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Experimental Study on Turbulence and Pressure Drop Characteristics in a Rectangular Duct Fitted with Semicircular Ribs

반원 리브의 거칠기를 가진 사각덕트에서의 난류 및 마찰 특성에 관한 실험적 연구

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Key Words : Semicircular Rib (반원 리브), Rectangular duct (사각덕트), Friction factor (마찰계수), Turbulence (난류)

Abstract : The article represents an experimental investigation on friction and turbulent flow characteristics of free airflow through a rectangular duct fitted with semicircular ribs of uniform height (e = 3.5 mm) on one principle wall. The aspect ratio of the rectangular duct was AR= 5 where the duct height (H) was of 30 mm. Four different rib pitches (P) of 28 mm, 35 mm, 42 mm and 49 mm were used for constant rib height to hydraulic diameter ratio (e/Dh = 0.07) and constant rib height to channel height ratio (e/H = 0.11). The experimental results show some significant effects on pressure drop as well as turbulent characteristics at various configurations among different numbers of rib arrangements varying Reynolds number in the range of 15000 to 30000. Pressure transducer and hot wire anemometer were used for data acquisition of this experiment.

1. Introduction

Several researches and inspections exist on pressure drop and heat transfer in rib roughened channel. The article focuses on pressure drop and turbulence using various numbers of rib pitch configurations in a rectangular channel. Periodic ribs are often employed in design of heat exchangers. The rig of periodic ribs in the channels interrupts hydrodynamic and thermal boundary layers. The flow around the ribs creates more vortices, circulations which enable to enhance thermal efficiency. The use of ribs not only works as a heat transfer enhancement but also creates huge pressure drop. The flow field also depends on rib geometry and the rib arrangement in the channels. Generally the rib angle, rib cross section, rib to channel height ratio and rib pitch to channel height ratio are considered which influences in a great scale to the channel flow characteristics.

The effect of the rib pitch to height variation in a tube was first studied by Webb et al. [1] the result was formulated into a correlation. Most early researchers studied limited number of rib roughness configurations. Nowadays the study is to find out optimal rib configuration for higher performance. Hanjalic and Launder [2] carried out detailed experiment of fully developed asymmetric flow in a plane channel. One of the surfaces was roughened by square silver steel ribs with a pitch to height ratio 10. Tanda [3] shows that 90° transverse ribs provided the lowest thermal performance and 60° parallel broken rib or 60°

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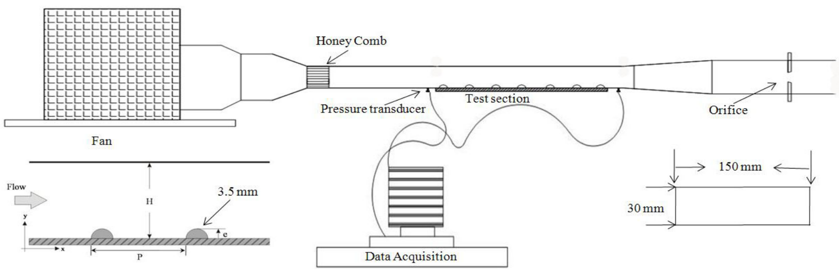

Fig. 1 Schematic diagram of experimental apparatus

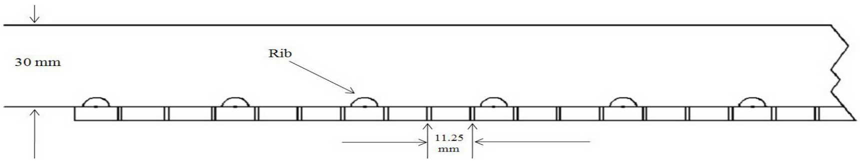

Fig. 2 A part of ribbed test section with pressure taps

V-shaped broken ribs yielded a higher heat transfer augmentation than 45° parallel broken ribs, we are using 90° parallel semicircular ribs. Han and Zhang [4] also found that 60° broken 'V' ribs higher heat transfer at about 4.5 times the smooth channel and better than the continuous ribs. Chandra et al. [5] carried out measurements on heat transfer and pressure loss in a square channel with continuous rib on one, two, three and four walls. They found the heat transfer augmentation increases with the rise in the number of ribbed wall. Huh et al. [6] shows the effect of rib spacing in 1:4 aspect ratio channel, rib pitch to rib height ratio were P/e = 2.5, 5 and 10 with a constant blockage ratio of e/D_h = 0.078. That study shows that P/e = 10 was good for the best heat transfer.

C. Thianpong et al. [7] studied effects of uniform rib heights of e= 4, 6, and 8 mm as well as non-uniform rib heights of e = 4, 6 mm on heat transfer and friction behaviour for single rib pitch of P = 40 mm and found the uniform rib heights performs better than the corresponding non uniform one.

The present article shows pressure drop and turbulent flow characteristics for different rib pitch ratios around semicircular ribs fitted in a rectangular channel. Experimental results are presented for four different rib configurations in turbulent channel flow in the range of Reynolds number from 15000 to 30000. The principle aim of this experiment is to analyse the flow characteristics around the semicircular rib and to optimize rib pitch ratio for plate fin heat exchanger which will make it easier to understand best performance of heat transfer.

2. Experimental Setup:

The schematic diagram of the experimental apparatus is presented in Fig. 1 where the details of the rib mounted in one principle wall of the rectangular duct are displayed. The measurement system of fluid characteristics is also described.

a) Experimental Apparatus

The rectangular duct is directly attached to a 0.5 KW low pressure blower. The channel geometry is characterized by the channel height (H) of 30 mm and the axial length 2500 mm which included the 900 mm test section with the channel width of 150 mm. The ribbed wall is copper plate of 5 mm thickness on which several rib pitches of 28 mm and 35 mm, 42 mm and 49 mm were mounted. The uniform rib height (e) is 3.5 mm and the thickness is of 7 mm. Air is tested fluid and the operating speed of the blower was varied by using a regulator to provide desired air velocity. An

Orifice meter is connected to the end of the channel to measure the flow rate. Flow rate can be calculated by measuring pressure differential between upstream and downstream of orifice. The diameter of orifice was 52.5 mm and the circular pipe is used as like same cross sectional area of rectangular channel. Two static pressure taps were located at the bottom principle wall of channel to measure axial pressure drop across the test section and used to evaluate friction factor. One of these tap was 45 mm upstream from the leading edge of the test section and the other was 45 mm downstream from the test section. Digital manometer is used for taking static pressure and hot wire anemometer is used to collect data of turbulence.

b) Pressure Drop Measurement

The pressure drop investigation was performed at normal atmospheric condition. Static pressure taps were equipped at eighty one locations in whole calculation domain "as shown in Fig. 2" and each of pressure tape of 1 mm diameter is 11.25 mm apart from another at the centre line of the channel. In order to provide cross sectional average value of static pressure among the rib roughened test section short copper tubes were used in every pressure taps and glued with plastic tubes and digital manometer. When static pressure was taken in one of those taps, the others had been kept closed using glue tape. In this way the whole 900 mm length of test sections static pressure were taken using digital micro manometer for both smooth and rib roughened surface. Then making linear regression average full section pressure drop per square meter has been calculated for four different pitch ratio arrangements.

c) Turbulence Test

Specific location of approximately $29 < X/D_h < 32$ has been selected from the inlet of the duct to get the aerodynamic characteristics at various Reynolds numbers between two ribs. Straight I-type probe has been calibrated and used carefully to get the stream wise flow characteristics. FFT analysis of the hot wire signal shows that 512 samples per second can capture the high amplitude fluctuations in the flow around the ribs. Only in one direction velocity fluctuation has been taken using I-type probe. In the direction of main stream, data has been taken between two ribs in a distance of 5 mm apart. But vertically data was taken from very near to bottom wall gradually step by step by the help of height gauge connected with hot wire anemometer stand, for 1st 1 mm from wall was measured as 0.1 mm apart, 2nd 1 mm was taken as 0.2 mm apart, 3rd 1 mm was as 0.5 mm apart, in this way the 30 mm channel height data was taken very carefully using I-type probe with the help of digital height gauge. Turbulence kinetic energy has been measured only for axial direction (u) of velocity. For every single position between two ribs the value of velocity with time has been calculated as mean. Then fluctuation velocity along u component has been calculated as rms value and turbulent intensity has calculated dividing rms value by mean value. The average turbulent kinetic energy between two ribs was calculated using the data taken from both in X and Y direction movement of straight I-type probe. The arithmetic average result can be seen in Fig. 8.

Bulk velocity (v_b) has been taken as arithmetic average velocity measured in both of axial and vertical direction at equally spaced by hot wire anemometer with the help of I-type probe over the whole 900 mm test section. Specially fabricated an upper plate segment of rectangular channel was equally perforated exactly 1 cm apart and could be slided along stream wise direction by exchanging the position with another plate over the test section. By changing the position of plate one after another with small part perforated plate the whole test section has been measured for getting bulk velocity. While measuring velocity through a single hole the other holes were sealed perfectly from inside to out to be ensured that there is no leakage. After measuring bulk velocity this special setting has been removed and a single smooth part upper plate has been used for other measurement process to overcome unusual friction effect.

3. Data Reduction

To optimize pitch ratio Reynolds number is an independent parameter for comparing with other characteristics. The Reynolds number (Re) based on the channel hydraulic diameter (D_h) and bulk velocity (v_b) is defined as following equation-

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

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-

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

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

As the range of using Reynolds number is from 10000 to 25000. For the validation of smooth surface with in this range for turbulent and fully developed flow Blasius correlation has been found in open literature [8].

$$\begin{cases} f_o = 0.316 Re^{-0.25} \ (Re \leq \ 20000) \\ f_o = 0.184 Re^{-0.2} \ \ (Re \geq \ 20000) \end{cases} \quad 3$$

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

Mean velocity (U)-

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

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

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

Turbulent Intensity (I) (%)

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

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

$$k = \frac{\overline{\acute{u}^2}}{2} \quad (m^2/s^2) \quad \text{for } u \text{ component only}$$

Average turbulent kinetic energy

$$\acute{k} = \frac{\sum_{i=1}^{n} k}{n} \quad 7$$

where n is the number of data taken from *i* number of position between two ribs to calculate average turbulent kinetic energy.

4. Result and Discussion

The introduction of rib in heat exchanger and the investigation of flow characteristics around the ribs enable to enhance the heat transfer rate.

The dimensionless pressure drop can be seen (Fig. 3) as a comparison among smooth and rib roughened surface. The graph shows a good validation for smooth surface friction factor with Blasius correlation. Here with increasing reynolds number and pitch to rob height ratio friction factor reduces significantly. It happens because at higher pitch to rib height ratio needs less number of ribs to fabricate that reduces friction factor. The static pressure value (Fig. 4) has been found experimentally near the wall over the whole test section through pressure taps by manometer between ribs which shows the regression line for individual pitch ratio at Reynolds number 19785. Pressure drop across the length of 1 meter along whole test section for different pitch ration is shown in Fig. 5. It is clear to see that with increasing pitch ration the overall pressure drop is reduced.

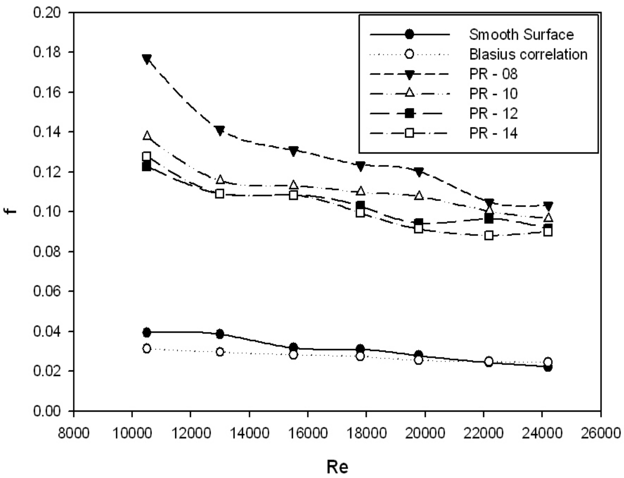

Fig. 3 Darcy friction factor for smooth and rib roughened surface

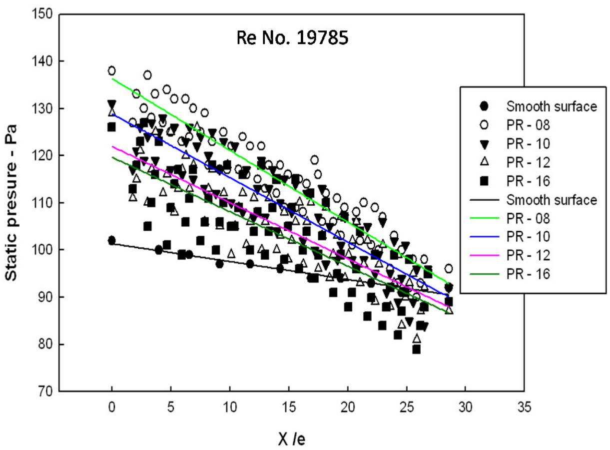

Fig. 4 Static pressure over whole test section

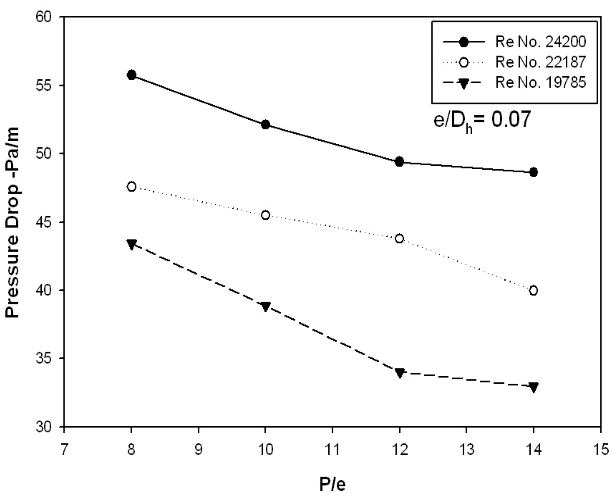

Fig. 5 Pressure drop enhancement comparing pitch ratio at different Reynolds number

Fig. 6 Line probes for measuring stream wise fluctuation component

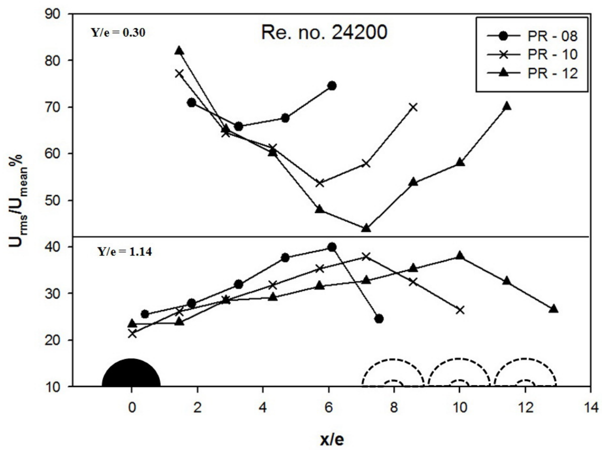

Fig. 7 Stream wise fluctuation component comparing different pitch to rib height ratio at Y/e = 0.30 and 1.14

Fig. 6 shows line probes for measuring stream wise fluctuation component which indicates the position Y/e = 0.3 and 1.14. These two position has been chosen to know turbulent characteristics very near to the plate between two ribs as well as to know the velocity fluctuation component in the flow separation zone just after the ribs at rib height. Stream wise fluctuation component comparing different pitch ratio at aforementioned position is displayed in Fig. 7. It can be seen near the wall at Y/e = 0.3 with increasing the X/e ratio and pitch to rib height ratio, fluctuation value decreases and again increases just before the ribs. It happens in the zone of recirculation is about and also another pick is identified in the zone of shorter vortex created just before the rib. So the fluctuation decay rate is independent of pitch ratio and it is amplified in second separation zone created just in front of the rib. But near the rib height region at Y/e = 1.14 it shows less fluctuation than near wall because the recirculation zone does not disturb this zone properly besides having some influences of main stream flowing through the duct.

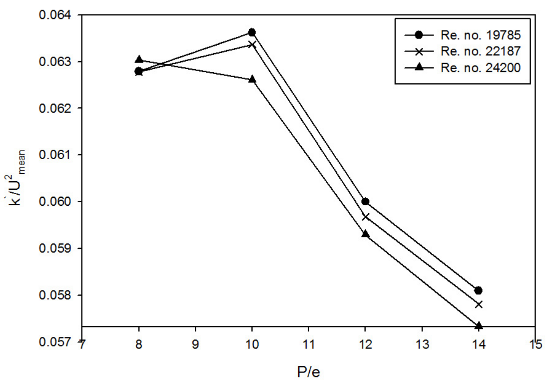

Fig. 8 Average turbulent kinetic energy vs PR

From Fig. 8 it is obvious that PR - 10 gives the higher value of turbulent kinetic energy because of the higher average turbulent intensity between two ribs. Except PR- 10 the others pitch ratio had low average turbulent kinetic energy at the same velocity. It can be said that the heat transfer enhancement is dominated by turbulent transport so the turbulent kinetic energy enhances heat transfer rate because of repeated impinges of flow directly on heat transfer surface. As the result shows in Fig. 8, PR - 10 can be considered as optimal pitch ratio which has higher turbulent kinetic energy.

5. Conclusion

The article focuses on experiment and it shows pressure drop and aerodynamic analysis for semicircular ribs fitted in rectangular ribs.

Stream wise velocity fluctuation gives higher value at recirculation zone which is significant for heat transfer. The average turbulent intensity depends upon the size of recirculation area.

Overall pressure drop and turbulent intensity are two major factors influencing the heat transfer. And PR - 10 is obviously optimal pitch ratio among all of them for good thermal performance.

Acknowledgements

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