한국동력기계공학회지 제16권 제6호 pp.30~37 2012년 12월

Effect of Rib Height on Turbulence and Convective Heat Transfer
리브의 높이가 난류 및 열전달특성에 미치는 영향

나인* · 김수진* · 정효민** · 정한식** · 라흐만***†
Md. J. Nine* · S. J. Kim* · H. M. Jeong** · H. S. Chung** · M. Sq. Rahman***†

(received October 18, 2012, revised December 07, 2012, accepted December 07, 2012)

Key Words : 사각 덕트(Rectangular duct), 리브 높이(rib height), 마찰 계수(Friction factor), 열전달(Heat Transfer)

Abstract : Effect of rib heights is found as significant parameter to enhance convective heat transfer performance under laminar and low turbulent regime. Circular ribs with different ribheight to channel height ratios, e/H = 0.05, 0.1, 0.15, are fabricated over the copper substraterespectively in a rectangular duct having 7.5 cross sectional aspect ratio. Only one rib pitch to rib height ratio (P/e = 10) has been chosen for all different height ribs. The result shows that the arithmetic average of turbulence intensity decreases with decreasing roughness height calculated between two ribs under laminar and low turbulent region. It occurs because the area of recirculation and reattachment zone also decreases with decreasing rib height. Optimum thermal enhancement factor is derived by 0.1 rib height to channel height ratio under low turbulent region but 0.15 rib height to channel height ratio gives maximum subjected to laminar flow.

1. Introduction

Roughness effect on friction factor and heat transfer draws a great attention of researcher. Investigation of high performance heat transfer surface is an important issue in the field of heat exchanger where artificial roughness is the key to fabricate novel and effective heat transfer surface. To enhance heat transfer by means of enhanced surface applying obstacles like fin increases turbulence on the surface as well. But friction losses get higher to create high turbulence by such a macro (Ribs) size roughness that drags the system to enormous energy loss. That's why the optimization of rib heights can be capable to save energy and facilitates high efficiency in the field of heat transfer. Convection is the most usual, effective heat transfer mood greatly influenced by the artificial roughness fabricated on heat transfer surface. The article reveals a comparative and comprehensive analysis of heat transfer efficiency employing different rib heights under laminar and low turbulent regime.

Early researches [1-4] just studied very limited number of rib roughness configurations and data were also acquired from limited number of locations. The effect of rib pitch to rib height variation in a tube was first studied by Webb et al. [5] and the result was formulated into a correlation. In 1993, Okamoto et al. [6] studied about two dimensional square ribs mounted on a smooth surface and they measured the water flow

라흐만(교신저자) : Dept. of Agricultural & Industrial Engineering, Hajee Mohammad Danesh Science & Technology University, Dinajpur-5200, Bangladesh
E-mail : m_sq_rahman@yahoo.com Tel : 017-1316-3319
나인, 김수진 : 경상대학교 정밀기계공학과
정효민,정한식 : 경상대학교 정밀기계공학과, 해양산업연구소

M. Sq. Rahman(corresponding author) : Dept. of Agricultural & Industrial Engineering, Hajee Mohammad Danesh Science & Technology University, Dinajpur-5200, Bangladesh
E-mail : m_sq_rahman@yahoo.com Tel : 017-1316-3319
Md. J. Nine and S. J. Kim : Department of Energy & Mechanical Engineering, GyeongSang National University
H. M. Jeong and H. S. Chung : Institute of Marine Industry, GyeongSang National University

structure over the ribs. They found that the effects of Reynolds number on the optimum pitch ratio for augmenting turbulence seemed to be insignificant. They also reported that at the optimum pitch ratio, the pressure loss due to the ribs was maximized. This was the cost of augmentation of heat transfer. Han et al. [7] studied the heat transfer in square channel with different angle rib arrays on two walls for P/e = 10 and e/Dh= 0.0625. They reported that the angle ribs and 'V' ribs provided higher heat transfer enhancement than the continuous ribs and the highest value is at the 60° orientation amongst the angled ribs. X. Gao and B. [8] Sunden studied the rib configuration with parallel and V-shaped into different channel aspect ratio. They found that the V-ribs pointing downstream produced highest heat transfer enhancement and friction factor and provided the best thermal performance. Parallel ribs provided better performance that V-ribs pointing upstream at high Reynolds number.

Last few years there have been several investigations on rib roughened surface to optimize the shape of rib and to find the effect of rib height.

R. Kamali and A.R. Binesh [9] performed a study on square, triangular, trapezoidal with decreasing height in the flow direction, and trapezoidal with increasing height in the flow direction.

They found that the heat transfer coefficient are strongly affected by the rib shape and trapezoidal ribs with decreasing height in the flow direction provide higher heat transfer enhancement and pressure drop than other shapes. M. Huh et al. [10] reports the effect of rib height on heat transfer in a rectangular channel with sharp entrance at high rotation number. D.N. Ryu et al. [11] studied the characteristics of turbulent flow in channels with two dimensional ribs and three dimensional blocks. So over the years the studies have been performed to investigate various significant parameters of rib roughened surface that influence the heat transfer performance such as rib shape, rib angle, rib height (e), channel aspect ratio (AR), rib height to channel height ration (e/H) etc.

The article represents the effect of roughness height in convective heat transfer emplying circular ribs. Axial pressure drop, turbulence and corresponding heat transfer has been investigated. The study is significant to find out the effect roughness height on thermal diffusion of fluid molecules in the vicinity of heat transfer surface. The comparison among three different rib roughened surfaces has been elaborately described in terms of friction factor and convective heat transfer.

2. Experimental Setup

The schematic diagram of the experimental

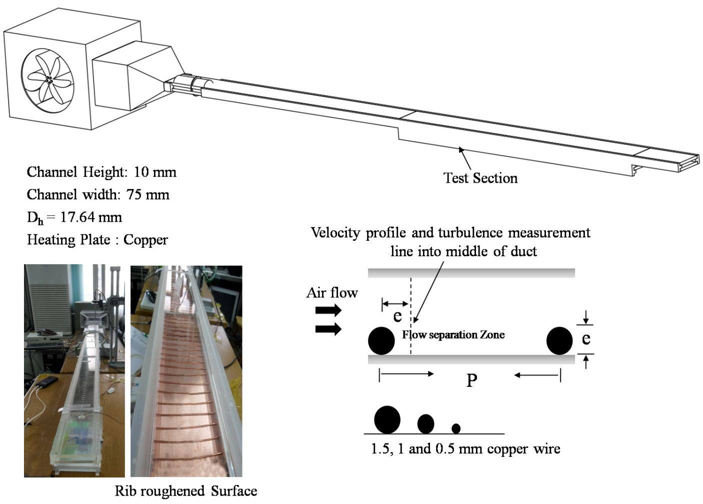


Fig. 1 Schematic diagram of device (above) and real experimental set up (inset)

apparatus is presented in Fig. 1 where the details of the rib mounted in one principle wall of the rectangular duct are displayed.

a) Experimental Apparatus

The rectangular duct is directly connected to a low pressure fan (shown in figure 1). The channel geometry is characterized by 10 mm channel height (H) and 2500 mm axial length which includes 1000 mm test section with the channel width of 75 mm. Ribbed wall is copper plate of 10 mm thickness on which circular ribs with different rib height to channel height ratio (e/H = 0.05, 0.1, 0.15) were mounted. The roughness on one principle wall of channel was created by uniform rib pitch (P) to rib height (e) ratio, P/e = 10. Air is tested fluid and the operating speed of the fan was varied by using a digital regulator to provide desired air flow rate. An orifice is installed just after the fan to measure constant flow rate constant for different roughness. Silicon rubber heating coil was perfectly attached with the help of another support plate at bottom of copper test plate and covered with 2 cm glass wool for thermal insulation in opposite of heat transfer surface. The electric heat input was 100 Watt. Seven RTD-type thermo sensors were used where two are installed at inlet and outlet of test section, five of them were precisely penetrated into the 10 mm thick heat transfer plate and spaced in equal distance to measure axial temperature distribution. Two static pressure taps were located at the bottom principle wall of channel to measure axial pressure drop across the test section. One of these tap was 45 mm upstream from the leading edge of the test section and the other was 45 mm downstream of the test section. Digital manometer is used for taking static pressure. All manipulated data has been taken after the system getting stable and it took about an hour to be stable or to be thermally equilibrium.

b) Turbulence Test

Straight I-type probe has been calibrated and used carefully to get the stream wise flow characteristics. Velocity profile and regarding turbulence were analyzed at inlet and middle section of the duct for different scale roughness by hot wire anemometer system. Specific location of approximately $29 < x/D_h < 32$ has been selected from the inlet of the duct to get the aerodynamic characteristics between two ribs at middle of duct. In Fig. 1, the position of data acquisition in the middle of duct is shown by a vertical line which is selected at the flow separation zone just downstream of the rib. Near wall data has been taken at 0.25 mm interval for first 2 mm from the heat transfer surface then rest of vertical path is taken at interval of 0.5 mm.

c) Experimental Validation

The validation of smooth surface is shown in figure. 2 in terms of dimensionless representation of pressure drop calculated by using Darcy-Weisbach equation (eq. 2), where the experimental result is compared with Blasius correlation found in open literature [12]. The figure shows a good agreement the maximum deviation between experiment and adopted correlation is about 6.28%.

The system has been examined several times to check the data reproducibility by recording wall temperature distribution at the same ambient

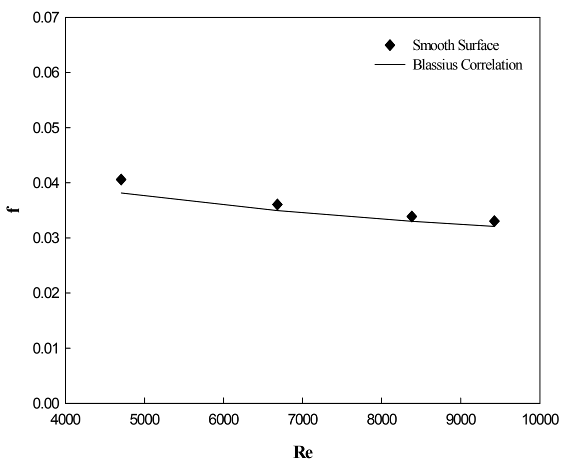


Fig. 2 Friction factor for smooth surface (Experimental and Blassius Correlation)

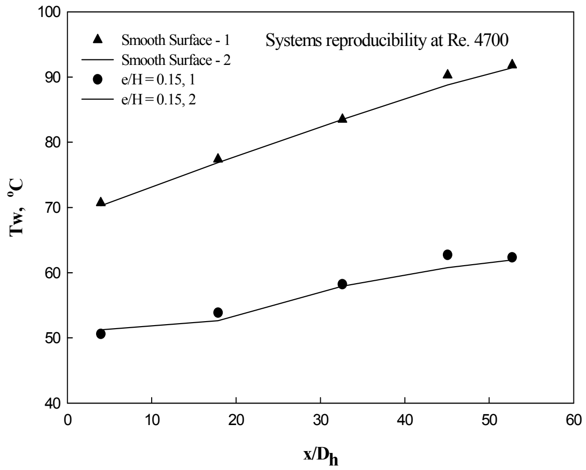


Fig. 3 Reproducibility of Experimental Device (Axial Wall Temperature)

condition for both of smooth and rib roughened surfaces. Figure 3 shows that the plotted data are almost overlapped in repeated experiment for both smooth surface and rib roughened surface. Digital manometer (Dwyer-Series 477) having tolerance ±0.5% at 16.6˚C to 27.6 ˚C has been used for static and differential pressure measurement. Calibration of I-type probe was done at the same of experimental ambient circumstance to be ensured the accuracy.

3. Data Reduction

Reynolds number is an independent parameter to comparing results with other characteristics. The Reynolds number (Re) based on the channel hydraulic diameter and bulk velocity is defined as eq. (1);

$$Re = \frac{\rho_a v_{b D_h}}{\mu} \tag{1}$$

Where μ is dynamic viscosity of air.

The dimensionless pressure drop (*f*) characteristics is obtained by using well known Darcy-Weisbach quation [7], Which can be is evaluated as below-

$$f = \frac{2}{L/D_h} * \frac{\triangle P}{\rho v_b^2} \tag{2}$$

Where L is total length of test section, $\triangle P$ is pressure drop along the test section and ρ is air density.

The range of Reynolds number conducted by the experiment is from 3000 to 10000. For the validation of smooth surface in this range Blasius correlation can be used found in open literature [12] as mentioned in eq. (3);

$$f_o = 0.316 Re^{-0.25} (3000 \le Re \le 20000) \tag{3}$$

Turbulence kinetic energy has been measured only for u component of velocity.

Mean velocity (U)-

$$U = \frac{\sum_{t=1}^{N} u(t)}{N} \tag{4}$$

Fluctuation velocity $(\acute{u})$ or rms value of u component

$$\acute{u} = \sqrt{\acute{u}^2} = \sqrt{\frac{\sum_{t=1}^{N} (U - u(t))^2}{N}} \tag{5}$$

Turbulent Intensity (I) (%)

$$I = \frac{\acute{u}}{U} * 100 \tag{6}$$

The kinetic energy of turbulence is the energy associated with turbulent eddies in a fluid flow. and it can be defined as folloing equation for u velocity direction (k)-

The heat transfer coefficients are evaluated from the measured temperatures and heat inputs. With heat added uniformly to fluid (Qair) and the temperature difference of wall and fluid (Tw−Tb), average heat transfer coefficient will be evaluated from the experimental data via the following equations

$$Q_{air} = Q_{conv} = m C_p (T_o - T_i) = VI \tag{7}$$

and convective heat transfer coefficient can be calculated as function of average wall temperature

Tw, fluid bulk temperature (Tb)

$$h = \frac{Q_{conv}}{A(\overline{T_w} - T_{b)})} \text{ where, } T_b = \frac{(T_o - T_i)}{2} \qquad (8)$$

Average Nusselt number is defined as eq. (9);

$$N = \frac{hD_h}{K} \qquad (9)$$

Where h is convective heat transfer co-efficient and K is thermal conductivity of working fluid.

The comparison in thermal performance (η) evaluation of the increased heat transfer and pumping power is considered as following expression (9);

$$\eta = \frac{\left(\frac{Nu}{Nu_o}\right)}{\left(\frac{f}{f_o}\right)^{1/3}} \qquad (10)$$

4. Result and Discussion

a) Effect of roughness heights on Friction factor

Generally pressure drop can be changed by different factors like the roughness height, roughness spacing, roughness shape and type. Pressure drop across all along the channel is shown in figure 4 regarding the roughness height in terms of dimensionless friction factor. Here only the roughness height is considered to calculate the normalized pressure drop following the optimized rib spacing (P/e = 10) reported by early researchers. The figure shows that the friction factor ratio differs remarkably with varying the height of roughness even the rib pitch to rib height ratio (P/e) is kept constant. To keep the parameter P/e constant the number of ribs must be increased for the lower height ribs comparing that of higher height. So it is clear that the effect of roughness height on pressure drop is more than the effect of roughness spacing or number of ribs.

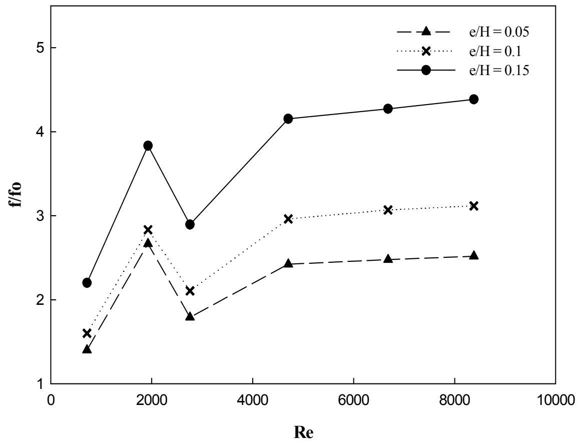


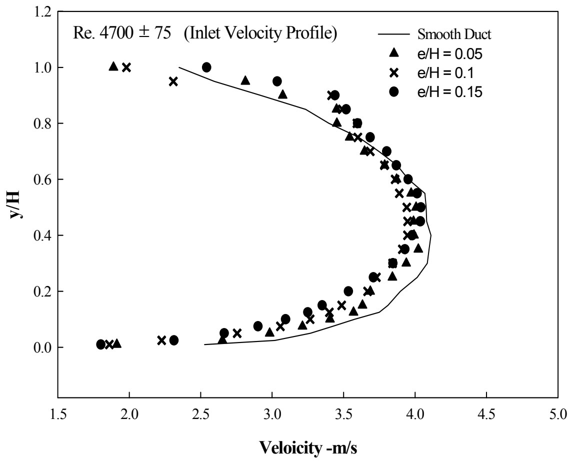
Fig. 4 Friction factor ratios for different roughness height

The figure is clearly showing that with decreasing roughness height the friction factor ratio approaches to lower magnitude. Rib roughened surface causes much pressure drops because of adverse pressure gradient grown between two ribs. Adverse pressure gradient occurs when static pressure increases in the direction of flow. The reason of adverse pressure gradient is flow blockage caused by periodic ribs and it depends upon the type of surface roughness. Rib height greatly affects pressure gradient.

Another significant phenomenon is noticeable that the transient state between laminar and turbulent shows least value of friction factor ratio. It obviously proves that the effect of transient regime between laminar and turbulent does not causes much pressure drop for rough surfaces as a result the heat transfer within this region is not significant. So this flow characteristic of transient state can be utilized for huge mass transfer from one place to another place through a channel having macro scale surface roughness without much extra pressure loss.

b) Effect of roughness heights on Velocity Profile and turbulence

Velocity and Turbulence is measured in vertical direction for only stream wise flow (u direction). It



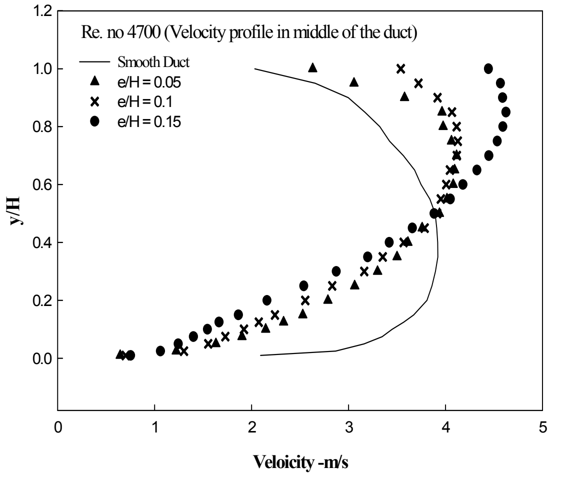


Fig. 5 Velocity profile a) Inlet velocity profile, b) Velocity profile in the middle of duct at Re = 4700

can be seen from figure 5, how the roughness height disturbs velocity profile. Figure 5(a) shows the inlet velocity profile with maximum tolerance ±50 Re. The flow is not disturbed because of smoothness at the inlet whereas the velocity profile is totally changed in the middle of duct influenced by different. Figure 5(b) shows that more than half of the duct perpendicular to the direction of main stream is subjected to the effect of roughness height.

The result shows rib height influences the flow a lot at the near wall region. The total turbulence between two ribs depends upon the height of ribs/roughness because of the large flow recirculation zone created by flow separation behind the rib and the flow impingement on the surface just in front of next rib as shown in figure 7. The impingement of flow at upstream the rib occurs high pressure gradient that causes back flow. So because of back flow and sudden pressure difference at flow separation zone there creates large scale turbulence near the wall. Figure 6 shows with decreasing rib height the magnitude of turbulence decreases simultaneously at the near wall zone.

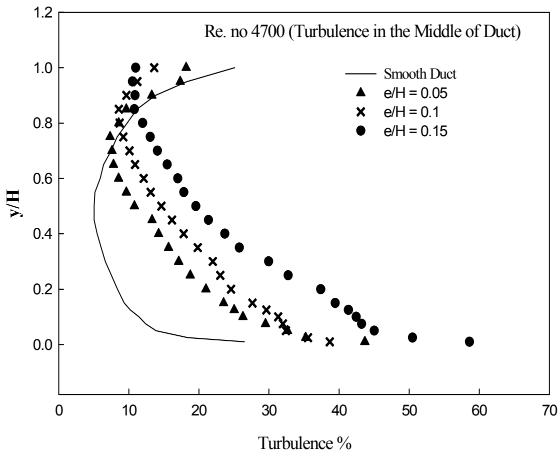


Fig. 6 Turbulent intensity measured in the middle of duct for different roughness height

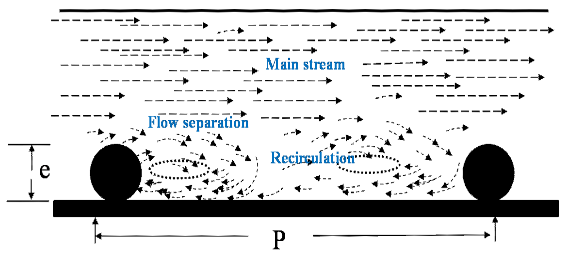


Fig. 7 Flow pattern between two ribs

c) Effect of roughness heights on convective heat transfer

It can be observed in Figure 8 that the surface temperature distribution changes with different roughness height in axial distance. With increasing the roughness height surface temperature is decreasing significantly.

The ratio of augmented Nusselt number to Nusselt number of smooth channel plotted against the Reynolds number value is displayed in figure 9. Heat transfer enhancement is clearly noticeable for roughened surface though it seems to be

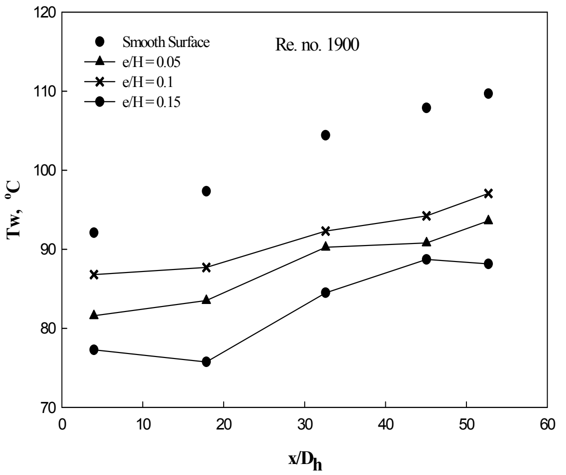


Fig. 8 Comparison of wall temperature distribution among various roughness heights

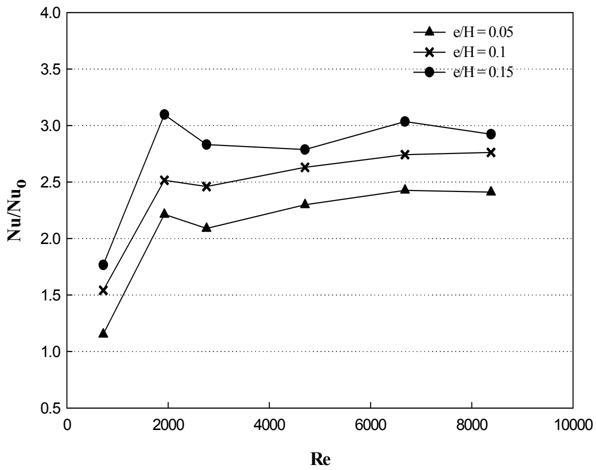


Fig. 9 Nusselt number ratios varying roughness height

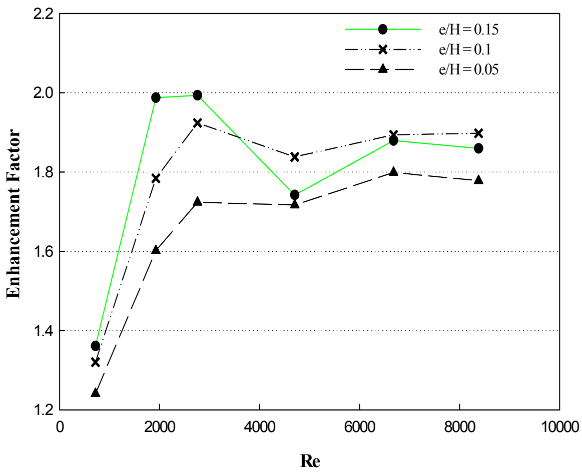


Fig. 10 Enhancement factor varying Re and roughness height

constant at low turbulent region and the reason of increasing heat transfer can be comprehensive from figure 6 and 7. Higher turbulence generated in the vicinity of wall by macro scale roughness and it happens because of recirculation and reattachment as well as flow separation around the ribs. Overall enhancement factor increases linearly at laminar region but it becomes flat at low turbulent region. Here e/H= 0.1 is found optimum that provides best performance under low turbulent because of comparatively low creating pressure loss among all of rib heights.

5. Conclusion

The study compares convective heat transfer performance of roughened channel with three different rib heights. Macro roughness like rib roughened surfaces works as fin and causes huge pressure drop and facilitates large scale turbulence into the channel.

All the results can be concluded as;

i. With decreasing roughness height friction factor ratio decreases but the transient state between laminar and turbulent does occurs extra pressure loss even the surface contains macro scale roughness. So if mass transfer is only becomes the main issue for any system, transient state is more suitable for only mass transfer through a channel having rough surface.

ii. Rib roughened surface affects the main stream velocity by creating more turbulence. Where the nano porous layer does not have any impact on turbulence though there occur a little additional pressure droop. The rib having 1/7th of channel height can disturb the full channel flow.

iii. Surface temperature decreases significantly with increasing the roughness height.

iv. Rib height affects more than 25 % of overall performance under laminar and low turbulent region investigated in this experiment.

Acknowledgements

This research was supported by Basic Science

Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology (No.2011-0021376).

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