Journal of Visualization, Vol. 11, No. 3 (2008)205-212

Regular Paper

Flow Visualization and Local Mass Transfer Studies for Turbulent Flow in a Wind Tunnel with Chamfered Ribs

Karwa, Rajendra*[1], Maheshwari, B. K.*[1] and Karwa, Nitin*[2]

*1 Department of Mechanical Engineering, Faculty of Engineering, Jai Narain Vyas University, Jodhpur 342011, India. E-mail: karwa_r@yahoo.com, and bkmaheshwari@hotmail.com
*2 Department of Mechanical Engineering, Technical University Darmstadt, Darmstadt 64287 Germany. E-mail: nitinkarwa@gmail.com

Received 17 September 2007
Revised 30 March 2008

Abstract : The paper presents results of flow visualization and mass transfer studies for fully developed turbulent flow of air in a square section wind tunnel with repeated chamfered rib roughness on the bottom of the tunnel (rib head chamfer angles ϕ of -15°, 0°, and 15°; relative roughness pitch p/e = 3, 5, 7.5, and 10). Direct video recordings of flow patterns were made using a simple technique of particles visualization. For the positively chamfered closely spaced ribs ($p/e \leq 5$) vigorous vortex shedding has been seen compared to the square or negatively chamfered ribs, which is found to be a function of the Reynolds number. For the widely spaced ribs, the study shows flow separation at the ribs and reattachment in the inter-rib region. Local mass transfer studies, based on the variation in colour of cobaltous chloride solution impregnated paper due to evaporation of water, showed a significant improvement in mass transfer rate in the recirculating region in the wake of ribs with the change in the chamfer angle from -15° to 15°. The positively chamfered 15° ribs are found to be better than square section ribs at $p/e \leq 7.5$. The performance of negatively chamfered ribs is found to be poor compared to other ribs irrespective of the relative roughness pitch.

Keywords : Rib roughness, Chamfer, Flow Structure, Mass Transfer Study.

1. Introduction

Roughness elements in the form of ribs of various shapes have been employed to enhance heat transfer in heat exchanger tubes, gas turbine blade cooling channels and solar air heaters (Webb et al., 1971; Liou and Hwang, 1993; Karwa et al., 2001). From the experimental studies of the effect of artificial roughness, investigators have shown that the geometry of the roughness elements (shape, rib pitch-to-height ratio, etc.) has a marked influence on the heat transfer and friction characteristics of such surfaces. Local heat transfer and flow studies have confirmed the existence of a recirculating flow in the wake of the roughness elements and associated hot zones due to a low heat transfer coefficient in the wake. Further, the recirculating region has been shown to vary with the rib shape.

Williams et al. (1970) have reported strong effect of chamfering of head of the rectangular section ribs provided on the outer surface of an inner tube for the flow through a circular annulus. Karwa et al. (1999) carried out experimental investigation of heat transfer and friction for flow of air in asymmetrically heated rectangular ducts with repeated chamfered rib-roughness on one of the broad walls (rib chamfer angles of -15°, 0°, 5°, 10°, 15°, and 18°), where 0° refers to rectangular or square section ribs. They observed that both friction factor and the Stanton number take their maximum values at 15° chamfer angle. Furthermore, it has been shown (Williams et al., 1970;

Williams and Watts, 1970; Karwa et al., 1999) that the closely spaced chamfered ribs (relative roughness pitch $p/e < 7$) are more effective in the enhancement. Karwa et al. (1999) hypothesized that the enhancement for closely spaced chamfered ribs is more due to the increased vortex shedding while in the case of widely spaced ribs the flow reattachment mainly contributes to the heat transfer enhancement.

Flow visualization techniques, heat-mass transfer analogy, and holographic interferometry (Williams and Watts, 1970; Sparrow and Tao, 1993; Hsieh and Hong, 1989; Locket and Collins, 1990; Liou and Hwang, 1993) have been used to study the flow patterns and local heat transfer for artificially roughened surfaces. Matsuzaki et al. (2004) employed hydrogen bubble method for visualization of flow structures in the wake of an inclined circular cylinder. Jang et al. (2007) investigated turbulent structure in the wake of a sphere using smoke-wire method.

Eschenbacher et al. (2001) visualized vortical structures behind a wing-type vortex generator immersed in a drag-reducing flow with a fluorescence dye illuminated with a planer laser sheet to investigate the enhancement mechanism of heat transfer. Calluaud et al. (2005) showed existence of vortex shedding process downstream a surface-mounted block, which was highlighted by *particles visualizations*. Williams and Watts (1970) developed large-scale technique for flow studies using water circuit in a tunnel for square and chamfered ribs. The flow patterns were made visible using polystyrene particles illuminated from above by slit lighting. They report more vigorous vortex between the chamfered ribs ($p/e = 3$; Re = 1.7×10^5), growing to full cavity size and shedding frequently as compared to square ribs which produce occasional vortex shedding only. They also carried out mass transfer study using cobaltous chloride solution impregnated paper whose colour changed from bright pink to pale blue due to the evaporation of water.

The present experimental study has been carried out for detailed flow visualization and local mass transfer studies, under fully developed turbulent flow conditions in a square section wind tunnel with repeated chamfered and square section ribs (zero chamfer angle) mounted transverse to the flow direction on the bottom of the tunnel, to understand the reasons for the differences in heat transfer performance of these ribs with change in the chamfer angle from -15^o to 15^o and relative roughness pitch p/e from 3 to 10. Such results have relevance to the flow in solar air heater and gas turbine blade cooling channels. The study has employed the simple and inexpensive technique of particles visualization and method of Williams and Watts for the mass transfer study.

2. Experimental Program

Figure 1(a) shows the longitudinal section of the wind tunnel and Fig. 1(b) shows the test section with mounted ribs. The flow system consists of a 1.21×1.21 m^2 bell mouth entrance with a honeycomb structure sandwiched between two wire mesh screens (for low free-stream turbulence), followed by 460 mm square section duct 6.25 m in length. The duct length consists of 1.25 m long entrance and 3.75 m long test sections. A 1.25 m long exit section is provided to remove any downstream effects from the test section. The side walls of the test section are made of plexiglass to provide optical access. The square duct is connected with a square to circular transition piece through a flexible rubber hose to the fan section as shown in the figure. A 1440 rpm, 7.5 hp induction fan sucks air through the tunnel. The power supply to the fan is through a variac to regulate its speed and, hence, the air velocity through the tunnel.

The ribs used in the study, as shown in Fig. 1(c), are of the same height e of 43 mm giving rib height to hydraulic diameter ratio of 0.0935. The rib head chamfer angles used are 0^o (square section ribs), -15^o and 15^o, where the positive or negative chamfer angle is defined with respect to the flow direction. The relative roughness pitch p/e is 3, 5, 7.5, or 10. The ribs were made from good quality seasoned wood with a smooth surface finish.

Video recording of the flow structure (by putting the video camera in two positions as shown in the figure) and mass transfer studies have been made between the last two ribs mounted in the test section of the tunnel. Total nine ribs were installed to ensure fully developed turbulent flow at the section of observation. The flow visualization videos have been taken with the base of the test section and wooden rib blocks painted black, and the tunnel wall opposite to the camera side window was also covered with a black and rough cloth. The mass transfer study has been confined to the inter-rib region.

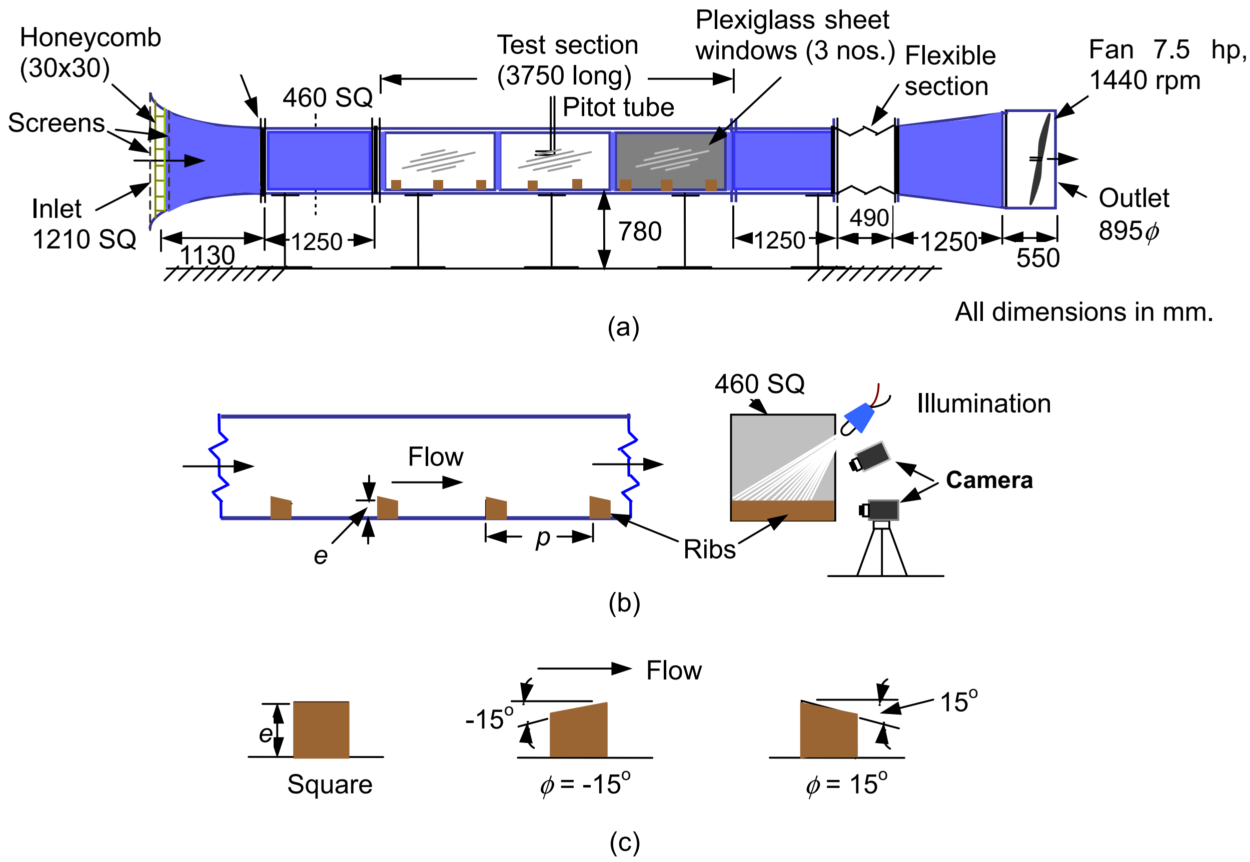


Fig. 1. (a) Wind tunnel (longitudinal section), (b) Test section with ribs, and (c) Rib shapes.

A vertical traverse of pitot tube with an inclined methyl alcohol U-tube manometer has been used to measure the air velocity distribution though the tunnel, which has been utilized to calculate mean velocity.

2.1 Mass Transfer Studies

For the local mass transfer study, the technique of Williams and Watts (1970) has been used, which involves study of the change in colour of cobaltous chloride solution impregnated paper from bright pink to pale blue due to evaporation of water.

At the start of the test, chloride solution was sprayed evenly over the surface of about 30 mm wide strip of absorbent paper affixed to the bottom surface of the test section between the last two ribs and then the fan was started. Since the time required for the chloride paper to turn from pink to blue is proportional to the heat transfer coefficient (Locket and Collins, 1990), the colour variation along the paper length between the ribs provided the information about the distribution of the heat transfer coefficient in the inter-rib region.

2.2 Flow Structure Studies

Flow patterns were made visible using white fibrous particles of plantago ovata husk (density 3600 kg/m^3; 40/60/100 mesh grade) illuminated with a cool light (CFL). The white particles were carried away by the flowing air and, thus, made the direct video recording of the flow pattern possible. Sony Handycam DCR-TRV285E Digital 8 Camcorder (CCD 1/6") has been used for the videography. For each run, a measured quantity of these particles was uniformly distributed over a marked width and along the complete length between the ribs. The flow velocity was varied for both studies, which provided flow Reynolds number of about 1.8 x 10^5 - 4.8 x 10^5 with maximum mean flow velocity of about 15.75 m/s.

3. Results and Discussion

A large number of video recordings were made for both the studies in addition to the visual inspection. However, it is not possible to reproduce here all of them.

Figure 2 shows mass transfer performance with time for the 0^o (square) and 15^o ribs at relative roughness pitch of 3. A comparison of the colour variation from pink to blue along the strips clearly shows the mass (heat) transfer performance advantage of the 15^o chamfered ribs over the 0^o ribs. Comparison of mass transfer performance of 0^o, 15^o and -15^o chamfered ribs ($p/e = 5$) presented in Fig. 3 also shows the superiority of 15^o ribs.

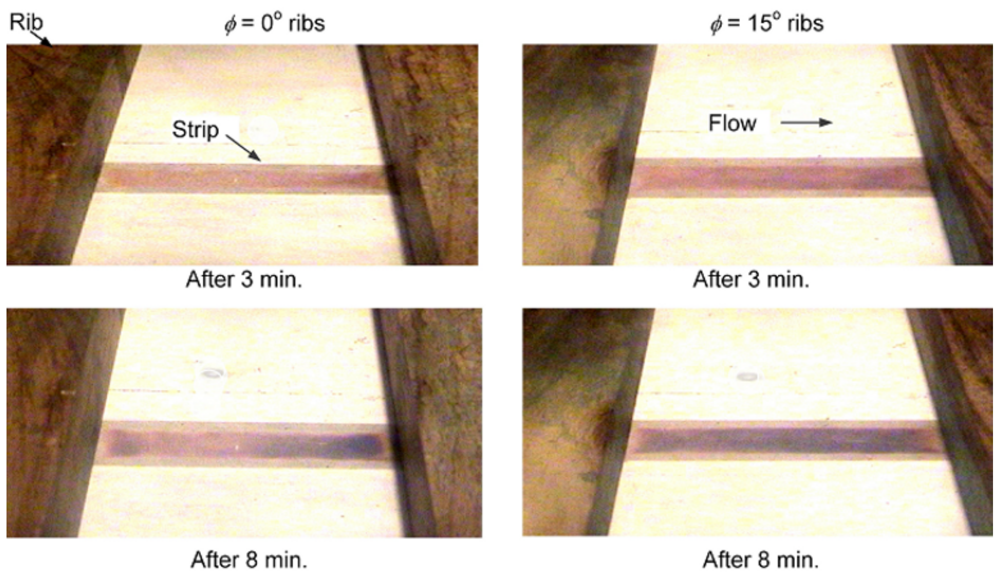


Fig. 2. Relative mass transfer performance of 0^o and 15^o ribs with time (p/e = 3).

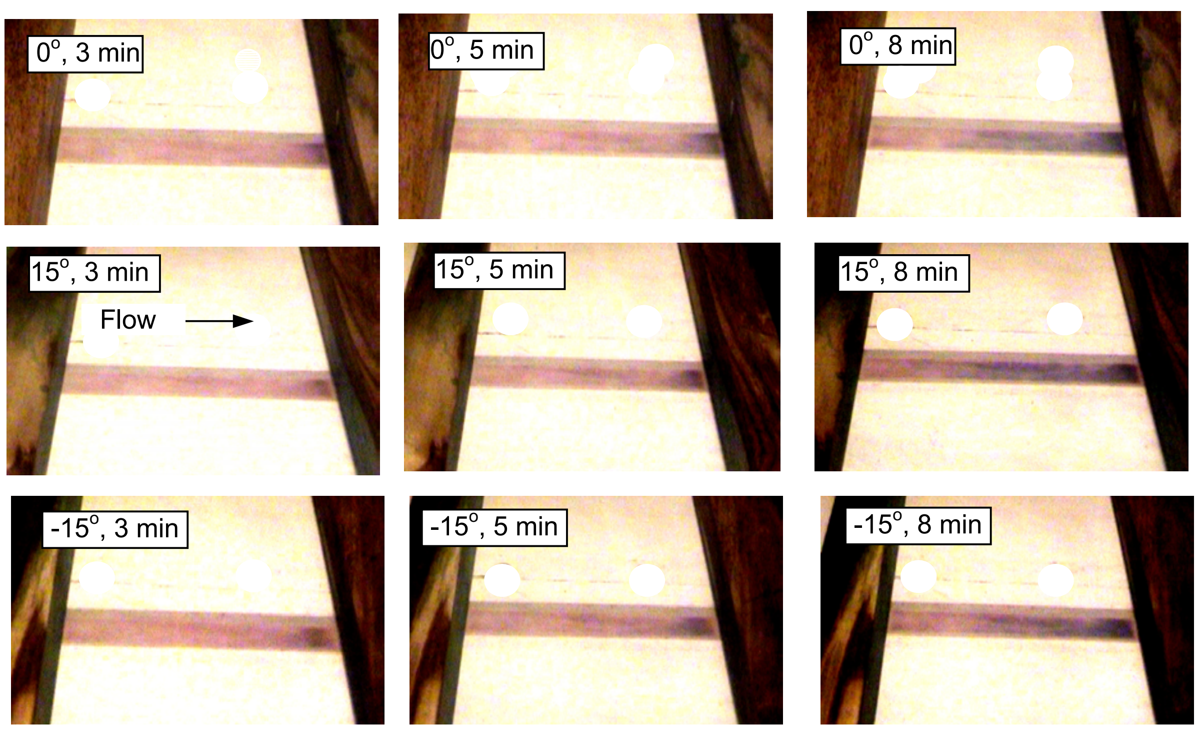


Fig. 3. Relative mass transfer performance of $\phi = 0^o$, 15^o and -15^o ribs with time (p/e = 5).

The essential features of the mass transfer study as observed for different configurations are compiled in Fig. 4, which is a qualitative depiction prepared with utmost care to highlight the difference in their behaviour. It is based on the large number of mass transfer studies made. The ordinate in the diagram is proportional to the mass transfer rate and variation in the height of the line diagram represents the mass transfer variation. Thus this figure qualitatively depicts the variation of local heat transfer rate in the inter-rib space.

For the widely spaced ribs ($p/e \geq 7.5$), the region of highest mass (heat) transfer rate has been seen to occur between 4-6 rib heights from the face A of the trailing rib. This region is termed as the reattachment region (marked I in Fig. 4) because the flow which separates at the trailing rib reattaches in this region. The reattachment point, judged by the appearance of the first spot due to change in colour of the strip from pink to blue, lies between 3.5-5 rib heights from A; a lower value has been seen for 15° chamfer angle. It has been observed that the change of the colour takes place rapidly in the reattachment region staring from the first appearing spot, which indicates a high mass transfer rate. Another peak of the mass transfer rate can be seen just before the leading rib. The colour change proceeds at a reasonable rate from both these peaks covering the region between these peaks (marked II), which indicates a reasonable heat transfer rate in this region. But the colour change proceeds at a much slower rate towards the trailing rib due to the recirculating flow in the wake of the trailing rib indicating a low mass transfer rate. At $p/e = 7.5$ and 10, the positively chamfered ribs (15° ribs) showed a reduced recirculating region and an improved mass transfer rate in the wake region (marked III) as compared to 0° or -15° ribs. However, this is also accompanied with a relatively poor mass transfer rate in region II for the 15° ribs as compared to the 0° ribs. In general, $p/e = 7.5$ and 10 surfaces differ mainly in the size of region II. For $p/e = 7.5$ arrangement, the region II is smaller than for $p/e = 10$ surface and, hence, overall performance of 15° ribs is better than that of 0° ribs. But it is difficult to decide the preferred type of ribs (0° or 15°) for $p/e = 10$ value from this study because the region II is larger in this case which offsets the improved mass transfer rate seen for 15° ribs in the wake region as compared to 0° ribs.

In the case of closely spaced ribs ($p/e \leq 5$), the change in colour of the strip from pink to blue is observed to start from the leading rib and proceeds towards the trailing rib (as also seen in Figs. 2 and 3). This can be attributed to the vortex type flow with no or little reattachment effect as seen from flow visualization studies discussed below. In general, the mass transfer study showed better performance of the 15° positively chamfered ribs for the relative roughness pitch $p/e \leq 7.5$; the advantage is seen to increase with decrease in the pitch.

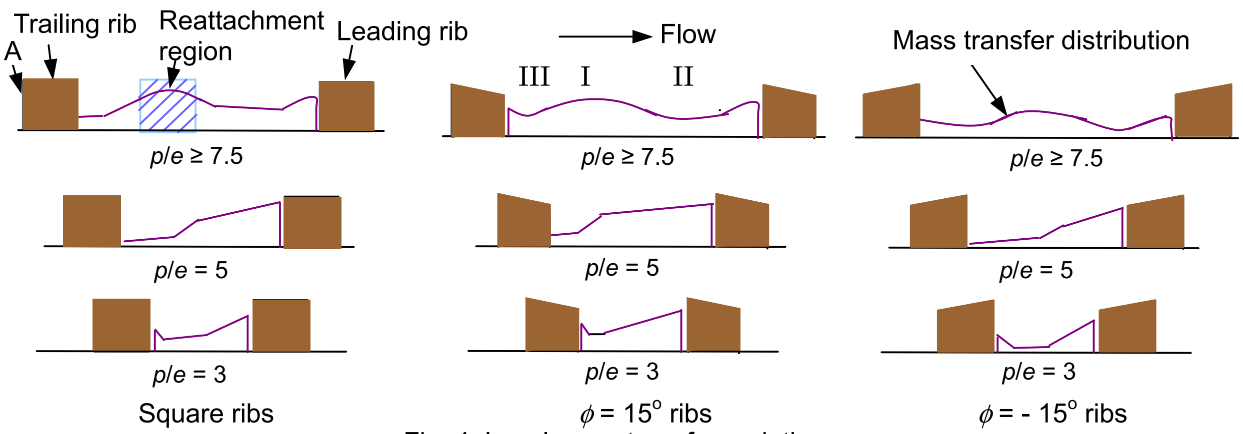


Fig. 4. Local mass transfer variation.

Figure 5 shows relative size of the vortex for 0° and 15° chamfered ribs at $p/e = 3$ where the vortex is seen to be much larger in size (and has also been observed to be more vigorous) for the 15° ribs. Typical photo sequence of flow pattern for 15° ribs at relative roughness pitch of 5 is presented in Fig. 6. Here also, vigorous vortex shedding has been observed for the 15° ribs as compared to other ribs. The vortex activity has been found to increase with the Reynolds number. It is to note that, unlike square and negatively chamfered ribs, reattachment effect has also been observed to be present along with the increased vortex activity in the trailing rib wake in the case of 15° ribs at p/e

= 5, which explains the reason for the vigorous activities seen at A and B in Fig. 6.

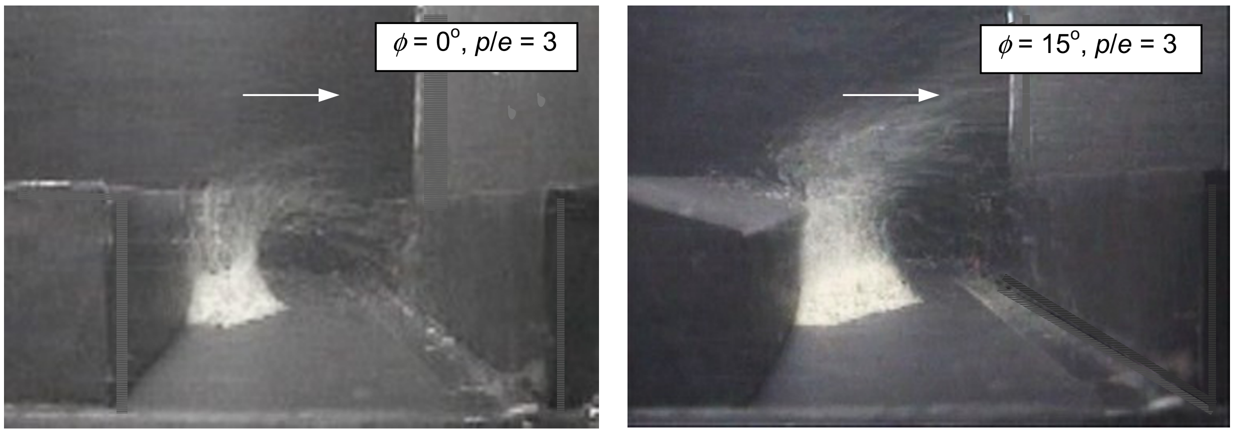


Fig. 5. Vortex at some instance, $\phi = 0^{o}$ versus $\phi = 15^{o}$ (p/e = 3).

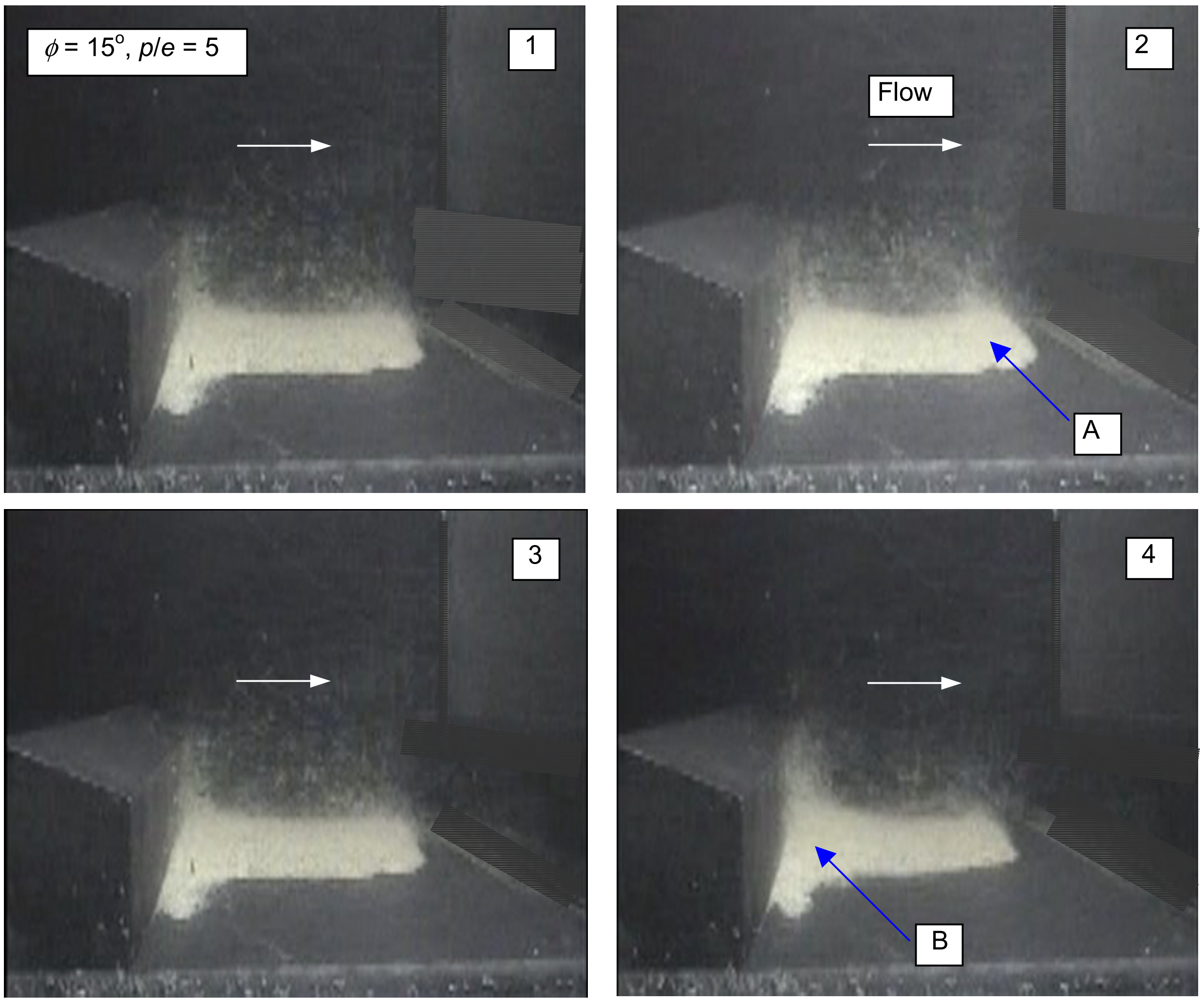
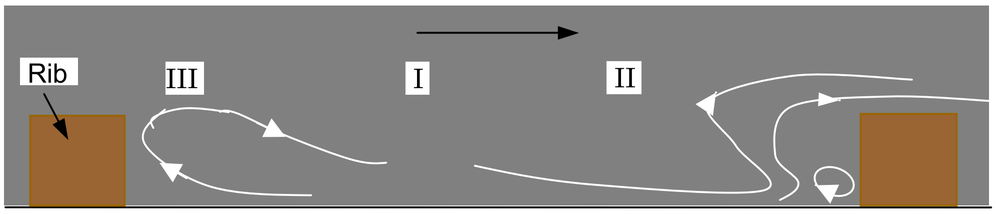
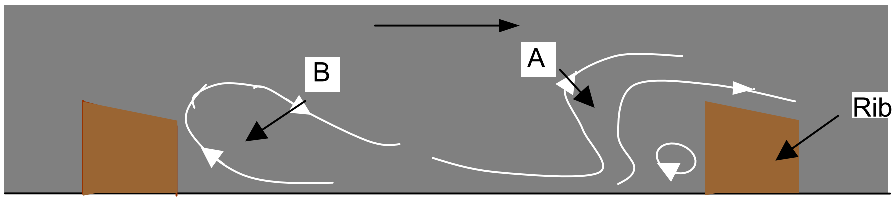


Fig. 6. A sequence of flow patterns for ϕ = 15o ribs (p/e = 5).

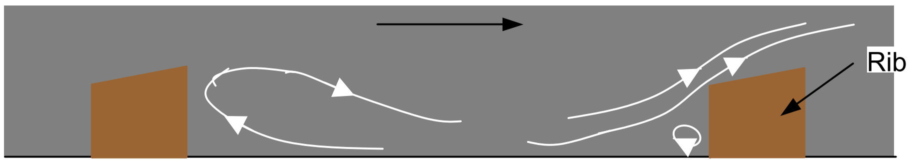
For p/e = 10 arrangement, the flow structure study shows separation at the trailing rib and reattachment in the inter-rib region. A greater vortex activity has been seen for 15^{o} ribs in the wake of trailing rib as compared to the other rib types. The essential features of the flow structure are presented as line diagrams in Figs. 7 and 8. In Figs. 7(a) and (b), the markings I, II and III, and A and B refer to Figs. 4 and 6, respectively. The performance of the negatively chamfered ribs is found to be poor compared to the squared or positively chamfered ribs irrespective of the relative roughness pitch. The results presented above confirm the hypothesis and results of Karwa et al. (1999) discussed in Section 1.



(a) Square ribs, $p/e \geq 7.5$.



(b) Chamfer angle +15°, $p/e \geq 5$.



(c) Chamfer angle -15°, $p/e > 5$.

Fig. 7. Flow patterns ($p/e \geq 5$).

Fig. 8. Flow pattern, $\phi = 0^{\circ}$ versus 15° ribs ($p/e = 3$).

4. Conclusions

Detailed flow visualization and local mass transfer studies have been carried out for repeated chamfered and square section ribs mounted on the bottom surface of a square section wind tunnel under fully developed turbulent flow condition. Rib head chamfer angles are -15°, 0°, and 15°, while the relative roughness pitch values are 3, 5, 7.5, and 10. The important findings of the study are:
For the widely spaced ribs ($p/e \geq 7.5$), the mass transfer study shows effects of flow reattachment in the inter-rib region and recirculating flow in the wake of the trailing rib. The reattachment length is found to be a function of the chamfer angle. The study showed better performance of the positively chamfered ribs as compared to the square section ribs for $p/e \leq 7.5$.

For the positively chamfered closely spaced ribs ($p/e \leq 5$), vigorous vortex shedding has been seen compared to the square or negatively chamfered ribs. The recirculating region found to reduce with variation in the rib head chamfer angle from -15° to 15° along with an increased vortex activity in the wake of the rib for the 15° chamfered ribs at $p/e \geq 7.5$ as found from flow structure study. Unlike square or negatively chamfered ribs, reattachment effect is present for 15° ribs at relative roughness pitch of 5.

The performance of the negatively chamfered ribs is the poorest of the all investigated ribs.

Acknowledgement

The facilities provided by the Department of Civil Engineering, Faculty of Engineering, Jai Narain Vyas University, Jodhpur (India) are gratefully acknowledged.

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Author profile

Rajendra Karwa: He received his B.E. degree in Mechanical Engineering from University of Jodhpur, Jodhpur (India) and M.E. (Honors) in Mechanical Engineering (Thermal Engineering) from the same university. He obtained his Ph.D. in 1998 from IIT Roorkee, India. Currently he is working as associate professor in Faculty of Engineering, Jai Narain Vyas University, Jodhpur, India since 1994. His areas of interest are heat transfer enhancement, solar energy and exergy analysis.

B.K. Maheshwari: He received his B.E. degree in Mechanical Engineering from University of Jodhpur, Jodhpur (India) and M.E. from the same university. Currently he is working as assistant professor in Faculty of Engineering, Jai Narain Vyas University, Jodhpur, India and also pursuing his Ph.D. course. His area of interest is heat transfer enhancement.

Nitin Karwa: He received his B.E. (Honours) degree in Mechanical Engineering from Jai Narain Vyas University, Jodhpur (India) and M.Tech. degree in 2005 from IIT Delhi, India. He worked on a project on spray technology for 2-1/2 years with GE, Bangalore (India) and is presently pursuing his Ph.D. course at Technical University Darmstadt, Germany. His areas of interest are heat transfer enhancement and spray cooling.