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Experimental investigation of convective heat transfer enhancement from 3D-shape heat sources by EHD actuator in duct flow

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ABSTRACT

Heat transfer enhancement from cylindrical heat sources as electronic components established at the bottom of duct with in-line arrangement and also from the bottom by electrohydrodynamic (EHD) actuator has been investigated experimentally. Air flow is drawn to the duct with various Reynolds numbers based on hydraulic diameter of inlet of the test section (Re = 0, 500, 1100, 2500 and 3870) that include natural convection (confined and unconfined cases) and forced convection (laminar and turbulent flows). Wire electrodes are arranged in transverse direction and perpendicular to the main flow with two various arrangements and high voltages are applied up to 30 kV in the wires. The results revealed that the second electrode arrangement (three wires over the ribs) is more effective due to more enhancement of heat transfer and less corona power consumption in comparison with the first one (four wires between the ribs). Also the electric field is obviously more effective for low Reynolds numbers.

1. Introduction

The heat generated by electronic components still requires more efficient cooling methods in order to maintain the equipments temperature at an acceptable level. Long life and reliable performance of a component may be attained by effectively controlling the device operating temperature by using a high voltage electric field. Under an intense electric field, air partially breaks down and is ionized and results in corona discharge. A significant aspect of corona discharge is the generation of corona wind. This phenomenon is caused by the ionization of air molecules and formation of electrons that accelerate in strong electric fields and collide with neutral molecules which results in more ionization. The ions are heavier than electrons; they accelerate and drag the neighboring air molecules. This results in formation of a secondary flow, known as corona wind that helps to increase convective heat transfer rate.

Many studies have been concluded to investigate convective heat transfer properties from heat sources in duct flow without applying electric field that make a good viewpoint for convective heat transfer in duct flows. A multi-faceted experimental investigation was carried out by Sparrow et al. [1] to study heat transfer and pressure drop for air flow in arrays of heat generating rectangular modules developed along one wall of a flat rectangular duct. In this study the effects of removing a module on heat transfer properties of other modules and also fully developed condition in the presence of modules have been studied. Hacohen et al. [2] investigated an experimental and theoretical study for both forced and free convection with both flush-mounted and protruding heat sources and compared them with each other. Mixed convection heat transfer from arrays of discrete flush-mounted heat sources that subjected to uniform heat flux and put in lower and upper surfaces of a horizontal channel was investigated experimentally by Dogan et al. [3]. From this experimental study, row-average surface temperature and Nusselt number distributions of the discrete heat sources were obtained. The results revealed that top and bottom heater surface temperatures increase with increasing Grashof number. Mohamed [4] experimentally investigated air cooling characteristics of an electronic devices heat sink with various square modules array and estimated the average heat transfer coefficient between the following air and modules array outer surfaces. The concluding results indicated that the average heat transfer little increased with increasing the following air velocities and the increasing of module to channel height ratio seemed to increase the average heat transfer coefficient.

A large number of papers on the electrohydrodynamic enhancement of heat transfer have been published in open literature. Some of them are presented here briefly. Owsenek and Seyyed-Yagoobi [5] experimentally investigated the corona wind enhancement of free convection using a heated horizontal flat plate with high voltage supplied to a needle suspended above heated plate. EHD enhanced heat transfer of natural convection inside an enclosure was investigated by Kasayapanand [6] in which the results revealed that heat transfer decreases with the Rayleigh number. Huang and Lai [7] investigated effects of Joule heating on EHD-enhanced natural

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Nomenclature

A_{eff}	effective area exposed to the air flow inside the duct (m^2)
A_{tot}	total area of outer surface of the ribs (m^2)
E	enhancement ratio
h_0	local heat transfer coefficient of the air $\left(\frac{W}{m^2K}\right)$
I	corona current (μA)
I_{Heater}	applied current in each heat source (A)
k	air conductivity $\left(\frac{W}{m^2K}\right)$
l	specific length (m)
Nu	local Nusselt number with the presence of electric field
Nu_0	local Nusselt number without the presence of electric field
P	corona power consumption (W)
$Q_{eleach\text{-}heater}$	electric power applied in each heat source (W)
$Q_{eleach\text{-}element}$	electric power applied in each element
$Q_{eleeff\ each\text{-}heater}$	effective electric power applied in the effective area of each heat source (W)
Q_{Loss}	heat power losses (W)
Re	hydraulic based Reynolds number in the test section
T_i	surface temperature measured by thermocouple number i without the presence of electric field (K)
T_i'	surface temperature measured by thermocouple number i with the presence of electric field (K)
T_∞	ambient temperature (K)
V	corona voltage (kV)
V_{Heater}	applied voltage in each heat source (V)
X	horizontal distance from test section entrance (cm)

convection. Yabe and Hijikata [8] conducted a corona wind between wire and plate electrodes to increase the convective heat transfer coefficient. Wangnipparnto et al. [9] investigated the air side performance of a thermosyphon heat exchanger with and without the presence of EHD in the low Reynolds number region, that the results showed that increasing in the Reynolds number, diminish the effects of EHD on heat transfer characteristics. Heat transfer enhancement with EHD technique in laminar forced convection inside a wavy channel with different wire electrode arrangements was numerically investigated by Kasayapanand and Kiatsiriroat [10]. They showed that flow pattern and thermal boundary layer are disturbed by the effect of electric field when it extends over the recirculation region. An experimental research was conducted by Molki and Bhamidipati [11] to study the level of heat transfer enhancement that can be achieved by corona wind in the developing region of circular tubes. In corona wind cooling of cylinders, multipoint electrodes result in higher enhancement than single-point electrodes [12]. When electrodes are placed parallel or perpendicular to air flow, corona onset voltage is independent of magnitude and direction of flow for all polarities [13]. Heat transfer augmentation in a rectangular duct with EHD was also done by Tada et al. [14] and Mathew and Lai [15].

Most of previous works about EHD are focused on reduce thermal boundary layers and disturb recirculation regions or dead zones to enhance heat transfer rate but in this study in addition to the recent applications, conduction of fresh and cool air from top space of the duct toward hot zones via applied electric field in the wire electrodes is investigated that can be very important. Here cylindrical heat sources with 3D nature put at the bottom of duct due to a better configuration of electronic components. The objective of the present work is to investigate heat transfer enhancement from cylindrical heat sources with constant heat flux established at the bottom of a rectangular duct by EHD actuator. These heat sources have put at the bottom of duct with in-line arrangement. Also heat transfer enhancement from the bottom of duct is studied. Two electrode arrangements have been considered. Both natural and forced convections with various ranges of air flow Reynolds number have been studied.

2. Experimental set-up and procedure

Fig. 1 shows a schematic representation of the experimental set-up. The set-up consists of three main parts: the inlet section, the test section and the outlet section.

The inlet section also consists of three parts: The honeycombs with 20 cm in length and hydraulic diameter of 1.143 cm which is small enough in comparison with hydraulic diameter of the main duct (7.0588 cm), has been used to straighten and unify the air flow and either to quicken the formation of hydraulic development condition for various possible velocities. Through a nozzle, it connects to the inlet duct with rectangular cross section and 2 m in length.

The test section is a rectangular duct with length × width × height of 40×30 × 4 cm and hydraulic diameter of 7.0588 cm which the main investigations are focused on this part. The sidewalls and top surface of the test section is made of Plexiglas in order to a better observation of the flow.

The outlet section consists of three parts: A rectangular outlet duct with 30 cm in length which is located after the test section that is connected to a circular pipe with diameter of 8.3 cm through a nozzle. An orifice with diameter of 2.075 cm has been put in the circular pipe in order to measure the pressure difference in both side of the orifice by using an inclined manometer containing water. Then formulas related to orifices [16] are used to calculate Reynolds number. The orifice has been designed and made according to the AFNOR standard [16]. There is a main valve on the pipe to adjust air flow rate. Also some slight changes can be applied in the air flow rate through a deviational pipe by adjusting a damper on its opening. A fan has been used at end of the set-up in the suction line to draw air through the duct assembly. The fan and its electric generator have been put on a strong concrete foundation.

Schematic form and photo of the test section are available in Figs. 2 and 3. The heat sources are cylindrical aluminum ribs, 3 cm in diameter and 2 mm in thickness, which have been established at the bottom of test section with five rows in the flow direction and three columns perpendicular to the flow direction. The ribs are heated with constant heat flux except the first and last

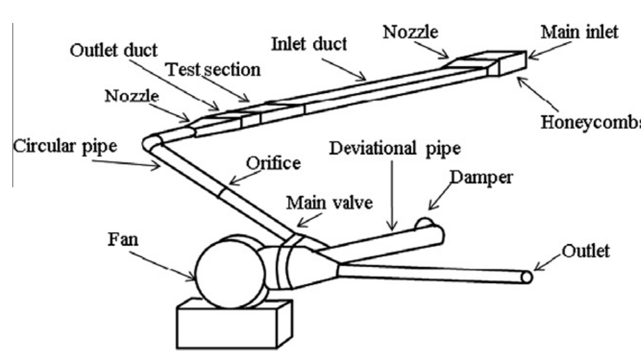

Fig. 1. The experimental set-up.