TURBULENCE HEAT/MASS TRANSFER IN A SERPENTINE CHANNEL WITH DIFFERENT ASPECT RATIO

Hiroshi Nakayama*, Masafumi Hirota*, Yasuhiro Ono**, Lei CAI†, Hideomi Fujita††

* Department of Micro-Nano System Engineering, Nagoya University
Furo-cho, Chikusa-ku 464-8603, Nagoya, Japan
**Toyota Motor Corporation, 1 Toyota-Cho, 471-8571, Toyota, Japan
† BorgWarner Morse TEC Japan, 1300-50, Yahata, Nabari, 518-0495, Mie, Japan
†† Department of Mechanical Engineering, Meijo University, 1-501, Siogamaguchi,
Tenpaku-ku,468-8502, Nagoya, Japan

Corresponding author: naka@mech.nagoya-u.ac.jp, phone:+81-52-789-2701, fax:+81-52-789-2703

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Abstract - Experimental study was conducted on the flow and convective heat/mass transfer in serpentine rectangular channels. PIV measurements were performed for flow field analysis at a Reynolds number of $2.0 \times 10^4$, and the velocity data obtained near the walls were compared with published local heat/mass transfer rates to clarify the mechanism of heat transfer. Special attention was directed to the influence of the channel aspect ratio on thermo-fluids characteristics in the channels. The local heat transfer enhancement after turn is strongly influenced by the magnitude of secondary flow velocity, convective mean velocity, turbulent kinetic energy, and their contributions ratio changes depending on the channel aspect ratios.

1. Introduction

Rectangular cross-sectioned serpentine channels with sharp turns are often used as the passage of fluid in various types of thermal equipment; the typical applications are flow passages in compact heat exchangers and internal cooling passages of an advanced gas-turbine blade. The flow characteristics in serpentine channels with smooth walls have highly complicated features due to the combined effects of secondary flow, separation, recirculation, and reattachment of the flow around the turn section [1]. Thus, under forced convection heat transfer, a non-uniform distribution of local heat transfer rates is induced by such a complexity of the flow field [2].

Over the past decades, a number of experimental and numerical studies for forced convection heat transfer in this type of channels have been conducted. Most of these studies have dealt with the effect of channel geometry on heat transfer, e.g. turn clearance [2], channel aspect ratio [3, 4], thickness [5, 6] or inclination angle [7,8] of the partition wall. These studies have proved that the change of the channel geometry has great influence on heat transfer. The present authors have also carried out a series of investigations on the local heat/mass transfer characteristics in this type channel by using the naphthalene sublimation method [2, 7, 8]. They have found that the channel aspect ratio $AR$ exerts significant influence on the heat transfer characteristics in/after the turn section and the heat transfer performance deteriorates as $AR$ is increased [8]. Although it is of engineering importance to make clear the heat transfer mechanism in serpentine channels with different $AR$, very few discussions have been made on this subject. Since fluid dynamics in the channels are closely correlated to heat transfer, the combined analysis of flow and heat/mass transfer are quite helpful for the better understanding of the heat transfer mechanism in the serpentine channels.

In the above situation, the objective of the present study is to clarify experimentally the relationship between flow and heat transfer characteristics in the serpentine channels with different channel aspect ratio. The channel aspect ratio $AR$ is defined as $A/B$, where $A$ and $B$ represent the width and height of the channel cross-section at the entrance (Fig.2), respectively, and three values of $AR$ (= 1, 2, 4) have been tested in this
study. We have conducted detailed velocity measurements for airflow by using PIV under a single Reynolds number $Re = 2.0 \times 10^4$. Moreover, the combined analysis of flow and heat/mass transfer has been conducted by comparing the near-wall flow characteristics with the local Sherwood number data previously measured by Cai et al. [8]. Based on this analysis, the flow parameters that dominate the heat transfer after the turn are investigated.

2. Experimental apparatus and procedure

2.1 Test section

Figure 1 shows the schematic diagram of the experimental apparatus. This apparatus has basically the same configuration as that of preceding studies [9]; it is operated in a suction mode and air flows into the test channel through a settling chamber. Figure 2 shows the details of the test section, which is made of transparent acrylic resin plates to allow direct optical access. A baffle plate is placed at the entrance of the test channel to form a sharp-edged entrance, which ensures that the airflow entering this test section has an abrupt contraction-entrance condition with strong turbulence.

The aspect ratio $AR$ of the channel is defined as $A/B$, where $A$ and $B$ represent the width and height of the channel cross-section at the entrance, respectively. The variation of $AR$ is realized by changing only the channel height $B$ with all the dimensions of the top and bottom walls kept constant. In this study, three aspect ratios, $AR = 1, 2$ and 4, have been tested, which correspond to three channel heights of $B = 40$ mm, 20 mm and 10 mm with a single channel width of 40 mm. The turn clearance $C$ is kept at 40 mm; namely the turn clearance is just the same as the channel width. This channel geometry is often adopted in the preceding studies on serpentine channels. The length between the channel entrance and the end wall is 267 mm. The partition wall thickness $Td$ is 8 mm. The origin of the coordinate system is located at the center of the partition-wall tip, and the $Y$-axis is paralleled with the bottom/top wall (spanwise coordinate), and the $Z$-axis is parallel to the partition/outer walls (transverse coordinate). In this paper, the $X$- and $Z$-coordinates are normalized by $C$ and $B/2$, respectively, and they are denoted as $X^*$ and $Z^*$. The $Y$-coordinate is normalized by the half length of the end wall $A+T/2$ or by the channel width $A$ and denoted as $Y^*$ and $Y^{**}$, respectively. The mean velocity components in the $X$, $Y$- and $Z$-directions are denoted as $U$, $V$ and $W$, respectively, and the fluctuating velocities are denoted as $u$, $v$ and $w$.

In all the experiments, the Reynolds number $Re$ ($= U_b d_h / \nu$; $U_b$ : bulk velocity, $d_h$ : hydraulic diameter at the channel entrance, $\nu$ : kinematic viscosity of air) is fixed at $2.0 \times 10^4$. The temperature of air is approximately 20 degree in centigrade.

2.2 PIV measurement

For velocity measurement, we used a PIV system. Pulsed laser sheets about 1.0 mm thick are supplied by the double pulse Nd:YAG lasers (15 mJ/pulse) with the frequency of 15 Hz. The time interval between two pulses is optimized according to the velocity in an observation area (about 5 ~ 30 $\mu$s in the present experiment). A CCD camera with 1K $\times$ 1K pixels is used to capture the particle images. The timing between the laser and CCD camera is controlled by a synchronizer system (TSI: 610032). The flow is seeded by oil particles (~ 5 $\mu$m in diameter)
provided by a Laskin-nozzle type particle generator. The captured particle images are processed by a direct cross-correlation code developed in our laboratory with sub-pixel accuracy. The interrogation window size is 31 × 31 pixels with 50% overlap. A post-processing program is used to eliminate the spurious vectors and to calculate the statistical flow properties. For statistical analysis, the mean velocity and the intensities of the velocity fluctuations are computed by ensemble averaging 500 instantaneous fields. To investigate the influence of the channel aspect ratio on the global flow characteristics and heat transfer mechanism, we have measured the velocity distributions in near-wall planes as well as in the symmetry and cross-sectional planes of the channels.

3. Results and Discussion

3.1 Flow developments in the symmetric plane

In order to survey the global flow characteristics in the channel, we first show the velocity distribution obtained within the symmetry plane of the channel ($Z^* = 0$). The mean velocity distributions are summarized in a form of vector diagrams in Figs. 3 (a) - (c) for three $AR$ studied.

In the straight section before the turn, a developing flow that is symmetric with respect to the spanwise centerline approaches the turn section. Near the turn entrance, it is observed that the flow is deviated toward the partition-wall side. In this section $AR$'s influences on the flow structure seem to be rather weak. Inside the turn, the flow near the partition wall is strongly accelerated and then the flow impinges on the end wall. At the first outer corner in the turn, a recirculation region appears and it becomes more clearly defined with the increases of $AR$, i.e., as the channel cross section becomes flatter, while the recirculation zone does not appear so clearly in the second outer corner.

In the straight section after the turn, the flow exiting the turn is separated at the tip of the partition wall, and a separation bubble grows to approximately 50% of the channel width along the partition wall. This separated flow reattaches on the partition wall. The heights of the separation bubble for three $AR$ are almost the same. Due to the choke of the flow passage by the separation bubble, the flow is accelerated in the outer-wall side: the maximum $U$ amounts to 2.05 $U_b$, 2.12 $U_b$ and 2.25 $U_b$ at $X^*$ = -0.6, -0.5, and -0.6 for $AR = 1, 2$ and 4, respectively. Figure 3 also shows that the distance between the partition wall tip and the flow reattachment point becomes longer as $AR$ is increased. The time-averaged locations of the flow reattachment point are 1.6 $C$, 1.7 $C$ and 2.6 $C$ away from the partition wall tip for $AR = 1, 2$ and 4, respectively. After the flow reattachment, the flow redevelops downstream; the flow with higher velocity is deviated to the outer-wall side. For $AR = 4$, due to the elongated separation bubble, the mainstream velocity has a non-uniform distribution in the spanwise direction at the exit of the measurement section of $X^* = -4$.

3.2 Secondary flow vectors and turbulence statistics in cross sections

The streamwise evolutions of secondary flows and two-dimensional turbulent kinetic energy $k_{yz}/U_b^2$ after the turn are shown in the upper and lower halves of Fig. 4, respectively. In these figures, the left periphery is the partition wall, and right periphery
Fig. 4 Secondary flow vectors (upper figure) and contour plots of normalized two-dimensional turbulent kinetic energy distributions $k_{yz}/U_b^2$ (lower figure)

corresponds to the outer wall. Although the measurements have been made in six cross sections after the turn, the typical results obtained in four cross sections are presented in this paper. Four figures for each $AR$ represent four streamwise locations, i.e., turn exit ($X^* = 0$), and three cross-sections after the turn ($X^* = -1, -2$ and $-3$).

At the turn exit ($X^* = 0$) of all the channels, the turn-induced centrifugal force pushes the fluid near the symmetric plane ($Z^* = 0$) toward the outer wall and a longitudinal vortex appears in the outer-wall side, which shows the same qualitative characteristics observed in the past studies [5]. As $AR$ is increased, due to suppression of the fluid motion in $Z$-direction, the transverse velocity $W$ becomes slower whereas the spanwise velocity $V$ is intensified. Thus, the longitudinal vortex loses its structural clarity at higher $AR$. Near the partition wall, the low $V$ region is observed, which corresponds to such a flow separation as observed in Fig. 3. As to the turbulence energy, $k_{yz}$ attains the local maximum in center of longitudinal vortex as well as in the separation shear layer near the partition wall. The high $k_{yz}$ near the vortex center is brought about by the increase of $\partial V/\partial Y$ as observed in the secondary flow vector diagram.

At $X^* = -1$, which corresponds to the streamwise midpoint of the separation bubble, the scale of the vortex becomes larger than that of the turn exit mentioned above. In this cross section, high $k_{yz}$ region around the center of the longitudinal vortex merges with that in the shear layer around the separation bubble. It is clearly observed that both the secondary flow velocities and $k_{yz}$ decrease as $AR$ is increased. This is explained as follows: the fluid motion in the $Z$-direction is suppressed by the influence of the top and bottom walls as mentioned above, and that in the $Y$-direction is damped by the viscous force that is intensified with a smaller channel height.

At $X^* = -2$, the secondary currents that proceed from the outer wall toward the partition wall along the top (bottom) wall are intensified. The influence of $AR$ on the secondary flow pattern is observed as follows. At $AR = 1$, the vortices spread over the entire cross section. As for $AR = 2$ and 4, in addition to the longitudinal vortex in the outer-wall side, a weak and small vortex rotating in the counter direction appears in the partition-wall side. Since this section is located after the reattachment point for $AR = 1$ and 2, the maximum values of $k_{yz}$ become smaller than those at the upstream sections.

In the further downstream cross section of $X^* = -3$, the vortex structure barely remains for $AR =$
3.3 Peak vorticity and cross-section averaged kinetic energy

Figure 5 shows the decay characteristics for the peak of the mean streamwise vorticity \( \Omega = d_d/U_b \) \((\partial W/\partial Z - \partial W/\partial Y)\) in six Y-Z cross-sections after the turn, where the peak \( \Omega \) is defined as the maximum value of \( |\Omega| \) and it is attained at the center of the longitudinal vortex observed in Fig. 4. As a whole, the peak \( \Omega \) shows smaller values as \( AR \) is increased, i.e., as the channel cross section becomes flatter. In \( AR = 1 \) and 2, the peak \( \Omega \) attains the maximum at \( X^* = -0.5 \) and decreases in the flow direction. In \( AR = 4 \), the maximum \( \Omega \) is observed just at the turn exit \( (X^* = 0) \) and it decreases gradually as the flow proceeds downstream. As observed in Fig. 4 as well, the longitudinal vortex tends to be maintained to the further downstream region in the channel with smaller \( AR \).

Next, in order to evaluate the influence of \( AR \) on the turbulent kinetic energy quantitatively, the streamwise variations of the cross-section averaged two-dimensional turbulence energy \( k_{yz-m} \) are shown in Fig. 6. Similar to the peak vorticity, \( k_{yz-m} \) shows larger values with smaller \( AR \). For all \( AR, k_{yz-m} \) attains a maximum at \( X^* = -1 \) and it gradually decreases downstream. The \( k_{yz-m} \) distribution for \( AR = 1 \) is comparable with that for \( AR = 2 \), whereas the values of \( k_{yz-m} \) for \( AR = 4 \) are about a half of those for \( AR = 2 \). These results clearly show that after the turn the fluid motion in the transverse direction is suppressed by the increase of the aspect ratio of the channel cross section.

3.4 Characteristics of near-wall flow

In order to examine the mechanism of heat transfer in the channels, we have measured the flow characteristics in the planes near the channel walls. Before examining the heat transfer mechanism, detailed data of the surface flow are presented in this section for the better understanding of the flow structure.

Figures 7 (a) - (c) are the mean velocity vector diagrams obtained near the channel walls. The measurement planes are set at 1 mm away from four walls (bottom wall, end wall, outer wall after the turn and partition wall after the turn). Inside the turn, unlike the flow development in the symmetry plane shown in Fig. 3, the surface-flow on the bottom wall is directed away from the end wall. This tendency is intensified with the decreases of \( AR \). At the first outer corner, similar to the flow in the symmetry plane, the recirculation zone becomes more clearly defined as \( AR \) is increased. As to the surface flow on the end wall, a center of the flow impingement on this wall is observed around \( Y^* = -0.4 \) for all \( AR \). This flow impinges again on the top and bottom walls, and most of the impinging flow is then accelerated toward the second outer corner \( (Y^* = 1) \). A part of the impinging flow is, however, reversed toward the first corner \( (Y^* = -1) \), and causes a recirculation zone there.

In the straight section after the turn, the surface flow on the bottom wall is directed toward the partition wall outside the separation bubble. This tendency is just opposite to the flow in the symmetric plane, and
Fig. 7 Mean surface-flow vector distributions at 1mm away from walls

it is intensified as $AR$ is decreased. This feature of the surface flow on the bottom wall after the turn is consistent with the secondary flow vectors presented in Fig. 4. In spite of such a difference of the flow characteristics between the near-wall plane and the symmetry plane, the time-averaged locations of the flow reattachment are almost the same in both planes for all $AR$.

On the outer wall after the turn, the surface flow characteristics are quite similar to those observed on
the end wall, but the reversed flow toward the second outer corner ($X^* = 1$) in the turn is not observed so clearly. The surface flow on the partition wall shows quite a uniform distribution in the spanwise ($Z$-axis) direction for all $AR$, and the flow that impinges on the top and bottom walls is not observed even in the vicinity of the flow reattachment point.

Next, the corresponding two-dimensional turbulent kinetic energy near the walls are shown in Figs. 8, where it is defined as $k_{xy} = (u^2 + v^2)/2$ for the bottom wall, $k_x = (v^2 + w^2)/2$ for the end wall, and $k_z = (u^2 + w^2)/2$ for the outer and partition walls. Inside the turn, high $k_{xy}$ is observed around $X^* = 0.5$ on the bottom wall and this is mainly attributed to relative large velocity gradient $\partial U/\partial Y$ that is caused by the interference of the flow separation at the upstream edge of the partition-wall tip and the secondary flow directing away from the end wall. As observed in Fig. 7, $\partial U/\partial X$, $\partial V/\partial Y$ in this region becomes larger as $AR$ is decreased, thus $k_{xy}$ in this region shows the largest value in the channel of $AR = 1$. As for the end wall, $k_{xy}$ attains the local maximums in the vicinity of the flow-impingement center ($Y^* = -0.4$) and near the second outer corner ($Y^* = 1$). In $AR = 1$, $k_{xy}$ near the flow-impingement center shows two local maximums at $Z^* = \pm 0.8$, whereas in $AR = 2$ and 4 it attains a single local maximum. It is estimated that this difference of $k_{xy}$ distributions is attributed to the combined effects of velocity gradients $\partial V/\partial Y$, $\partial W/\partial Z$ and $\partial U/\partial X$. On the other hand, large $k_{xy}$ near the second corner is mainly caused by the increase of $\partial V/\partial Y$ as recognized from the velocity vector on the end wall in Fig. 7.

In the straight section after the turn, $k_{xy}$ on the bottom wall shows sharp peaks along the shear layer around the separation bubble. This high $k_{xy}$ region is attributed to the large velocity gradient $\partial U/\partial Y$ caused by the presence of the separation bubble. The distributions of $k_{xy}$ in the channels of $AR = 1$ and 2 agree quantitatively with each other, whereas the $k_{xy}$ values for $AR = 4$ are generally smaller. On the partition wall, $k_x$ attains the local maximum around the flow reattachment point ($X^* = -1.6, -1.7$ and -2.6 for $AR = 1, 2$ and 4, respectively). These values become larger as $AR$ is decreased. In the distributions of $k_x$ on the outer wall, similar to the distributions on the end wall, $k_x$ attains two local maximums for $AR = 1$ and a single local maximum for $AR = 2$ and 4. From these characteristics of the turbulence energy, it is again ascertained that the surface flow on the outer wall after the turn has a feature similar to that on the end wall.

### 3.5 Correlation between local heat transfer and near-wall flow parameters

In order to clarify the heat transfer mechanism after the turn, the combined analysis of flow and heat transfer has been conducted by comparing the distributions of the near-wall velocities described above with the local Sherwood number previously measured by Cai et al. [8]. In this study, the analysis has been made on the bottom wall that has the largest heat/mass transfer area in the channel: three near-wall flow parameters, i.e., $W/U_b$ (mean velocity component normal to the wall bottom), $(U^2 + V^2)^{0.5}/U_b$ (mean velocity parallel to the wall), $k_{xy}/U_b^2$ (2-D turbulent kinetic energy), measured at 1 mm away from the bottom wall are used to investigate the influence of the flow parameters on the heat transfer from the bottom wall.

The analysis has been made by evaluating the cross correlations between each flow parameter and the local Sherwood number, which are defined by the following equations [10].

\[
\frac{W}{W_{\text{min}}} \left( \frac{Sh}{Sh_0} \right) \quad (1)
\]
\[
\left( \sqrt{U^2 + V^2} \right) \left( \sqrt{U^2 + V^2} \right)_{\text{max}} \left( \frac{Sh}{Sh_0} \right) \quad (2)
\]
\[
\left( \frac{k_{xy}}{k_{xy,\text{max}}} \right) \left( \frac{Sh}{Sh_0} \right) \quad (3)
\]

The subscripts max and min denote the maximum and the minimum values of the flow parameters in the reference area, respectively. In case of $W$, the velocity facing to the bottom wall that is responsible for the heat transfer is expressed with $W < 0$, thus the minimum value of $W$ in the reference area ($W_{\text{min}}$) is adopted as the normalization parameter. $Sh_0$ is Sherwood number for the fully developed turbulent flow in a straight channel, which is calculated by Dittus-Boelter equation modified for mass transfer [8].

Figure 9 shows the distributions of the local Sherwood number $Sh/\ Sh_0$ on the bottom wall. It is found that in $AR = 1$ the high heat/mass transfer regions are formed in the partition-wall side after the separation bubble and along the outer wall in and after the turn section. As $AR$ is increased, the heat/mass
transfer in those regions tends to be deteriorated. Figures 10, 11 and 12 show the distributions of heat–flow correlations represented by Eqs. (1), (2) and (3), respectively. The correlation becomes higher if the local Sherwood number and the corresponding flow parameter show large values concurrently at the same location on the bottom wall [10], and the high correlation indicates that the corresponding flow parameter mainly contributes to the heat transfer in that region.

We begin the discussion with the channel of $AR = 1$. As described above, in Fig. 9 (a), high $Sh$ regions appear in the vicinity of the outer wall and in the partition-wall side after the separation bubble. As suggested from Figs. 10 (a) and 11 (a), the local maximum of $Sh$ near the outer wall is well correlated with both $W$ and $(U^2 + V^2)^{0.5}$. From Fig. 7 showing the mean surface flow, it is recognized that the velocity component normal to the bottom wall $W$ is generated by the impingement of the primary flow on the outer wall. This impinging flow then impinges on the bottom wall and enhances the heat transfer. The high correlation between $W$ and $Sh$ is limited to quite a narrow region near the outer wall. Another mechanism of high heat transfer rate in this region is ascribed to the acceleration of the surface flow parallel to the bottom wall.

On the other hand, the high $Sh$ region in the partition-wall side is highly correlated with the 2D turbulence kinetic energy $k_{xy}$ shown in Fig. 12 (a).
Thus, the heat transfer in this region is dominated by high turbulence produced in the shear layer around the separation bubble. This turbulence exerts noticeable influence on the heat transfer in a wide region on the bottom wall.

$AR$ exerts significant influence on the $Sh$ distributions on the bottom wall. In the first corner inside the turn section and in the separation bubble after the turn, the recirculation-induced low $Sh$ regions become more clearly defined as $AR$ is increased. Meanwhile, the local maximum regions near the end wall and near the outer wall after the turn become narrower with $AR$. As observed in Figs. 10 and 11, in the outer-wall side of the channel with high $AR$, the correlation between $W$ and $Sh$ is considerably lowered while high correlation is maintained between $(U^2+V^2)^{0.5}$ and $Sh$. This means that, in the region near the outer wall for higher $AR$, the velocity component $W$ is weakened due to the restraint of the fluid motion in the $Z$-direction and high $Sh$ is caused by the acceleration of the wall-parallel mean velocity component as observed in Fig. 7.

The $Sh$-values in the high $Sh$ region after the separation bubble are remarkably decreased as $AR$ is increased and $k_{xy}$-$Sh$ correlation is also lowered there with the increase of $AR$. This result is consistent with the decrease of $k_{xy}$ for higher $AR$ as observed in Fig. 4, and it follows that turbulent heat transfer after the turn is generally deteriorated in the channel with higher $AR$ due to the restraint of the fluid motion by the channel walls.

4. Conclusions

In this study, the effect of the aspect ratio of the channel cross section $AR$ on flow characteristics in rectangular channels with sharp 180-deg turn has been investigated in detail by using PIV. Based on the experimental data, the combined analysis of flow and heat/mass transfer has been conducted by comparing the near-wall flow parameters with the local Sherwood number distributions. The flow parameters that dominate the heat transfer after the turn have been examined with this analysis. The results are summarized as follows.

1. The influence of $AR$ on the flow characteristics is significant in and after the turn section. The position of the flow reattachment on the partition wall within the symmetry plane moves downstream and the turbulent kinetic energy decreases as $AR$ is increased.

2. A longitudinal vortex is formed in the outer-wall side after the turn. In the channel with higher $AR$, this longitudinal vortex is considerably suppressed and diminishes rapidly in the streamwise direction.

3. The flow parameter that dominates the local heat transfer on the bottom wall after the turn changes depending on the locations. The high $Sh$ region in the vicinity of the outer wall is caused by the mean velocity components both normal and parallel to the bottom wall. Heat transfer enhancement in the partition wall-side after the separation bubble is highly correlated with the 2D turbulent kinetic energy $k_{xy}$. Basically, although high $Sh$ regions decay with the increase of $AR$, high $Sh$ region near the outer wall is maintained due to the acceleration of the mean velocity component parallel to the wall.

References


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