LOCAL HEAT/MASS TRANSFER MEASUREMENTS IN A RECTANGULAR DUCT WITH DISCRETE RIBS

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ABSTRACT

The influence of the arrangement and the length of discrete ribs on heat/mass transfer and friction loss is investigated. The mass transfer experiments are conducted to obtain detailed local heat/mass transfer coefficients on the duct wall. The aspect ratio (width/height) of the duct is 2.04 and the rib height is one tenth of the duct height, such that the ratio of rib height to hydraulic diameter is 0.0743. The ratio of rib-to-rib distance to rib height is 10. The discrete ribs are made by dividing continuous ribs into 2, 3 and 5 pieces and attached periodically to the top and bottom surfaces of the duct with a parallel orientation. After examining the effects of rib angle of attack (α) for continuous ribs, the combined effects of the rib angle and the length of discrete ribs on heat/mass transfer on the duct wall are investigated for α=90° and 45°. As the number of broken pieces of a rib increases, the more disturbed flows affect greatly heat/mass transfer and increase the uniformity of heat/mass transfer distributions. For α=90°, the heat/mass transfer enhancement with the discrete ribs is remarkable, so that the discrete ribs augment up to 27% of the average heat/mass transfer coefficients compared with the transverse continuous rib. However, the heat/mass transfer performances of the discrete ribs are slightly higher than that of the transverse continuous rib due to the accompanied high friction loss penalty. For α=45°, the average heat/mass transfer coefficients are decreased slightly with the discrete ribs, and the heat/mass transfer performances of the angled discrete ribs are also decreased even though the friction losses are lower.

NOMENCLATURE

AR duct aspect ratio, W/H
Dh duct hydraulic diameter
Dm, mass diffusion coefficient for naphthalene vapor in air
dt run time
dy sublimation depth of the naphthalene surface
e rib height
f friction factor
fg friction factor of a fully developed turbulent flow in a smooth pipe
H duct height
h heat transfer coefficient
h*, mass transfer coefficient
l discrete rib length
m local naphthalene mass transfer rate per unit area
Nu Nusselt number, hD/k
Pr Prandtl number
p rib-to-rib pitch
Re Reynolds number, Du/V
Sc Schmidt number
Sh Sherwood number, h*Dh/Dm
Sh transverse Sherwood number of a fully developed turbulent flow in a smooth pipe
Sh average Sherwood number
V mean velocity
W duct width
x streamwise distance from the starting line of the naphthalene-coated region
y vertical distance from the duct surface
z lateral distance from the center of the duct

Greek Symbols
α rib angle of attack
ΔP pressure drop
η heat/mass transfer performance, (Sh/Sh,)(0.5)α
ρv bulk vapor density of naphthalene
ρ,v vapor density of naphthalene on the surface

INTRODUCTION

Rib turbulators are used to augment heat transfer in internal
cooling passages of modern gas turbine blades that must be protected from hot gas stream. Heat transfer in a duct roughened with ribs is augmented remarkably because the ribs disturb flows, promote flow mixing and turbulence, and induce diverse secondary flows. Various rib conditions, such as rib height (e), rib angle of attack (α), rib-to-rib pitch (p), rib shape and rib arrangement, have great effects on heat transfer and friction, and a number of studies have been performed (Han et al., 1978, 1984, 1985; Taslim et al. 1991; Lau et al. 1991a; Mochizuki et al. 1997). One of recent subjects of investigations on heat transfer in rib roughened ducts is for breaking ribs to several pieces and rearranging them. Broken or discrete ribs disturb and mix duct flows more complicated ways than continuous or full ribs, so that heat transfer in ducts can be augmented more effectively. Lau et al. (1991b, 1991c, 1992) examined the effects of rib angle of attack on average heat transfer enhancement for a wide range of Reynolds numbers with a square duct roughened with discrete ribs. They used two or five pieces of the discrete ribs per one pitch, and concluded that the largest average heat transfer coefficient was obtained at α=60° for five-piece-discrete ribs, whereas at α=90° for two-piece-discrete ribs. Taslim et al. (1996) and Ekkad and Han (1997) performed the experiments using the liquid crystal technique and measured the local distribution in a duct roughened with discrete ribs. Besides, there are other interesting studies on the different experimental conditions, such as a very narrow duct with two-piece-discrete ribs by Chyu and Natarajan (1989) and a converging passage with seven-piece-discrete ribs by Hu and Shen (1996).

The previous studies mainly focused on the average heat transfer except some researchers. Berger and Hau (1979) measured the mass transfer distribution in ribbed pipes by an electrochemical analogue technique over a wide range of Schmidt number and found that the mass transfer distributions were independent of the Schmidt number. Clifford et al. (1985) conducted heat transfer experiments with a triangular-sectioned duct rotating in the orthogonal-mode and measured local heat transfer coefficients at some axial locations. The effect of rib angle on local heat/mass transfer distribution in a two-pass rib-roughened duct was investigated by Chandra et al. (1988) and seven local mass transfer coefficients were measured at every lateral position in an inter-rib region. The more detailed local measurements were performed by a few investigators such as Chyu and Wu (1989), Aliaga et al. (1994) and Acharya et al. (1997) for a surface roughened with transverse ribs. Kukreja et al. (1993), Cho et al. (1998) and Wu et al. (1998) investigated the very detailed local heat transfer characteristic in a duct roughened with the ribs of various conditions such as rib arrangements, rib angles of attack and rib cross-section shapes. Moreover, there are only a few investigators for the local transfer characteristics of discrete ribs.

Although it can be inferred from the results of the previous studies that properly arranged discrete ribs would augment heat transfer more effectively than continuous ribs, there are few studies on the effects of the number of broken pieces of a rib or the rib length-to-height ratio. Therefore, it is worth investigating systematically the length and the arrangements of discrete ribs. In addition, it is important to understand the effects of flow patterns on heat transfer and to find thermally weak regions such as hot spots for the purpose of rib design. Thus, it is taken for the main focus in the present study to provide the insight into the heat/mass transfer augmentation by discrete rib turbulators through local heat/mass transfer measurements in detail.

In the present study, first, numerical analysis is performed for the continuous ribs of α=90° and 45° to understand the flow patterns in a rectangular ribbed duct. Secondly, heat/mass transfer experiments are
Table 1 Detailed rib configurations

<table>
<thead>
<tr>
<th>Case</th>
<th>No. of broken pieces</th>
<th>( \alpha )</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>A90N1</td>
<td>1</td>
<td>90°</td>
<td>continuous rib</td>
</tr>
<tr>
<td>A63N1</td>
<td>1</td>
<td>63°</td>
<td>continuous rib</td>
</tr>
<tr>
<td>A45N1</td>
<td>1</td>
<td>45°</td>
<td>continuous rib</td>
</tr>
<tr>
<td>A33N1</td>
<td>1</td>
<td>33°</td>
<td>continuous rib</td>
</tr>
<tr>
<td>A90N2</td>
<td>2</td>
<td>90°</td>
<td>discrete rib</td>
</tr>
<tr>
<td>A45N2</td>
<td>2</td>
<td>45°</td>
<td>discrete rib</td>
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<tr>
<td>A90N3</td>
<td>3</td>
<td>90°</td>
<td>discrete rib</td>
</tr>
<tr>
<td>A45N3</td>
<td>3</td>
<td>45°</td>
<td>discrete rib</td>
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<tr>
<td>A90N5</td>
<td>5</td>
<td>90°</td>
<td>discrete rib</td>
</tr>
<tr>
<td>A45N5</td>
<td>5</td>
<td>45°</td>
<td>discrete rib</td>
</tr>
</tbody>
</table>

Fig. 2 Types of rib arrangement.

conducted for continuous ribs of which rib angles \( (\alpha) \) are 90°, 63°, 45°, and 33° to find the effects of rib angles. On the basis of the numerical and experimental results of the continuous ribs, heat/mass transfer characteristics are investigated for discrete ribs such as two-, three-, and five-piece-discrete ribs of which rib angles \( (\alpha) \) are 90° and 45°. Mass transfer experiments are conducted using the naphthalene sublimation method instead of heat transfer experiments to obtain detailed local heat/mass transfer coefficients. The effects of intricate flow patterns on local heat/mass transfer can be examined by the detailed local measurements. The area-weighted average heat/mass transfer coefficients are also presented to compare the overall heat/mass transfer enhancements. Rib turbulators not only enhance heat/mass transfer in ducts but also increase pressure drop, and in general, the maximum heat/mass transfer is accompanied by the largest pressure drop. Therefore, the increased friction loss penalty should be considered simultaneously in evaluating the heat/mass transfer augmentation results. Thus, the friction factors of the duct and the heat/mass transfer performances for constant pumping power are presented.

**NUMERICAL ANALYSIS CONDITIONS**

The numerical calculation using the commercial package program, FLUENT, is accomplished to understand the flow patterns in a ribbed duct. The calculated geometry is the duct height \( (H) \) of 50 mm and the duct width \( (W) \) of 100 mm, which is nearly the same as the experimental condition. The square ribs of which height is 5 mm with \( \alpha=90^\circ \) and 45° are considered. The rib-to-rib pitch is ten times of the rib height \( (p/e=10) \). The grid of 93 x 30 x 41 in the \( x \), \( y \) and \( z \) direction, respectively, is generated to obtain the results of grid independence. It is assumed that the ribs attached to the bottom and top walls of the duct parallel by the symmetry condition. The hydrodynamically fully developed region is taken into account with the mean stream velocity of 15 m/s and the Reynolds number is 66,000. The RNG \( k-e \) turbulence model is used to calculate the turbulent separation flows in a ribbed duct.

**EXPERIMENTAL APPARATUS**

The schematic view of the test duct is illustrated in Fig. 1. The cross section area \( (W \times H) \) is 102 mm by 50 mm, thus the duct aspect ratio \( (AR) \) is 2.04. The hydraulic diameter \( (D_h) \) of the duct is 67.3 mm and its length is 1,300 mm \( (19D_h) \). The air flow entering the inlet contraction of which the area ratio is 6:1 passes through the test duct and the plenum, and is discharged out of the room by the blower. The orifice flowmeter between the plenum and the blower is used to measure the mass flow rates of air stream. The nominal mean velocity through the test duct is 7 m/s in the mass transfer experiments resulting in the Reynolds number of 30,000 based on the hydraulic diameter \( (D_h) \).

The ribs have a square cross-section and the height of the ribs is 5 mm which is 1/10 of the duct height. Thus, the rib height-to-hydraulic diameter ratio \( (e/D_h) \) is 0.0743. The ribs are inactive in mass transfer and glued onto the bottom and top walls of the duct by double-sided tape with an in-line orientation. The rib-roughened region is 1000 mm \( (15D_h) \) long. The rib-to-rib pitch is 50 mm so that \( p/e=10 \). Rib angles of attack, \( \alpha=90^\circ, 63^\circ, 45^\circ \), and 33° are considered for the continuous rib tests. The discrete ribs are made to have three lengths: a half, a third, and a fifth of the continuous rib length. The types of rib arrangement are presented in Fig. 2 and with these arrangements, the area covered by ribs on the walls is the same as that for the continuous ribs.
Experiments are performed for four types of continuous ribs and six types of discrete ribs and the detailed rib configurations are presented in Table 1. Numerals, A90, A63, A45 and A35 represent the angle of attack of the ribs. Similarly, N2, N3 and N5 indicate the number of broken pieces of a rib. For example, N3 corresponds to three-piece-discrete ribs. Thus, N1 is assigned to the continuous ribs. Rib positioning error is less than ±1 mm (0.2e) by using precisely positioned templates, hence rib-to-rib pitch (p) varies within 2%.

In the present study, the mass transfer experiments are performed by using the naphthalene sublimation method instead of heat transfer experiments. The naphthalene-coated surface starts from the position that is 7.6D, downstream from the first rib in the duct and extends over 4.5D, downstream. Since the mainstream passes over from 8 to 10 ribs before the naphthalene-coated surface, the boundary layer of mass transfer starts to develop in the hydrodynamically fully developed duct flows. The boundary condition of the naphthalene-coated surface corresponds to the constant temperature condition of heat transfer experiments. Since the mass transfer active ribs are attached onto the naphthalene-coated surface, the boundary condition is distorted to some extent. However, it is noted that Tazlim and Spring (1994) mentioned that heat transfer coefficients are not sensitive to the choice of wall thermal boundary conditions.

The average heat transfer coefficients from the smooth surfaces of inter-rib regions (exclusive of the heat transfer active ribs) are not significantly different from those from the total heat transfer surfaces (inclusive of the heat transfer active ribs). The deviations between the average heat transfer coefficients from active rib experiments and those from active rib ones were less than 10% in sub-section for comparison by Han et al. (1988), Chandra et al. (1988), and Ekkad and Han (1997). Since the main focus of the present study is to providing the insight into the heat/mass transfer augmentation by rib turbulators through local heat transfer measurements in detail, the present experimental method suits well the object of the present study. A large number of local heat/mass transfer coefficients are obtained in the present experiments and the number of data in an inter-rib region amounts up to approximately 1,000.

The coordinate system of the duct takes the mainstream, lateral and vertical directions for x, z and y, respectively, and the middle point of the start line of the naphthalene-coated area for its origin. Therefore, the measured domain of mass transfer coefficients covers 0 ≤ z ≤ 560 in the mainstream direction and −10.2 ≤ z ≤ 10.2 in the lateral direction. The ribbed region of 15D, is divided into three sections: the middle section coated with naphthalene (4.5D, long), the upstream section (7.6D, long) and the downstream section (2.9D, long).

The test surface is cast with naphthalene using a set of mold positioned templates, hence rib-to-rib pitch (p) is 2%.

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The test surface is cast with naphthalene using a set of mold composed of the test plate and the molding plate polished highly to be smooth ultimately like a mirror. To obtain the local mass transfer rate, the sublimation depths of naphthalene surface are measured at the numerous positions using the automated positioning table and LVDT (linear variable differential transformer) of which the resolution is 0.025 μm and the diameter of measuring tip is 1.588 mm. The error due to the measurement is less than 1% of the average sublimation depth, 0.0762 mm (3 mil). Since the vapor density of naphthalene is very sensitive to temperature and varies 10% per the temperature change of 1°C, the iron-constantan thermocouple is installed in the test plate to measure the temperature at the naphthalene surface accurately. The 25 pressure taps with 1.3 mm hole diameter are positioned at the location y=H/2 of the one of the side walls to measure pressure drop through the duct. The pressure tap spacing is 50 mm which is the same as the rib-to-rib pitch. The micromanometer of which the resolution is 0.01 mmH2O is used to measure the static pressure difference between the taps for the Reynolds number range of 25,000 to 70,000.

DATA REDUCTION

The depths of the naphthalene-coated surface are measured over before and after the run of the duct experiment. Sherwood number (Sh), the dimensionless local mass transfer coefficient, is calculated from the differences of the surface depth (the naphthalene sublimation depth) with correction of the sublimation due to the natural convection during the measuring time and the test plate installing/uninstalling time. The local mass transfer coefficients acquired by the above procedure are expressed as

\[ \text{Sh} = \frac{h_o D_p}{D_{app}} \]  

where \( d \) is the mass transfer rate of naphthalene per unit area and \( \rho_o \) and \( \rho_s \) are the vapor density at the naphthalene surface and the bulk vapor density of naphthalene, respectively. Since the bulk vapor density of naphthalene, \( \rho_s \), at the exit of the duct is less than 0.9% of \( \rho_o \), the denominator of Eq. (1), \( \rho_o \rho_s \), can be reduced to \( \rho_o \). Therefore, the local mass transfer coefficients are determined from the naphthalene sublimation depth (dy), the run time (dt), the density of solid naphthalene (\( \rho_s \)) and the vapor density on the naphthalene surface (\( \rho_o \)). From these local mass transfer coefficients, the Sherwood numbers are calculated as

\[ \text{Sh} = \frac{h_o D_p}{D_{app}} \]  

where \( D_{app} \) is the diffusion coefficient of naphthalene in air. The uncertainty in the Sherwood number is estimated within 7.1% at the 95% confidence level by using Kline and McClintock's uncertainty estimation method (1953). The major causes of this error are the uncertainty in the Sherwood number (Goldstein and Cho, 1995) such as the vapor density with 3.77% error and the diffusion coefficient with 5.1% error. Nusselt numbers can be obtained from Sherwood numbers by the heat and mass transfer analogy. The correlation between Nusselt and Sherwood numbers, \( \text{Nu/Sh} \), is significant from the data for turbulent flows can be presented as

\[ \text{Nu/Sh} = (Pr/Sc)^{0.4} \]  

The results in this paper are presented as the Sherwood number ratios, \( \text{Sh/Sh}_n \), to estimate the heat/mass transfer augmentation effectively, where \( \text{Sh}_n \) presents the Sherwood number for fully developed turbulent flow in a smooth circular tube. The reference Sherwood number, \( \text{Sh}_n \), correlated by McAdams (1942) can be written via the heat and mass transfer analogy as

\[ \text{Sh}_n = \frac{h_o D_p}{D_{app}} \]
In the present study, the Sherwood number in the smooth duct decreases rapidly from the start position of the naphthalene-coated surface, x/e=0, and remains almost constant value after x/e=25. This baseline Sherwood number is proportional to Re^0.8 and it is approximately 12% higher than Sh_o calculated from Eq. (4) due to the geometrical difference. Nevertheless, Sh_o of Eq. (4) is chosen as the reference Sherwood number in normalizing the measured data because the measured baseline Sherwood numbers change with positions.

The average Sherwood number (Sh) is obtained from the numerical integration of the local Sherwood numbers weighted by area. The streamwise distributions of the heat/mass transfer coefficients between the ribs are repeated with the nearly same values after x/e=10. Therefore, the region of 35≤x/e≤55 is used to calculate the average Sherwood numbers, where the distance between measuring points is 0.2e. The static pressure decreases linearly along the duct except the regions near the duct inlet and exit. Therefore, the average pressure drop is obtained from the slope calculated by a linear curve-fitting of the local pressure difference data in the middle region of the duct (ΔP/ΔL=dP/dx). The friction factor is calculated with the above average pressure drop as

$$f = \frac{ΔP}{4(ΔL/D_o)(1/2)ρV^2}. \quad (5)$$

The uncertainty in the friction factor is within 4.4% estimated by the above-mentioned method. The friction loss results are presented as the friction factor ratio, f/f_o, where f_o presents the friction factor for fully developed turbulent flow in a smooth circular tube. The empirical equation that closely fits the Kármán-Nikuradse equation over the range 10^4<Re<5×10^6 proposed by Petukhov (1970) is employed as

$$f_o = 2(2.236 \ln \text{Re} - 4.639)^{-2}. \quad (6)$$

The deviations between the experimentally obtained friction factors in the smooth duct and f_o calculated from Eq. (6) are within 5% for the range 25,000<Re<70,000.

The heat/mass transfer performance, η, obtained by considering both heat/mass transfer augmentation and friction loss is based on the constant pumping power condition and expressed as the following equation.

$$\eta = \left(\frac{\text{Sh} / \text{Sh}_o}{f / f_o}\right)^{0.5}. \quad (7)$$

RESULTS AND DISCUSSION

1. Continuous Ribs
Flow Patterns. Figure 3 shows the numerical analysis results for α=90° and 45°. The lateral center of the duct corresponds to x=0, so the range of z/e is -10≤z/e≤10. The results are for the range 0≤y≤H/2 and the identical results can be obtained for the range H/2≤y≤H by symmetric condition. For α=90°, the flow over the rib reattaches on the wall between the ribs and the recirculation flow is developed behind the rib, as shown in Fig. 3(a) which depicts x and y components of the velocity vectors at the lateral center of the duct (z/e=0). These calculated flow patterns are repeated over all lateral positions except the domain near the side walls of the duct. When the duct is roughened with angled ribs (α<90°), the flows close to the ribbed walls are deflected along the ribs, which induces

![Fig. 3 Calculated velocity vectors in the ribbed duct.](image-url)
large secondary flows going ahead with helical rotating motion. These secondary flows are plotted in Fig. 3(b) which shows the velocity vectors in the angled cross section parallel to ribs in the middle of the inter-rib region for $\alpha=45^\circ$. The upward flows occur near the left side wall at $z/e=10$ of the vector plot and the downward flows in the right part of the duct by the rotating secondary flows. The reattachment of the flows over the ribs is strengthened, weakened or even vanished, due to these downward/upward flows as shown in Figs. 3(c)-(d).

**Local Heat/Mass Transfer.** The contour plots of the local heat/mass transfer ratios (Sherwood number ratios) are presented in Fig. 4 for various angles of attack. For $\alpha=90^\circ$, as shown in Fig. 4(a), the high Sherwood number regions are observed in the upper middle parts of the inter-rib regions. This is because of the aforementioned reattachment of the flows over the ribs. The heat/mass transfer decreases as the flow boundary layers develop after the reattachment zones and the low Sherwood number regime is shown behind the ribs due to the recirculation flows. The lateral distribution of the local heat/mass transfer coefficients is fairly uniform over most parts of the inter-rib region and is distorted in the vicinity of the side walls.

For the angled ribs, as shown in Figs. 4(b)-(d), the laterally uniform distributions of the mass transfer coefficients which are observed for $\alpha=90^\circ$ are disheveled due to the downward/upward secondary flows. Mass transfer in the downward flow region is augmented more than 4 times compared with the case of smooth ducts. On the contrary, the low Sherwood number regions are shown near the left side wall ($z/e=10.2$) in Figs. 4(b)-(d) due to the upward flows. It is because the downward flows lead the almost naphthalene-free fluid from the core of the duct and impinge onto the ribbed walls, while there are secondary flows into the upward flow region which contain much more naphthalene vapor moving along the angled ribs near the ribbed wall. The high mass transfer coefficients are shown in the narrow zone in front of the ribs because the corner vortices develop strongly along the ribs as described by Fann et al. (1994), while these vortices remain stationary for $\alpha=90^\circ$. The high Sherwood number regions,

![Fig. 4 Contour plots of Sh/Sh_o for continuous ribs (a) $\alpha=90^\circ$. (b) $\alpha=63^\circ$. (c) $\alpha=45^\circ$. (d) $\alpha=33^\circ$.](image)

![Fig. 5 Streamwise distributions of Sh/Sh_o for continuous ribs.](image)
the mass transfer coefficients are low except the some narrow regions. Consequently, for \( \alpha=33^\circ \), the corner vortices. This is a typical pattern of heat/mass transfer distribution on the ribbed surface with flow separation and reattachment. Considering the difference in the rib height-to-hydraulic diameter ratio, \( e/D_h \), the average heat/mass transfer coefficients of the present study agree well with the experimental investigation using the ducts of AR=2.5, 0.5, 1, 2 and 4 by Han and Park (1988) and Han et al. (1989) showed that the effect of rib angle on heat transfer enhancement is significantly influenced by the duct aspect ratio. For \( \alpha=33^\circ \), the heat/mass transfer performance because of the smallest friction loss. The comparison of the results with other references is also presented in Fig. 6. It is noted that the experimental investigation using the ducts of AR=0.25, 0.5, 1, 2 and 4 by Han and Park (1988) and Han et al. (1989) showed that the effect of rib angle on heat transfer enhancement is significantly influenced by the duct aspect ratio. The reason may be that the actual area blocked by ribs out of the duct cross-section changes as the duct aspect ratio although the rib height-to-hydraulic diameter ratio, \( e/D_h \), is constant. The different duct aspect ratio results in the different flow patterns in ribbed ducts. Considering the difference in the rib height-to-hydraulic diameter ratio, \( e/D_h \), the Sherwood number changes very rapidly from the most upstream position due to the more salient effects of reattachment which is reinforced by the downward secondary flows. In contrast, the low values exist in the region with the positive \( z/e \) due to the weakened reattachment flows and the inflows containing relatively dense naphthalene vapor along the angled ribs. The Sherwood number has flat distributions without reattachment flows at the lateral positions near the side wall located at \( z/e=10.2 \), for instance, at \( z/e=9.0 \) and 9.8. The sharp peaks are shown in the vicinity of the ribs for most lateral positions due to the corner vortices moving along the ribs. Mass transfer decreases with increasing \( z/e \) except at the lateral position of \( z/e=9.8 \) which is very close to the side wall located at \( z/e=10.2 \). The reason is that the corner vortices between the side and bottom walls are induced by the upward flows.

Average Heat/Mass Transfer Coefficient and Heat/Mass Transfer Performance Comparison. Figure 6 shows the average Sherwood numbers and the heat/mass transfer performances. The maximum average Sherwood number appears at \( \alpha=63^\circ \) reaching to approximately 2.8 times as large as that of smooth ducts. The maximum friction loss accompanies at the same angle of attack, \( \alpha=63^\circ \) so that the highest heat/mass transfer performance comes out at \( \alpha=45^\circ \). For \( \alpha=33^\circ \), the average Sherwood has the minimum value which is lower than that for \( \alpha=90^\circ \), but the moderate value is observed in the heat/mass transfer performance because of the smallest friction loss. The comparison of the results with other references is also presented in Fig. 6. It is noted that the experimental investigation using the ducts of AR=0.25, 0.5, 1, 2 and 4 by Han and Park (1988) and Han et al. (1989) showed that the effect of rib angle on heat transfer enhancement is significantly influenced by the duct aspect ratio. The reason may be that the actual area blocked by ribs out of the duct cross-section changes as the duct aspect ratio although the rib height-to-hydraulic diameter ratio, \( e/D_h \), is constant. The different duct aspect ratio results in the different flow patterns in ribbed ducts. Considering the difference in the rib height-to-hydraulic diameter ratio, \( e/D_h \), the average heat/mass transfer coefficients of the present study agree well with those of Han and Park (1988)'s results in the case of the same duct aspect ratio, AR=2. The performance results are consistent qualitatively with Han and Park (1988)'s results but the difference in value is up to 15% due to higher friction factor resulting from higher blockage ratio, \( e/D_h \), of the present study.

It is evident that the heat/mass transfer characteristics of the transverse ribs of \( \alpha=90^\circ \) are very different from the angled ribs of \( \alpha<90^\circ \). The distributions of the transfer coefficients have a similar pattern for all angled ribs of \( \alpha=63^\circ \), \( \alpha=45^\circ \) and \( \alpha=33^\circ \). Therefore, the experiments for discrete ribs are carried out for \( \alpha=90^\circ \) and 45° and the results for discrete ribs are compared with those of the continuous ribs.

2. Discrete Ribs

Local Heat/Mass Transfer. The contour plots of the local Sherwood number are presented in Fig. 7: Figs. 7(a)-(c) for \( \alpha=90^\circ \) and Figs. 7(d)-(f) for \( \alpha=45^\circ \). For \( \alpha=90^\circ \), the distribution of the mass transfer coefficients is symmetric with the centerline of \( z/e=0 \) in all cases of the discrete ribs. The Sherwood number changes very rapidly near the tips of the discrete ribs resulting in the complicated distributions. However, far from the tips, the transfer coefficient distributions for the discrete ribs are similar to those for the continuous ribs presented in Fig. 4(a). For the discrete ribs A90N2 and A90N3, the very high mass transfer coefficients are observed in the wide region around the rib tips. The reason is that the flows near the ribbed wall...
Fig. 7 Contour plots of $\text{Sh}/\text{Sh}_o$ for discrete ribs (a) A90N2, (b) A90N3, (c) A90N5, (d) A45N2, (e) A45N3, (f) A45N5.

Fig. 8 Streamwise distributions of $\text{Sh}/\text{Sh}_o$ for discrete ribs at $\alpha=90^\circ$. 
are skewed to pass around the tips of discrete ribs, being accelerated between the rib tips as well as reattached over the ribs. In addition, the corner vortices separated from the rib tips and the additional disturbances due to a lot of discrete ribs cause vigorous flow mixing and promotes turbulence. For the discrete rib A90N5, the local Sherwood numbers have the moderate values around the rib tips compared with those for the discrete ribs A90N2 and A90N3, so the fairly uniform distribution of the mass transfer coefficients is observed with the discrete rib A90N5. The reason is that the rib length-to-height ratio (l/e) of the discrete rib A90N5 is relatively small compared to other discrete ribs, resulting in a moderate flow acceleration. For example, the length-to-height ratios (l/e) are 6.8 and 4.1 for discrete ribs A90N3 and A90N5, respectively. The width of the flow path between the backward-face and forward-face of the sequent discrete ribs is 4e (i.e., the rib-to-rib pitch is 5e), so that the rib length of the discrete rib A90N5 is similar to the width of the flow path. Therefore, the flow near the wall with discrete rib A90N5 does not undergo such flow acceleration resulted from abrupt path changes. The regions of the low mass transfer coefficients behind the ribs due to recirculation flows are narrower than those of continuous ribs, because there are inflows into these regions of discrete ribs by flow turning around the rib tips. This can reduce potential hot spots in ribbed ducts.

Figures 7(d)-(f) show the results for α=45°. As the number of discrete ribs increases, the distribution of the mass transfer coefficients becomes more uniform in the same manner as the case of α=90°. However, the big Sherwood number increase is not observed around the rib tips as obtained in the cases of α=90°. The reason is that the flows near the ribbed walls for α=45° do not have sudden path changes such as those for α=90° by being led to the one inclined direction along the angled ribs. The regions where mass transfer is augmented notably by the downward secondary flows with the angled ribs are observed even for the short discrete rib A45N5 as well as the other discrete ribs, A45N2 and A45N3. These regions are also observed for the angled continuous ribs as shown in Figs. 4(b)-(d). According to the flow visualizations and the flow pattern sketch on the rough wall with angled discrete ribs by Hu and Shen (1996), the separated flows cause circulation in front of the ribs to be vortices going along the angled ribs, and finally, these vortices separate at the rib tips. These vortices separate only at the downstream tips of discrete ribs due to the secondary flows heading for the side wall at z/e=10.2 along the angled ribs on the walls. Therefore, the high Sherwood number regions are shown near the downstream tips of discrete ribs but not around the upstream tips. For α=45°, the low Sherwood number regions behind the ribs do not shrink even though discrete ribs are used. This is because the flows near the ribbed walls are deflected in front of the angled rib and go rather straight ahead between the discrete ribs, thus the flows hardly get into these low Sherwood number regions. It is interesting that the contour patterns of the mass transfer coefficients do not change largely with the short discrete rib A45N5. The common characteristics of the distributions of the local mass transfer coefficients
for the angled discrete ribs as followed: 1) The mass transfer coefficients have high values in the regions near the side wall at $z/e=10.2$ and low values in the regions near the side wall at $z/e=10.2$ due to the dominant effects of the large rotating secondary flows along the angled ribs as shown in the case of the angled continuous ribs (Fig. 3(b)), and 2) the mass transfer are enhanced highly in the regions near the only downstream tips of discrete ribs.

The streamwise distributions of the local Sherwood number are presented at some lateral positions to investigate the detailed heat/mass transfer characteristics in Figs. 8 and 9. For $\alpha=90^\circ$, as shown in Fig. 8, the streamwise distribution has the same pattern as that of the transverse continuous ribs at the lateral positions far from the discrete-rib tips such as $z/e=9.0$. Thus, the first peak by reattachment flow is shown in the upper middle region and its magnitude is almost the same for the continuous rib A9ON1 and the discrete ribs A9ON2-A9ON5. For the discrete ribs A9ON2 and A9ON3, the closer to the rib tips the lateral position is, the more intricate and higher mass transfer coefficients are observed. The secondary sharp peaks in the vicinity of the forward faces of ribs are shown clearly every lateral position and increase as the vortex going to the rib tips with acceleration. Among the lateral positions near the rib tips of the discrete rib A9ON3, the local maximum at $z/e=3.0$ is much higher than that at $z/e=4.0$, because the flow acceleration in turning to pass by the rib tips is larger at $z/e=3.0$ due to the smaller flow passage. However, for the discrete rib A9ON5, the local mass transfer coefficients are not very high even near the rib tips such as $z/e=3.0$ and -2.0. Judging from these results, the effects of discrete ribs on mass transfer augmentation become weak with the discrete ribs of short length which induce small flow passage changes.

For $\alpha=45^\circ$, as shown in Fig. 9, the rapid changes of the local mass transfer coefficients are also observed near the rib tips as shown in the results for $\alpha=90^\circ$. For all angled discrete ribs A4SN2-A4SN5, the first peaks by the flow reattachments strengthened by the downward secondary flows are observed at $z/e=9.0$ where is very close to the right side wall located at $z/e=10.2$. Note that it is also shown for the continuous angled ribs (Fig. 5(b)). As the number of broken pieces of a rib increases from N2 to N5, these downward secondary flows become weaker so that the magnitudes of the peaks decrease. A pair of sharp secondary peaks in the vicinity of ribs are observed as the corner vortices flow along angled ribs. As shown at $z/e=1.0$ in Fig. 9(a) and at $z/e=-3.0$ and 5.0 in Fig. 9(b), the distinct peaks are observed in the middle of inter-rib regions which are near the downstream tips of discrete ribs. These peaks decrease with increasing $z/e$, as shown at $z/e=-5.0$, -1.0 and 3.0 in Fig. 9(c) for the discrete rib A4SN5.

**Friction Loss.** Figure 10 shows the results of the pressure drop experiments in friction factor ratios, $f/f_{ref}$. In the present study, friction losses in the ribbed duct are more than eight times of that in a smooth duct. Friction factors for $\alpha=90^\circ$ are always higher than those for $\alpha=45^\circ$ for all the continuous and discrete ribs.

For $\alpha=90^\circ$, the discrete ribs A9ON2 and A9ON3 which enhance remarkably heat/mass transfer cause a great increase of friction factors which is about twice as large as that of continuous ribs, and the discrete rib A9ON5 has the highest friction loss in the test conditions. The friction loss for the discrete rib A9ON5 is very low as the heat/mass transfer augmentation is also lower than those for the other discrete ribs of $\alpha=90^\circ$. The friction factors for the discrete ribs of $\alpha=45^\circ$ are lower than that for the angled continuous rib except the discrete rib A4SN2.

![Friction factor ratios, $f/f_{ref}$, for continuous- and discrete-ribbed ducts.](image)

Fig. 10 Friction factor ratios, $f/f_{ref}$, for continuous- and discrete-ribbed ducts.

![Continuous and discrete ribs at Re=30,000](image)

Fig. 11 Continuous and discrete ribs at $Re=30,000$

(a) Average Sherwood number ratios, $Sh/\overline{Sh}$
(b) Heat/mass transfer performances, $\eta$. 
while those for the discrete ribs of \( \alpha=90^\circ \) are higher than that for the transverse continuous rib.

Although the friction factors are almost constant or decrease slightly as the Reynolds number increases, the friction factor ratios increase with Reynolds number. This implies that the more additional pressure drop penalty by ribs should be paid if a ribbed duct is operated at the higher coolant flow rate. These increasing rates of the friction factor ratios for the discrete ribs A90N2 and A90N3 are somewhat higher than those for other ribs.

**Average Heat/Mass Transfer Coefficient and Heat/Mass Transfer Performance.** For \( \alpha=90^\circ \), as shown in Fig. 11, heat/mass transfer is highly augmented with the discrete ribs A90N2 and A90N3, so that the average Sherwood number ratios reach to 3.2, increasing 27% compared with the case of the continuous rib A90N1. On the other hand, the average Sherwood number for the discrete rib A90N5 is similar to that for the continuous rib. However, the heat/mass transfer performances for the discrete ribs A90N2 and A90N3 are only 3-5% higher than that for the continuous rib A90N1, because the large friction loss is also obtained for the discrete ribs A90N2 and A90N3.

For \( \alpha=45^\circ \), the average Sherwood numbers are slightly different for all cases A45N1-A45N5 as expected in the local mass transfer results, and the highest value is observed for the continuous rib A45N1. The present results for the angled discrete ribs are different from the results presented by Lau et al. (1991) and Han and Zhang (1992), while the results for discrete ribs of \( \alpha=90^\circ \) are qualitatively consistent with those of other studies, such as Chandra et al. (1988) and Tashim et al. (1996) as well as the above-mentioned references. Lau et al. (1991) and Han and Zhang (1992) concluded that three-piece-discrete ribs or five-piece-discrete ribs at \( \alpha=45^\circ \) enhanced more heat transfer compared with the case of \( \alpha=90^\circ \). The rib height-to-hydraulic diameter ratio \((e/D_t)\) for their experiments is 0.0625 which is similar to that of the present study, \(e/D_t=0.0743\), with the same rib-to-rib pitch, \(p/e=10\). However, they used a square duct while the rectangular duct of the aspect ratio \(W/H=2.04\) is used in the present study. Hence, the rib height-to-duct height ratio, \(e/H\) is 0.1 in the present study, which is about twice larger than that of their investigations. Since duct aspect ratios affect heat transfer significantly as shown by Han (1988), Han and Park (1988), and Han et al. (1989), this discrepancy can be caused by the different duct aspect ratios. Chyu and Natarajan (1989) also obtained the different results for two-piece-discrete ribs at \( \alpha=90^\circ \) from the other references using square ducts roughened with discrete ribs, because they conducted experiments with the very wide, that is, the high aspect ratio duct.

The heat/mass transfer performance for the angled continuous rib A45N1 is similar to those for all angled discrete ribs except the discrete rib A45N2 that has the lowest value. In considering rib angle of attack, the average Sherwood number at \( \alpha=45^\circ \) is slightly higher than that at \( \alpha=90^\circ \) for the continuous ribs, but the values at \( \alpha=90^\circ \) are much higher than those at \( \alpha=45^\circ \) for all the discrete ribs. However, the heat/mass transfer performance at \( \alpha=45^\circ \) is slightly higher than that at \( \alpha=90^\circ \) for all rib configurations except for the discrete rib A45N2.

**CONCLUSIONS**

Heat/mass transfer and friction loss in a duct roughened with various discrete ribs are investigated and compared with the results of continuous ribs. The main conclusions are described as follows:

(i) The reattachment flows over the ribs and the rotating secondary flows induced by the angled ribs have large effects on heat/mass transfer augmentation. The local heat/mass transfer is also enhanced notably by the diverse vortices near the rib tips and the intricate other secondary flows.

(ii) For \( \alpha=90^\circ \), the discrete ribs A90N2 and A90N3 enhance highly heat/mass transfer around the broken-rib tips. However, heat/mass transfer is not enhanced very effectively with the discrete rib A90N5, because the rib length of the discrete rib A90N5 is relatively short so that it is nearly the same in length as the flow path width in the flow direction between the rib tips.

(iii) For \( \alpha=45^\circ \), the Sherwood number distributions for the discrete ribs are similar to those for the angled continuous ribs due to the dominant effects of the large rotating secondary flows along the angled ribs on the walls.

(iv) For \( \alpha=90^\circ \), the friction factors for the discrete ribs A90N2 and A90N3 are almost twice as large as that for the continuous rib. For \( \alpha=45^\circ \), the lower friction loss is observed as the number of discrete ribs increases. Friction factors for \( \alpha=90^\circ \) are always larger than those for \( \alpha=45^\circ \).

(v) The highest average Sherwood number are obtained for the discrete ribs A90N2 and A90N3, and the heat/mass transfer increases 27% compared with the case for the transverse continuous rib. However, the heat/mass transfer performances for the discrete ribs A90N2 and A90N3 are slightly higher than that of the transverse continuous rib due to the large friction losses.

(vi) The average heat/mass transfer and the heat/mass transfer performance for the angled ribs are affected slightly by the discretization of ribs.

**REFERENCES**


