Heat transfer from a surface fitted with rectangular blocks at different orientation angle

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Abstract An experimental investigation was carried out to study the enhancement of the heat transfer from a heated flat plate fitted with rectangular blocks of $1 \times 2 \times 2$ cm$^3$ dimensions in a channel flow as a function of Reynolds number ($Re_b$), spacing ($S_y$) of blocks in the flow direction, and the block orientation angle ($\alpha$) with respect to the main flow direction. The experiments were performed in a channel of 18 cm width and 10 cm height, with air as the working fluid. For fixed $S_y = 3.81$ cm, which is the space between the blocks in transverse to the flow direction, the experimental ranges of the parameters were $S_y = 3.33$–$4.33$ cm, $\alpha = 0$–$45^\circ$, $Re_b = 7625$–$31550$ based on the hydraulic diameter and the average velocity at the beginning of the test section in the channel. Correlations for Nusselt number were developed, and the ratios of heat transfer with blocks to those with no blocks were given. The results indicated that the heat transfer can be enhanced or reduced depending on the spacing between blocks, and the block orientation angle. The maximum heat transfer rate was obtained at the orientation angle of $45^\circ$.

List of symbols
- $A_4$ projected area
- $b$ block height, cm, Fig. 1
- $D_h$ hydraulic diameter of channel, m
- $H$ channel height, cm
- $h$ mean heat transfer coefficient
- $k$ conductivity of air
- $L_b$ block length and width, cm, Fig. 1
- $L_y$ test surface length, cm
- $Nu$ Nusselt number, $hD_h/k$
- $Q$ heat transfer
- $Re_b$ Reynolds number, $VD_h/b$

1 Introduction
Conjugate heat transfer, especially in microelectronic equipment is becoming increasingly important in thermal management of components. Due to the progress of circuit integration the heat dissipation is concentrated in fewer components, while the system volume shrinks, thereby reducing the space for coolant flows. The rapid advances in the development of high-density, large scale-integrated chips have led to numerous miniaturized electronic devices. This trend produces the increase of thermal resistance due to such reduction of the heat dissipating path (i.e. denser packaging), and, consequently, heat from such sophisticated electronic components is excessively generated. Unless high-powered heat is effectively removed, the excessive heat generated within the electronic devices will rapidly degrade the performance of these sensitive systems. Therefore, enhancing the convective cooling of chips is a primary concern in the study of electronic packaging.

One of the methods for enhancing heat transfer from surface is to use surface modifications, resulting in an increase of the available surface area as well as the turbulence and mixing levels in the flow. The basic principles of convective heat transfer enhancement are common to a host of engineering applications, and these areas have received great attention resulting in a considerable amount of research directed at understanding the complex flow patterns and heat transfer in these situations. Heat transfer
enhancement in arrays of rectangular blocks has been investigated by many researchers. In some of the studies, the rectangular attachments was accepted to resemble electronic chips. For example, the convective cooling problem from a chip-simulated block has been tackled by Davalath and Bayazitoglu (1987), Kang et al. (1990), and Kim et al. (1994) among others.

The subject of heat transfer in arrays of rectangular blocks, especially for the fully developed flow, has been addressed by many investigators. Sparrow et al. (1982, 1983) reported heat transfer and pressure drop in arrays of rectangular blocks with barriers and mixing blocks. The focus of their work was to study the effect of the missing block and barriers on the thermal hydraulic behavior of the array. Moffat et al. (1985, 1991) investigated various aspects of thermal-hydraulic behavior of the arrays of electronic components in a series of experimental work. Their overall objective was to develop the techniques and the databases for the prediction of the working temperature of the blocks.

The local convective mass transfer from a wall-mounted single cube was investigated by Chyu and Natarajan (1991), Natarajan and Chyu (1994), using the naphthalene sublimation technique and a strong variation in the mass transfer coefficients was determined. Meinders et al. (1998) performed an experimental work on the local convective heat transfer from a wall-single array of cubes employing infrared and liquid crystal technique. They determined that there was a high non-uniformity in the local convective heat transfer over the surface of the individual elements. In another study by Vafai and Zhu (1999), the thermal performance and temperature distribution were investigated for a two-layered micro channel heat sink for cooling of the electronic components. Molki et al. (1995) performed an experimental work to study the heat transfer in the entrance region of an array of rectangular heated blocks and correlated the adiabatic heat transfer coefficients and thermal wake effects.

Gerimela and Shlitz (1995) studied heat transfer enhancement from a discrete square section of a wall in a narrow channel using two and three-dimensional mixing devices, in which the heat transfer was enhanced by raising the heat source off the wall in the form of a protrusion. They determined that the highest enhancement in the heat transfer relative to the flush heat source was obtained when the roughness elements were used in combination with a single on the opposite wall.

Experimental investigations and numerical simulating by Amon and Mikic (1990), Amon et al. (1992), Farhanieh et al. (1993), Herman (1994) and Herman and Kang (2001), indicated that the redevelopment of the thermal boundary layer along each heated block, inherent in electronic cooling applications, was accompanied by high heat transfer coefficients. However, the overall heat transfer along one heated block-groove periodicity unit was imbedded by the inefficient groove region. Warm fluid was trapped in the slow recirculation flow in the groove, heated by both upstream and downstream blocks, with diffusion being the dominant heat transfer mechanism over the shear layer between groove region and main channel flow (Farhanieh et al. 1993; Nigen and Amon 1993; Herman 1994; Herman and Kang 2001). They implied that one of the possibilities to enhance heat transfer in grooved channels was to improve lateral mixing by disrupting the shear layer separating the bulk flow and the recirculating flow in the groove and introducing vertical velocity components in this region.

Local Nusselt numbers along the grooved surface for the steady state situation were obtained numerically, among others, by Sunden and Trollheden (1989), and experimentally by Herman (1994), Herman and Kang (2001) and Farhanieh et al. (1993). They studied at Reynolds number in laminar, transitional and beginning of turbulence region. In the study by Herman et al. (1998) it has been shown that holographic interferometry is an effective method for the visualization of the Tollmien-Schlichting waves and it allowed gaining quantitative insight into fast changing flow structures.

Egan and Amon (2000) combined finite element numerical simulations, physical experimentation, and analytical models to understand the thermal phenomena of embedded electronic design and to explore the thermal design space. Analytical models using thermal resistance networks predicted the heat flow paths within the embedded electronic artifact as well as the role of conductive fillers used in polymer composites. In another study by Leoni and Amon (2000), physical experiments and numerical simulations were performed on an embedded electronics prototype system of a wearable computer. Through the use of orthogonal arrays and optimal sampling, an efficient exploration of the parameter space was performed to determine thermal conductivities, thermal contact resistances and heat transfer coefficients.

Vesligaj and Amon (1999) described an investigation of solid to liquid phase change materials (PCMs) for passive energy storage during the condition of time varying workloads on portable electronics. A thermal control unit (TCU) embedded in an epoxy polymer was an enclosure that contained phase change material (PCM), and a thermal conductivity enhancer was located near the power source, and acted as an energy storage and heat-spreading module. The results indicated that using a TCU for passive energy storage significantly increased the portable electronics system’s operational performance.

In a work performed by Campbell et al. (1997) they introduced an algorithm that uses simulated annealing to perform electronic component layout while incorporating constraints related to thermal performance. Murakami and Mikic (2001) presented an optimization study using a method of determining optimum values of the channel diameter, flow rate and number of channels for minimum pumping power or minimum pressure drop. For a current electronic cooling requirement, the optimized diameter of a channel lied in the micro-scale range when water was used as working fluid.

In a work performed by Tam et al. (1993), the turbulent convection from a horizontally-orientated simulated printed-circuit board was investigated; the electronic components were impersonated by electrically-heated rectangular ribs mounted uniformly on the upper surface of a horizontally rectangular plate. Leung and Kang (1997) extended the investigation to study the combined effect of