Abstract
To enhance the performance of laminar forced convection in a two-dimensional channel carrying a board mounted with block heat sources, this study proposes a method of constructing slots in the board. The effects of the slot position and board location on the flow structure, temperature distribution and heat transfer coefficient are numerically investigated. Results show that the maximum enhancements on the average Nusselt numbers are about 81%, 57% and 55% for the front, top and rear surfaces of blocks, respectively, when $Pr = 0.7$, $Re = 500$, $L_x = 0.5$, $L_y = L_z = 1$, $H_b = L_h = 0.3$, $D_b = 0.7$, $D_f = 0.1$, $0 \leq L_s \leq 0.2$, $0.1 \leq D_a \leq 0.4$ and $0.2 \leq C_2 \leq 0.5$. In addition, the convective transfer behaviors are more sensitive to the variation of slot position when the spacing between the board and bottom channel plate $C_2$ is smaller.

Introduction
Heat transfer from block heat sources to forced convective gas stream is widely encountered in engineering applications, such as in the cooling of electronic systems, solar collectors, gas-cooled nuclear reactors, furnace and chemical processing equipments. Over the years, a lot of researchers have contributed their efforts to investigate the characteristics of convective flows over block heat sources. These reports indicated that the heat transfer coefficient progressively decreases in the flowing direction. In addition the recirculation cells in the gaps among blocks results in poor heat transfer performance of the front and rear surfaces of block heat sources. On the other hand, the heat flux in thermal devices has become more and vaster due to the increasing requirements of compactness for the respective systems. Therefore, it should be important to search for ways to effectively augment the characteristics of convective heat transfer from block heat sources. The main objective of this study is to examine the possibility of enhancement of heat transfer performance for block heat sources mounted on a board through constructing slots in the board.

Because of its frequent occurrence in the industrial situations, the convective heat transfer from heated blocks have been studied by numerous researchers in the past two decades. Due to space limitation, only a brief review of the previous literature is presented below. Lehmann and Wirtz [1], and Agonafer and Moffatt [2] experimentally and numerically investigated the characteristics of flows over an array of two-dimensional, rectangular components mounted on channel wall. Heat was applied to the top surface of one component. It was found that the variation of heat transfer coefficient along the heated surface is rather different to that for smooth channel wall. Experiments have been carried out by Kang et al. [3], and Nakayama and Park [4] to examine the effects of block height and wall conduction on...
the heat convection for air flow over an isolated block heat source mounted on plate. Davalath and Bayazitoglu [5] numerically predicted the behaviors of forced convection between parallel plates mounted with two-dimensional multiple blocks. Results indicated that the heat flux distributions at the rear surfaces of blocks are much smaller than those at the front and top surfaces. An analysis of heat transfer from rectangular heated block mounted on vertical and horizontal channel walls was carried out by Kim et al. [6]. They mentioned that the impact of buoyancy effect on the flow and thermal fields is more pronounced for the vertically oriented channel. Sparrow et al. [7] presented an experiment on heat transfer and pressure drop for air flow in arrays of heat generating modules deployed along one wall of a flat rectangular duct by using the naphthalene sublimation technique. The effects of missing elements, height difference between modules and implanted barriers were investigated. Asako and Faghri [8, 9] performed a three-dimensional analysis for laminar flow through an array of heated square blocks. Their results illustrated that the local heat flux on the top surface of block is higher than those on the front, side and rear surfaces. In addition, the Nusselt number decreases with the increasing block height and gradually approaches an asymptotic value. An experimental study on the convective heat transfer for water cooling of inline and staggered arrays of protruding elements has been reported by Garimella and Eibeck [10]. It was concluded that staggering the elements of the arrays could significantly enhance the heat transfer coefficient. Recently Furukawa and Yang [11] numerically investigated the thermal-fluid flow behaviors in parallel board with heat producing blocks. Herman and Kang [12], and Tsay et al. [13] conducted the effects of curved vanes and baffles on heat transfer characteristics of heated blocks.

The preceding review reveals that the information on heat transfer enhancement of block heat sources mounted on a board placed in a channel is rather limited. This study investigates numerically the effects of constructing slots in the board on the characteristics of heat transfer from block heat sources to air stream in a two-dimensional channel.

Analysis

The physical system under consideration, as illustrated in Figure 1, is a two-dimensional plate channel carrying a thin board which is installed with the leading edge $l_c$ downstream from the channel inlet, and with $c_2$ above the bottom channel plate. Five block heat sources with height $h_b$ and length $l_b$ are mounted on the upside of the board, and the front, top and rear surfaces of the block heat sources are subjected to uniform heat flux. A coolant stream enters the channel with a uniform velocity $u_e$ and temperature $T_e$. The stream divides into two sub-streams as it approaches to the leading edge of board. The up sub-stream flows through the upside of the board and removes the heat dissipated from the blocks. It is known that the heat transfer characteristics for the front and rear surfaces of the block heat sources are poor owing to the appearance of recirculation cells. Aiming to enhance the heat transfer characteristics of the block heat sources, this study proposes a method of constructing slots in the board. It is expected that only if a small portion of fluid passes across the slots, either upward or downward, the structures of recirculation cells would be changed. Thus the heat transfer performance of the block heat sources might be enhanced if the slots are well constructed. In an initial effort to investigate the effects of slots on the flow and thermal characteristics, the slots are all with the same length $l_s$. For the forward four slots, each slot is located with $d_a$ behind each block heat sources. In addition the last slot is with $d_f$ behind the last (fifth) block heat source.

Owing to the vast parameters governing this problem, the thickness of the boards is assumed to be infinitely small, and the heat conduction through the board is ignored. Thus the attention of present study can be more concentrated on the effects of slots on the transfer characteristics of block heat sources. The basic equations in dimensionless form describing the steady
ENHANCEMENT OF HEAT TRANSFER FROM BLOCK HEAT SOURCES MOUNTED ON A BOARD
TO AIR STREAM IN A CHANNEL BY CONSTRUCTING SLOTS IN THE BOARD

laminar forced convection in a two-dimensional plate channel are as follow:

Continuity equation
\[ \frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \]  

(1)

X-momentum equation
\[ U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re} \left[ \frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right] \]  

(2)

Y-momentum equation
\[ U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re} \left[ \frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} \right] \]  

(3)

and Energy equation
\[ U \frac{\partial \theta}{\partial X} + V \frac{\partial \theta}{\partial Y} = \frac{1}{Re Pr} \left[ \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \right] \]  

(4)

The governing equations are subjected to the following boundary conditions:

For 0 ≤ Y ≤ 1, at X = 0, U = 1, V = \theta = 0  

(5)

For 0 ≤ Y ≤ 1, at X → ∞,
\[ \frac{\partial U}{\partial X} = \frac{\partial V}{\partial X} = \frac{\partial \theta}{\partial X} = 0 \]  

(6)

For 0 < X < ∞, at Y = 0 and Y = 1, U = V = 0,
\[ \frac{\partial \theta}{\partial Y} = 0 \]  

(7)

and
\[ \frac{\partial \theta}{\partial n} = -1, \; U = V = 0 \; \text{on the front, top and rear surfaces of block heat sources} \]  

(8)

Equations (5)-(9) refer to the usual no-slip conditions on all the solid walls, and the assumption of thermal insulation for channel plates and board. The stream is with uniform velocity and uniform temperature at the channel inlet, and with hydrodynamic and thermal fully developed conditions at the exit far downstream to the trailing edge of board. With \( n \) representing the outward normal direction, equation (8) imposes an uniform heat flux along the block surfaces exposed to the stream, while equation (9) describes the thermal insulation for board surface.

The local Nusselt number along the front, top and rear surfaces of each block heat sources is of interest to the thermal system designer. It is defined as
\[ Nu = \frac{h c_{fl}}{k} = \frac{q_c c_{fl}}{k(T_f - T_c)} = \frac{1}{\theta_s} \]  

(10)

In addition, the average Nusselt number for the front, top and rear surfaces of each block heat source is calculated by
\[ \overline{Nu} = \frac{1}{L_h} \int_0^{L_h} Nu \, dX_h \]  

(11)

where \( X_h \) is the dimensionless coordinate along the block surface and \( L_h \) is the length of the front, top and rear sides of each block.

Solution Method

The governing equations (1) - (4) and boundary conditions (5) – (9) were solved by a numerical scheme derived from the SIMPLER algorithm. The proposed numerical algorithm was validated in two ways. First, different numbers of grid lines in both the X– and Y– direction were employed to ensure that the solution is grid independent. The differences in U, V and \( \theta \) at all grid points obtained from the 100 × 300 and 150 × 450 grid systems were less than 1% for a typical case with \( Pr = 0.7, Re = 500, H_b = L_b = 0.3, L_a = L_f = 1, D_a = D_f = 0.1, L_a = 0.2 \) and \( D_b = 0.7 \). Therefore the 100 × 300 grid system was set in the computation of the various cases to be presented. In addition, because of the elliptic nature of the present problem, it was necessary to inquire whether the boundary conditions at X → ∞ given by equation (6) do not artificially constrain the solution. To ensure that the results are not affected by the computation domain, tests are performed by varying the computation length downstream to the trailing edge of board \( L_c \). The difference between the results for \( L_c = 30 \) and \( L_c = 50 \) were within 0.4%. Thus, in all the subsequent numerical simulation the computation domain with \( L_c = 30 \) are considered to be sufficient to simulate the very long channel. Secondly, the results for the limiting case without the appearance of slots in the board are compared to the relevant literatures. Good
agreement was found between the present predictions and the results presented by Davalath and Bayazitoglu [5]. Through these program tests the proposed numerical scheme is considered to be appropriate for the problem under investigation.

Results and Discussions

Inspection of the forgoing analysis indicates that the flow and heat transfer characteristics in the present system depend on 12 parameters. Since a vast number of governing dimensionless parameters are required to characterize the system, a comprehensive analysis of all combinations of problems is not practical. The objective here is to present a sample of results that illustrates the enhancing performance for heat transfer from heated blocks mounted on a board to air stream in a channel through slotting the board. While computation can be performed with any combination, the effects of $C_2$, $D_a$ and $L_s$ are investigated in this work. In particular, air ($Pr = 0.7$) flowing through the channel with $L_e = 0.5$, $L_a = L_f = 1$, $H_b = L_b = 0.3$, $D_b = 0.7$, $D_f = 0.1$ and $Re = 500$ is considered. The results are presented for the case with $C_2$ varying from 0.2 to 0.5, $D_a$ from 0.1 to 0.4 and $L_s$ from 0 to 0.2.

Initially, the effects of $L_a$ and $D_a$ on flow distribution in the channel is portrayed by the streamlines for the system with fixed $C_2 = 0.2$, $Re = 500$. For the limiting case without slot ($L_s = 0$) in the board, the results in Figure 3(a) show that a primary recirculation cell appears in each gap between the blocks. The structures of the cells are similar to those in many previous articles, such as reported by Davalath and Bayazitoglu [5]. A scrupulous investigation on this figure reveals that, in the region near the trailing edge of board, the sub-stream beneath the board flows upward, and a portion of it flows reversely toward the last block. The phenomena are different to those for the situation with a board having very long length downstream from the last block [5]. For the case with slots $L_a = 0.2$ and $D_a = 0.1$ in the board, the results in Figure 2(b) indicate that, in the channel entrance region, the streamlines at the positions about $Y = C_2$ are rather parallel to the channel plates. This means that there is not fluid flows from $Y < C_2$ upward to $Y > C_2$ in the region near the leading edge of board, which is different to that for the case without slot in the board. Thus, in the leading edge of board, the flow rate of the sub-stream flowing into the passage below the board for the case with slots is larger than that without slot. In addition, it can be clearly observed that there is fluid of the sub-stream below the board passing across the slots into the gaps among the blocks. The tracks of these fluid are rather interesting. Some of the fluid directly flow toward downstream and pass over the top surfaces of blocks. The other portion of the fluid flows adversely toward upstream, then circulate in the gaps before it flow toward downstream and pass over the top surfaces of blocks. Comparing the streamlines plotted in Figure 2(b) and 2(c), it is more evident for $D_1 = 0.4$ that the fluid passing across the slots circulates in the gaps before it leaves the gaps. An overall inspection on Figures 2(a) – 2(c) reveals that the appearance of slots in the board can strongly change the structures of recirculation cells in the gaps and behind the last block.

Figures 3(a) – 3(c) plot the streamlines for the cases with the board placed at $C_2 = 0.5$. For the limiting case without slot in the board, it is seen in Figure 3(a) that, in the entrance region, the streamlines at the positions about $Y = C_2$ distort downward into the region below the board. The results illustrate that there is fluid flowing from the region of $Y > C_2$ downward to the region of $Y < C_2$. In the region near the trailing edge of board, the streamlines of the sub-stream below the board are rather parallel to the channel plates. These phenomena are rather different to those for the case with $C_2 = 0.2$. For the case with slots $L_a = 0.2$ and $D_a = 0.1$ in the board, the results in Figures 3(b) show that the distortions of streamlines for $Y > C_2$ are weakened, and more densely packed in the channel entrance region. In addition there is fluid flows downward into the gaps, and circulates along the front surfaces of blocks. Then the fluid flows forward, and finally passes across the slots. It is noted in Figure 3(b) that the direction of fluid passing across the slot behind the last block is upward, which is different to those passing across the
slots in the gaps. A comparison on Figures 3(b) and 3(c) reveals that the flow structures in the gaps are rather different. For the case with slots at $D_a = 0.4$, the streamlines plotted in Figures 4(c) indicate that the directions of fluid passing across the slots in the second and third gaps are upward. These fluid, instead of flowing over the top surfaces of blocks, circulates in the gaps. Then, the fluid downward passes across the slots.

Figures 4(a) – 4(c) illustrate the effect of slots on the temperature distributions for the system with the board placed at $C_2 = 0.2$. For the limiting case without slot in the board, the isotherms plotted in Figure 4(a) indicate that the thermal layers along the top and front surfaces of blocks are thicker for latter blocks. However, the smallest of the thermal layers along the rear surfaces of blocks is for the last block. This is due to the fact that there is fluid flowing from the region $Y < C_2$ upward to $Y > C_2$, and the fluid circulates around the rear surface of last block before that flows downstream. Consequently the heat is more easily dissipated from the rear surface of last block. In addition the isotherms in the region vicinity to the rear surfaces of blocks look rather parallel. A comparison of the isotherms plotted in Figures 4(a) and 4(b) reveals that the thermal layers along the rear surfaces of blocks are thinner for the case with slots at position $D_a = 0.1$. This can be attributed to the fact that, for the case with the appearance of slots, the fluid can pass across the slots from $Y < C_2$ upward into the gaps, and circulates toward the rear surfaces of blocks before those fluid leaves the gaps. When the slot positions move from $D = 0.1$ to $D = 0.4$, it is observed in Figure 4(c) that the thermal layers along the front surfaces of the second to fifth blocks are rather thin. This can be made plausible that the fluid upward passing across the slots circulates in the gaps very near the front surfaces of the blocks, as shown in Figure 2(c). Shown in Figures 5(a) – 5(c) are the temperature distributions for the cases with the board placed at $C_2 = 0.5$. An examination on the results in Figures 4(a) and 5(a) indicates that the differences in temperature distributions between $C_2 = 0.2$ and $C_2 = 0.5$ are not substantial in the regions vicinity to the blocks. This implies that, for the system without slot in the board, the heat transfer characteristics for the blocks are not sensitive to the variation of board position as $0.2 \leq C_2 \leq 0.5$. The isotherms in Figures 5(b) and 5(c) for the cases with slots in the board are rather different to those in Figure 5(a) for the case without slot. In addition the isotherms are rather packed for the system with the existence of slots in board.

Figures 6(a) – 6(c) represent the variations of local Nusselt numbers along the front, top and rear surfaces of the first to fifth blocks, respectively, as the board is placed at $C_2 = 0.2$. For the limiting case without slots in board, generally the Nu is smaller for the block at a further downstream location. For a given block, the maximum heat transfer coefficient occurs at the front corner. The Nu of rear surface is substantially smaller than those of front and top surfaces of blocks. However, it is noted that, for the rear surfaces, the fifth block has largest Nu among the blocks. This behavior is resulted from the flow and temperature distributions shown in Figures 2(a) and 4(a), respectively. When the board with slots at $D_a = 0.1$, the results in the Figure 6(b) show that the Nu’s for rear surfaces are significantly enhanced. While the Nu’s become worse for the front surfaces of second to fifth blocks. For the board with slots at $D_a = 0.4$, the results in Figure 6(c) show that the Nu’s for the front and rear surfaces are simultaneously promoted. Thus it is mentioned that the existence of slots can effectively enhance the heat transfer characteristics of blocks, and the variation of slot position will cause substantial change in the transfer phenomena. When the board is located at $C_2 = 0.5$, the results in Figure 7 illustrate that the local heat transfer coefficients for the front, top and rear surfaces of blocks can all be effectively enhanced when $D_a = 0.1$ and $D_a = 0.4$.

It can be clearly observed in Figures 6 and 7 that the heat transfer characteristics of blocks are sensitive to the variation of slot position. In general, the heat transfer performance are better when the slots are at $D_a = 0.4$. Finally, to conveniently investigate the enhancement of transfer characteristics through constructing
slots in the board, Table 1 and 2 list the average Nusselt number for the system without slot and with slots at $D_a = 0.4$. When the board is located at $C_2 = 0.2$, an examination on the data in Table 1 reveals that the maximum enhancement of $\overline{N_u}$ is about 81 for the front surfaces of blocks. While it is about 55 for the rear surfaces. When the board is located at $C_2 = 0.5$, it can be read from Table 2 that the maximum enhancements of $\overline{N_u}$ are about 71, 67 and 33 for the front, top and rear surfaces of blocks, respectively.

Conclusions

This study aims to investigate numerically the effects of constructing slots in the board on laminar forced convection in a channel carrying a board mounted with five block heat sources. Owing to the appearance of the slots in the board, a portion of the air stream passes across the slots, either upward or downward. Thus the structures of recirculation cells in the gaps among the blocks are altered, and the heat transfer characteristics of the block heat sources are significantly enhanced. The maximum enhancements on the average Nusselt numbers are about 81%, 67% and 33% for the front, top and rear surfaces of blocks, respectively, when $Pr = 0.7$, $Re = 500$, $L_e = 0.5$, $L_a = L_f = 1$, $H_b = L_h = 0.3$, $D_b = 0.7$, $D_t = 0.1$, $0 \leq L_s \leq 0.2$, $0.1 \leq D_a \leq 0.4$ and $0.2 \leq C_2 \leq 0.5$. In addition, the convective transfer behaviors are more sensitive to the variations of slot positions when the spacing between the board and bottom channel plate $C_2$ is smaller.

Acknowledgement

The financial support of this study by the Engineering Division of National Science Council, R.O.C., through the contract NSC-93-2212-E-150-003 is greatly appreciated.

Nomenclature

- $C_2$: dimensionless spacing between the board and bottom channel plate, $c_2/c_1$
- $D_a$: dimensionless distance between the slots in gaps and rear surfaces of blocks, $d_a/c_1$
- $D_b$: dimensionless distance between blocks, $d_b/c_1$
- $D_t$: dimensionless distance between the last slot and rear surface of last block, $d_t/c_1$
- $H_b$: dimensionless height of block heat source, $h_u/c_1$
- $h$: heat transfer coefficient
- $k$: thermal conductivity
- $L_a$: dimensionless distance between the leading edge of board and the front surface of first block, $l_a/c_1$
- $L_b$: dimensionless length of the blocks, $l_b/c_1$
- $L_e$: dimensionless distance between the channel inlet and the leading edge of board , $l_e/c_1$
- $L_f$: dimensionless distance between the trailing edge of board and the rear surface of board, $l_f/c_1$
- $P$: dimensionless pressure, $p/(\rho u_e^2)$
- $Pr$: Prandtl number, $\nu/\alpha$
- $q_u^\prime$: heat flux on block surface
- $Re$: Reynolds number, $\pi c_1/\nu$
- $T_s$: surface temperature at block
- $U$: dimensionless longitudinal velocity, $u/u_e$
- $V$: dimensionless transverse velocity, $v/u_e$
- $X$: dimensionless longitudinal coordinate, $x/c_1$
- $Y$: dimensionless transverse coordinate, $y/c_1$
- $\alpha$: thermal diffusivity
- $\theta$: dimensionless temperature, $(T-T_e)/(q_u^\prime c_1/k)$
- $\theta_s$: dimensionless surface temperature at block, $(T_s-T_e)/(q_u^\prime c_1/k)$
- $\nu$: kinematic viscosity
Reference


Table 1. The comparison of the average Nusselt numbers $\overline{\text{Nu}}$ for cases without and with slots in the board when $C_2 = 0.2$

<table>
<thead>
<tr>
<th>Block No.</th>
<th>Front surface A</th>
<th>Top surface A</th>
<th>Rear surface A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>1</td>
<td>15.51</td>
<td>15.42</td>
<td>14.10</td>
</tr>
<tr>
<td></td>
<td>14.10</td>
<td>14.64</td>
<td>4.98</td>
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<tr>
<td>2</td>
<td>10.03</td>
<td>18.13</td>
<td>14.03</td>
</tr>
<tr>
<td></td>
<td>13.60</td>
<td>6.46</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>8.16</td>
<td>13.51</td>
<td>11.73</td>
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<td></td>
<td>11.54</td>
<td>6.21</td>
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<td>4</td>
<td>7.41</td>
<td>11.79</td>
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<td>5</td>
<td>6.88</td>
<td>9.46</td>
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<tr>
<td></td>
<td>9.68</td>
<td>6.04</td>
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</tr>
</tbody>
</table>

A: without slot; B: with slots $L_2 = 0.2$ and $D_2 = 0.4$

Table 2. The comparison of the average Nusselt numbers $\overline{\text{Nu}}$ for cases without and with slots in the board when $C_2 = 0.5$

<table>
<thead>
<tr>
<th>Block No.</th>
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<th>Rear surface A</th>
</tr>
</thead>
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<td>B</td>
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<td>B</td>
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<td>14.53</td>
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</table>

Table 1 and Table 2: The comparison of the average Nusselt numbers $\overline{\text{Nu}}$ for cases without and with slots in the board when $C_2 = 0.2$ and $C_2 = 0.5$ respectively.

Figure 1. Schematic diagram of the physical system.
Figure 2. The effects of slot length and slot position on the distributions of streamlines for Re = 500, C = 0.2, D = 0.7 and (a) L_a = 0 i.e. without slot; (b) L_a = 0.2, D_a = 0.1; (c) L_a = 0.2, D_a = 0.4.

Figure 3. The effects of slot length and slot position on the distributions of streamlines for Re = 500, C = 0.5, D = 0.7 and (a) L_a = 0 i.e. without slot; (b) L_a = 0.2, D_a = 0.1; (c) L_a = 0.2, D_a = 0.4.

Figure 4. The effects of slot length and slot position on the isotherms of streamlines for Re = 500, C = 0.2, D = 0.7 and (a) L_a = 0 i.e. without slot; (b) L_a = 0.2, D_a = 0.1; (c) L_a = 0.2, D_a = 0.4.

Figure 5. The effects of slot length and slot position on the isotherms of streamlines for Re = 500, C = 0.5, D = 0.7 and (a) L_a = 0 i.e. without slot; (b) L_a = 0.2, D_a = 0.1; (c) L_a = 0.2, D_a = 0.4.

Figure 6. The effects of slot length and slot position on the variations of local Nusselt numbers along the front, top and rear surfaces of blacks for Re = 500, C = 0.2 and D = 0.7.

Figure 7. The effects of slot length and slot position on the variations of local Nusselt numbers along the front, top and rear surfaces of blacks for Re = 500, C = 0.5 and D = 0.7.