	consumed power ratio
E_0	electric field ($V\ m^{-1}$)
H	channel height (m)
h	heat transfer coefficient ($W\ m^{-2}\ K{-}1$)
h_s	heat transfer coefficient for plain case ($W\ m^{-2}\ K^{-1}$)
I_0	electric current of corona wind (A)
I_{EHD}	strength of EHD
L	width of rib (m), characteristic length (m)
L_1	length of upstream flow (m)
L_2	length of downstream flow (m)
$\dot{m}$	the mass flow rate ($kg\ s^{-1}$)
n	number of holes
N_{EHD}	EHD number
P	pressure (Pa)
q''_{rib}	constant heat flux from rib to fluid flow ($W\ m^{-2}$)
q_{e0}	electric charge of one electron (Coulomb)
Re	Reynolds number
Re_{D_h}	Reynolds number basis on hydraulic diameter
r	radius of wire electrode (m)
r_{eff}	effective radius of wire to ground electrode (m)
S	space between the ribs (m)
T	temperature, K (°C)
u	velocity ($m\ s^{-1}$)
u_i	velocity of electric ions ($m\ s^{-1}$)
W	width of channel (m)
x	cartesian coordinate, entrance length (m)
y	cartesian coordinate
z	cartesian coordinate

Greek symbols

α	the angle of view between wire and ground electrodes
α'	the coefficient in Eqs. (5) and (6)
β	the ratio of orifice to pipe diameter
η_e	performance evaluation criteria (PEC)
υ	kinematics viscosity ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
ρ_f	density of fluid ($kg\ m^{-3}$)
ρ_e	density of electric charge ($kg\ m^{-3}$)
γ	the ratio of all holes area to the side wall area of ribs
ζ	the coefficient in Eq. (9)
Δ	difference

Subscripts

Actual	actual condition
D	diameter of pipe
e	electron, efficiency
f	fluid
Ideal	ideal condition
i	ions
P	particle
ref	reference conditions
w	the rib wall

Superscripts

.	time rate
$''$	flux
–	average

modeling includes the interactions among electric field, flow field, and temperature field. The numerical simulation is firstly conducted with the experimental data in case of rectangular flat channel. Then the modeling is carried out in the case of wavy channel.

Kasayapanand et al. [6] investigated the effect of the electrode arrangements in a tube bank on the characteristic of electrohydrodynamic heat transfer enhancement for low Reynolds numbers. The numerical modeling of the laminar forced convection includes the interactions among the electric field, the flow field, and the temperature field. From the numerical results, they showed that the heat transfer enhanced by the EHD at a low Reynolds number and the short distance between the wire electrodes and the tube surface.

Tada et al. [7] investigated the heat transfer enhancement in a convective field by applying ionic wind. Experiments were performed in an air channel flow where a series of wire-electrode arrangement. They showed that the possibility of the practical applications of the ionic wind.

Sultan [8] indicated an enhancement in heat transfer by inducing distributions in vortexes due to the existence of holes behind the ribs. But in the analysis of fluid motion in wake regions, he considered the effect of density variation and buoyancy forces. According to the negligible Richardson number of flow, buoyancy forces contribute only a minor role in this phenomenon. In addition, by definition of critical Reynolds, a specified characteristic length was established, which is not conformant with the geometry and physical models of this case. Both applying repeated ribs and their distance from each other in channels or external flow on plain surfaces can influence patterns of the flow field.

In our previous work [9], numerical study on the heat transfer enhancement of rectangular ribs with constant heat flux located in the floor of a 3D duct flow has been achieved. In this study, the effects of the arranged holes between the rectangular ribs in channels have been reported.

Webb et al. [10,11] investigated experimental studies on cross barriers and their obtained flow patterns for distances between ribs. They showed that if the ratio of ribs distance to ribs height (S/b) is less than 8, its produced vortexes will fill the entire area between ribs. They claimed that by increasing the distance, reattachment of flow would occur in the space between the ribs and then the heat transfer coefficient in the vicinity of the reattachment point would reach its maximum value.

Abdel-Rahman et al. [12] looked at experimental and numerical investigations on flow and heat transfer, under the conditions of a rectangular duct with an injection of secondary flow. They investigated the effects of air injections on the heat transfer of rectangular ducts through a porous medium.

Arman and Rabass [13,14] performed a numerical study on the turbulent flow with 2D rectangular ribs in the vicinity of a wall using k–ε and Chen Patel two layer models. Computations were made for zones near the wall and core of flow. They predicted the reattachment positions with high accuracy. Their results were in agreement with experimental results made by other scientists regarding Nusselt and friction coefficients.

Liou et al. [15,16] investigated the effects of cross ribs on heat transfer via numerical simulation. They also examined the effects of a rectangular duct flow with ribs containing holes. They