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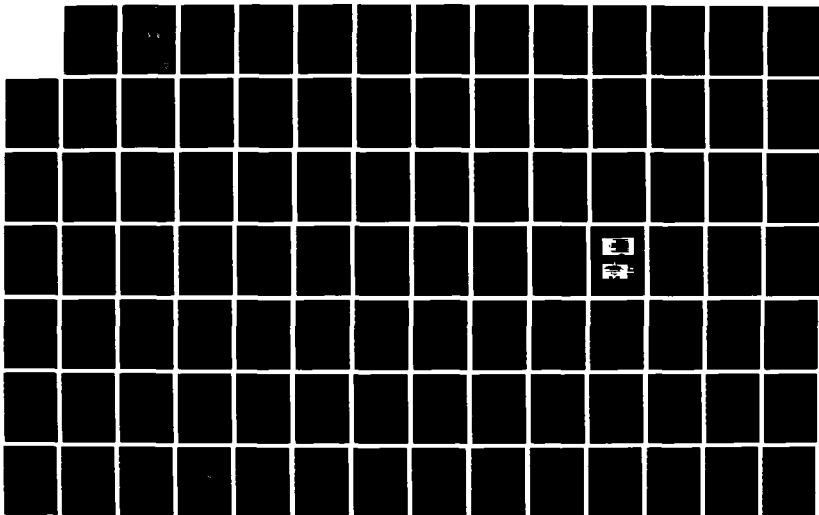
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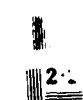
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# Local Heat/Mass Transfer and Pressure Drop in a Two-Pass Rib-Roughened Channel for Turbine Airfoil Cooling

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## NOMENCLATURE

|                            |                                                                  |
|----------------------------|------------------------------------------------------------------|
| $D$                        | channel width; also hydraulic diameter                           |
| $e$                        | rib height                                                       |
| $\bar{f}_{at}$             | fully developed average friction factor after the turn           |
| $\bar{f}_{bt}$             | fully developed average friction factor before the turn          |
| $\bar{f}(FD)$              | fully developed four-sided smooth channel friction factor        |
| $g_c$                      | conversion factor                                                |
| $G$                        | mass flux, $\rho V$                                              |
| $h_m$                      | local mass transfer coefficient, equation (1)                    |
| $K_C$                      | loss coefficient due to contraction                              |
| $K_t$                      | loss coefficient due to sharp turn                               |
| $\dot{m}''$                | local mass transfer rate per unit area, equation (2)             |
| $M$                        | cumulative mass transfer                                         |
| $Nu$                       | Nusselt number                                                   |
| $P$                        | rib pitch                                                        |
| $\Delta P$                 | pressure drop across the test section                            |
| $P_w$                      | naphthalene vapor pressure at the wall, equation (4)             |
| $Pr$                       | Prandtl number of air                                            |
| $\dot{Q}$                  | volumetric flow rate of air                                      |
| $Re$                       | Reynolds number based on channel hydraulic diameter              |
| $Sc$                       | Schmidt number for naphthalene                                   |
| $Sh$                       | local Sherwood number, equation (6)                              |
| $Sh_0$                     | Sherwood number of fully developed turbulent flow in square duct |
| $\overline{Sh}$            | average Sherwood number on each of the channel surfaces          |
| $\overline{\overline{Sh}}$ | overall average Sherwood number on all surfaces                  |
| $t$                        | thickness of the inner (divider) wall                            |

|            |                                                       |
|------------|-------------------------------------------------------|
| $\Delta t$ | duration of the test run                              |
| $T_w$      | naphthalene wall temperature, equations (3) and (4)   |
| $V$        | average velocity of air                               |
| $X$        | axial distance from channel entrance                  |
| $\bar{D}$  | diffusion coefficient, equation (6)                   |
| $\alpha$   | rib angle-of-attack                                   |
| $\rho$     | average density of air                                |
| $\rho_b$   | bulk naphthalene vapor density, equation (5)          |
| $\rho_s$   | density of solid naphthalene                          |
| $\rho_w$   | local naphthalene vapor density at wall, equation (3) |
| $\nu$      | kinematic viscosity of pure air                       |

## 1.0 SUMMARY

This is an extended research report for the program of Measurement of Heat Transfer and Pressure Drop in Rectangular Channels with Turbulence Promoters. This project was conducted by the Turbomachinery Laboratories of the Texas A&M University and was funded in part through Curtis Walker at the U.S. Army Research and Technology Laboratories. The project was monitored by Robert Boyle at the NASA-Lewis Research Center under NASA Contract No. NAS 3-24227.

Based on the research results from the NASA Contract No. NAS 3-24227, a final report entitled "Measurement of Heat Transfer and Pressure Drop in Rectangular Channels with Turbulence Promoters" was published (NASA CR 4015 September 1986 or AVSCOM TR 86-C-25 by J.C. Han, J.S. Park, and M.Y. Ibrahim). In that report, the combined effects of the channel aspect ratio and the rib angle-of-attack on the friction factor and on the local and the average heat transfer coefficients in straight, rectangular channels with a pair of opposite ribbed walls were investigated for three Reynolds numbers ( $Re = 10,000, 30,000$  and  $60,000$ ), two rib spacings ( $P/e = 10$  and  $20$ ), two rib heights ( $e/D = 0.047$  and  $0.078$ ), four rib angles ( $\alpha = 90^\circ, 60^\circ, 45^\circ$ , and  $30^\circ$ ), and three channel aspect ratios ( $W/H = 1, 2$ , and  $3$ , ribs on side  $W$ ). The test channels were heated by passing current through thin stainless steel foils and instrumented with 180 thermocouples. The local distributions of the heat transfer coefficient on both the smooth side and the ribbed side walls from the channel entrance to the downstream region were measured.

The present investigation was aimed at measuring the detailed mass transfer distributions in a two-pass smooth, square, channel and in a

similar two-pass square channel with a pair of opposite rib-roughened walls, via the naphthalene sublimation technique. The top, bottom, outer, and inner walls of the test channel were all naphthalene-coated plates. For ribbed channel tests, metallic ribs (without naphthalene coating) were placed on the top and bottom walls of the naphthalene-coated test channel such that the corresponding ribs on the two walls were directly opposite each other. The highly detailed mass transfer distributions on the top wall (rib-roughened), the outer wall (smooth), and the inner wall (smooth) were determined between the channel entrance and far downstream of the second straight channel, for three Reynolds numbers ( $Re = 15,000, 30,000, \text{ and } 60,000$ ), two rib spacings ( $P/e = 10 \text{ and } 20$ ), two rib heights ( $e/D = 0.063 \text{ and } 0.094$ ), and three rib angles ( $\alpha = 90^\circ, 60^\circ, \text{ and } 45^\circ$ ). The mass transfer coefficients before the turn, in the turn, and after the sharp  $180^\circ$  turn on each wall of the test channel were then averaged, compared, and correlated. The corresponding pressure drops and the friction factors were also measured and correlated.

## 2.0 INTRODUCTION

### 2.1 Background

In advanced gas turbine airfoils, as depicted in Figure 1, rib turbulators are cast onto two opposite walls of internal cooling passages to enhance the heat transfer to the cooling air. A typical cooling passage can be modeled as a straight or a multipass rectangular channel with two opposite rib-roughened walls. Han (1984) and Han et al. (1984, 1985) investigated systematically the effects of the rib pitch, the rib height, and the rib angle-of-attack on the average heat transfer and the pressure drop in a fully developed air flow in a uniformly heated, straight, square channel with two opposite ribbed walls. The results showed that ribs with oblique angles-of-attack ( $\phi$ ) of  $30^\circ$  and  $45^\circ$  provided higher heat transfer enhancement than ribs with an angle-of-attack of  $90^\circ$  for the same pumping power consumption.

Recently, Han et al. (1986) reported the combined effects of the channel aspect ratio and the rib angle-of-attack on the friction factor and on the local and the average heat transfer coefficients in straight, rectangular channels with a pair of opposite ribbed walls for Reynolds numbers varying from 10,000 to 60,000. The channel aspect ratio ( $W/H$ ) was varied from 1 to 2 and to 4. The rib height-to-hydraulic diameter ratio ( $e/D$ ) was varied from 0.047 to 0.078, the rib pitch-to-height ratio ( $P/e$ ) was varied from 10 to 20, and the rib angle-of-attack ( $\phi$ ) was varied from  $90^\circ$  to  $60^\circ$  to  $45^\circ$  and to  $30^\circ$ , respectively. The test channels were heated by passing current through thin stainless steel foils and instrumented with 180 thermocouples. The local distributions of the heat transfer coefficient on both the smooth side and the ribbed side walls from the channel sharp entrance to the downstream region were

measured. The results confirmed that, in the square channel, the heat transfer for the slant ribs ( $\alpha = 30^\circ$  to  $45^\circ$ ) was about 30% higher than that the transverse ribs ( $\alpha = 90^\circ$ ) for the same pumping power consumption. However, in the rectangular channels ( $W/H = 2$  and  $4$ , ribs on side  $W$ ), the heat transfer at  $\alpha = 30^\circ$  to  $45^\circ$  was only about 5% higher than that  $\alpha = 90^\circ$ . The results also showed that, in the square channel, the highest heat transfer was obtained at  $\alpha = 60^\circ$  accompanying with the highest pressure drop, however, in the rectangular channel with  $W/H = 4$ , both the highest heat transfer and pressure drop were obtained at  $\alpha = 90^\circ$ .

In a multipass rectangular channel, in addition to the rib turbulators, the flow separation and recirculation in the turn around regions and the flow redevelopment downstream of the turns are expected to have significant effects on the distribution of the local heat transfer coefficient and on the overall channel heat transfer. Boyle (1984) studied the heat transfer in a two-pass square channel with four smooth walls and in a similar two-pass square channel with two smooth walls and two opposite ribbed walls ( $\alpha = 90^\circ$ ). The top and bottom walls of the test channels were heated uniformly by passing current through thin foils and were instrumented with thermocouples, while the other two walls were unheated. The results showed that the heat transfer coefficients at the turn in the smooth channel and in the rib-roughened channel were about 2 to 3 and 3 to 4 times the fully developed values, respectively. In both cases, the heat transfer decreased in the main flow direction after the turn. Since the test channels for the study were sparsely instrumented with thermocouples, the detailed distributions of the heat transfer coefficient around the sharp  $180^\circ$

turns could not be determined.

Experimental data on the detailed distributions of the heat transfer coefficient around sharp  $180^\circ$  turns in multipass channels are important for two reasons. Firstly, they help design engineers understand the effect of sharp  $180^\circ$  turns on the surface heat transfer in multipass channels. Knowledge of the flow field and heat transfer characteristics in multipass channels facilitates the design of effectively cooled turbine blades which are not susceptible to structural failure due to uneven thermal stresses. Secondly, detailed local heat transfer results provide a data base for researchers and engineers to develop numerical models to predict the flow field and heat transfer characteristics in multipass channels of various geometries.

## 2.2 Objective

The present investigation was aimed at measuring the detailed mass transfer distributions around sharp  $180^\circ$  turns in a smooth channel and in a rib-roughened channel, via the naphthalene sublimation technique. The test section was a two-pass square channel, which resembled turbine blade cooling passages. The top, bottom, outer, and inner walls of the test channel were all naphthalene-coated plates. For ribbed channel tests, metallic ribs (without naphthalene-coated) were placed on the top and bottom walls of the naphthalene-coated test channel such that the corresponding ribs on the two walls were directly opposite each other. The rib height-to-hydraulic-diameter ratios ( $e/D$ ) were 0.063 and 0.094. The rib pitch-to-height ratios ( $P/e$ ) were 10 and 20. The rib angles-of-attack ( $\alpha$ ) were  $90^\circ$ ,  $60^\circ$ , and  $45^\circ$ . In both the smooth channel and the ribbed channel experiments, the highly detailed mass transfer distributions on the top wall (rib-roughened), the outer wall (smooth),

and the inner wall (smooth) were determined between the channel entrance and far downstream of the second straight channel, for three Reynolds numbers of 15,000, 30,000, and 60,000. The mass transfer coefficients before the turn, in the turn, and after the turn on each wall of the test channel were then averaged, compared, and correlated. Fourteen test runs were performed. The test conditions of the runs are given in Table 1. The corresponding pressure drops and the friction factors were also determined.

### 3.0 EXPERIMENTAL APPARATUS AND DATA REDUCTION

#### 3.1 Experimental Apparatus and Instrumentation

The main components of the test apparatus are the test section, a settling chamber, a calibrated orifice flow meter, a control valve, and a centrifugal blower. The entire apparatus, together with the measuring instruments, was located in an air-conditioned laboratory, which was maintained at a constant temperature of  $21^{\circ}\text{C}$  ( $70^{\circ}\text{F}$ ) throughout the tests.

##### Test Section

A schematic diagram of the test section is shown in Figure 2. The test section was a multipass channel with a 2.54-cm (1-in.) square cross-section. The top, the bottom, and the outer walls of the channel were constructed of 0.95-cm (0.375-in.) thick aluminum plates. The inner (divider) wall was constructed of two 0.325-cm (0.125-in.) thick aluminum plates, bonded together back-to-back with double-sided tape. The clearance at the tip of the divider wall was 2.54 cm (1 in.). To simulate actual turbine cooling passages, the ratio of the before-turn (and also after-turn) channel length to the channel width,  $X/D$ , and the ratio of the divider wall thickness to the channel width,  $t/D$ , were kept at 13 and 0.25, respectively.

All of the aluminum plates which made up the walls of the test channel were hollowed out and were filled with naphthalene by casting against a highly polished stainless steel plate. As a result, all of the interior surfaces of the test channel were smooth naphthalene surfaces. For the roughened channel experiments, brass ribs (with no naphthalene) with a 0.159-cm (0.063-in.) or 0.238-cm (0.094-in.) square cross-section were glued periodically on to the top and bottom

naphthalene surfaces of the two straight sections of the test channel. The rib pitch-to-height ratio was 10 or 20. There was no rib in the turn region. The rib height-to-hydraulic-diameter ratios corresponding to the two types of ribs were 0.063 and 0.094. The glue thickness was estimated to be less than 0.0127 mm (0.005 in.).

A relatively large metallic baffle was attached to the inlet of the test section to provide a sudden contraction flow entrance condition. During a test run, air from the naphthalene-free laboratory was drawn through the test section and ducted to the outside of the building.

#### Instrumentation

The most important part of any naphthalene sublimation experiment is the instrumentation used to measure the highly detailed distributions of the local mass transfer on the naphthalene surfaces. In this investigation, a Starrett electronic depth gage with an accuracy of 0.00001 in./0.0001 mm was used to determine the contours of the various naphthalene surfaces before and after a test run. The depth gage consisted of an electronic amplifier and a lever-type gaging head. The naphthalene plate, whose contour was to be measured, was mounted firmly on a coordinate table. The coordinate table facilitated the traversing of the naphthalene plate in two perpendicular directions tangential to the plate surface. The gaging head was affixed to a stand mounted on the stationary base of the coordinate table, and was hung over the naphthalene plate to be measured.

To measure the elevation at a point on the naphthalene surface, the platform of the coordinate table was moved so that the gaging head rested against the naphthalene surface at the measurement point. The deflection of the tip of the gaging head was converted into an

electrical signal (DC voltage) by the amplifier. The signal was recorded with a Texas Instruments Professional Computer which was connected to the amplifier through an A/D converter. The elevation measurement stations for a typical ribbed channel experiment are shown in Figure 3a. The photos of the test section, the traversing table, and the associated instrumentation are shown in Figure 3b.

Five, 36-gage, copper-constantan thermocouples were used along with a digital temperature indicator to measure the temperature of the flowing air and the temperatures at four stations on the naphthalene surfaces during a test run.

#### Procedure

After all of the naphthalene plates were prepared under a fume hood, they were tightly sealed individually in plastic bags to prevent sublimation. They were then left in the laboratory for six to eight hours to attain thermal equilibrium. Before a test run, the surface contours of all the naphthalene plates were measured and recorded. In a ribbed channel test run, ribs were glued on to the appropriate naphthalene surfaces. The test section was then assembled and attached to the rest of the test rig.

To initiate the test run, the blower was switched on to allow air to flow through the test channel at a predetermined rate. During the test run, the air temperature, the temperatures at the four stations on the naphthalene surfaces, the pressure drop across the orifice, the static pressure upstream of the orifice, and the atmospheric pressure were recorded periodically. A typical run lasted about 30 minutes. At the completion of the test run, the contours of the naphthalene surfaces were measured again. From the corresponding before-run and after-run

surface contours, the depth change at each measurement station on the naphthalene surfaces was calculated.

Separate tests were conducted to determine the mass losses from the various naphthalene surfaces due to natural convection while the surface contours were being measured and while the ribs were being glued on to the appropriate naphthalene surfaces. It was found that the total mass loss by natural convection was no more than four percent of the total mass transfer during any test run. The mass losses due to natural convection were referred to the Appendix A. In calculating the local Sherwood numbers, these losses of mass from the various naphthalene surfaces were taken into account accordingly.

### 3.2 Data Reduction

The local mass transfer coefficient at any measurement point was determined from the rate of mass transfer per unit surface area and the local naphthalene vapor density at the measurement point, and the local bulk naphthalene vapor density.

$$h_m = \dot{m}'' / (\rho_w - \rho_b). \quad (1)$$

The rate of mass transfer per unit surface area at the measurement point was evaluated from the density of solid naphthalene, the measured change of elevation at the measurement point, and the duration of the test run.

$$\dot{m}'' = \rho_s \cdot \Delta Z / \Delta t. \quad (2)$$

The local naphthalene vapor density was calculated from the ideal gas law in conjunction with the measured naphthalene surface temperature and with the vapor pressure-temperature relationship for naphthalene developed by Soxin (1958).

$$P_w = P_w / (R_v T_w), \quad (3)$$

$$\log_{10} P_w = A - B/T_w, \quad (4)$$

where  $R_v$ ,  $A$ , and  $B$  were given by Sogin (1958).

The local bulk naphthalene vapor density was evaluated by the equation

$$\rho_b = M/\dot{Q}. \quad (5)$$

The cumulative mass,  $M$ , was the total mass which entered the airstream from the four channel walls between the entrance and the measurement station over the duration of the test.

Based on the definition of the local Sherwood number,

$$Sh = h_m \cdot D/\bar{D} = h_m \cdot D/(v/Sc), \quad (6)$$

where the Schmidt number for naphthalene was 2.5, according to Sogin (1958). The local Sherwood number was normalized by the Sherwood number for fully developed turbulent flow in a smooth square channel.

$$\frac{Sh}{Sh_0} = \frac{h_m D/\bar{D}}{0.023 Re^{0.8} Pr^{0.4} (Sc/Pr)^{0.4}}, \quad (7)$$

where the correlation of Dittus and Boelter and the heat/mass transfer analogy,  $Nu/Sh = (Pr/Sc)^{0.4}$ , were used.

#### Uncertainties in Data Reduction

For a  $0.56^\circ\text{C}$  ( $1^\circ\text{F}$ ) variation in the naphthalene surface temperature, it was found that there was a 6 percent change in the local naphthalene vapor density, according to equations (3) and (4). In the present study, the naphthalene surface temperatures were measured at two

stations in each of the two straight sections of the test channel. The variation of the four temperatures for any test run was never more than  $0.28^{\circ}\text{C}$  ( $0.5^{\circ}\text{F}$ ). Therefore, the uncertainties in the local vapor density calculations were relatively small although the surface temperatures at all the elevation measurement stations were not measured.

It should be noted that the measured naphthalene surface temperatures were about  $0.56^{\circ}\text{C}$  ( $1^{\circ}\text{F}$ ) higher than the inlet air temperature in any test run. If the naphthalene surface temperatures had not been measured and if the naphthalene surface temperatures had been assumed to be the same as the inlet air temperature, the calculated local vapor densities would have been 6 percent too low. As a result, the local Sherwood numbers would have been 6 percent higher than what they were supposed to be.

Since the surface contours were measured at discrete points along one, two, or three lines on the naphthalene surfaces, errors were introduced into the calculations of the bulk vapor densities when they were determined from the cumulative mass transferred into the airstream. Fortunately, the bulk vapor densities were generally much smaller than the local naphthalene vapor densities. The maximum values of the former did not exceed 10 percent of the latter.

The maximum uncertainty in the calculations of  $(\rho_w - \rho_b)$  was estimated to be 6 percent. Other uncertainties in the calculations of the density of solid naphthalene ( $\rho_s$ ), of the contour measurement ( $\Delta Z$ ), and of the duration of the test run ( $\Delta t$ ) were estimated to be 2, 4, and 3 percent, respectively. By using the uncertainty estimation method of Kline and McClintock (1953), it was found that the maximum uncertainty in the calculated local Sherwood numbers was less than 8 percent.

#### 4.0 EXPERIMENTAL RESULTS AND DISCUSSION

The local mass transfer results are presented in this section as the axial distributions of a normalized Sherwood number ratio,  $Sh/Sh_0$ , as given in equation (7). For each set of data, the Sherwood number ratios along the inner line, the center line, and the outer line (Figure 3a) on the top wall are plotted separately from those along the two axial lines (inner line and center line) on the inner and outer walls. Along the axial lines, the  $Sh/Sh_0$  data are not evenly distributed. For the smooth channel test runs, there are more data points around the turn than along the straight sections of the channel. For the ribbed channel runs, there are many data points between adjacent ribs on the top wall to illustrate the axially periodic nature of the  $Sh/Sh_0$  distributions. A list of mass transfer test runs with all the variable parameters is presented in Appendix B.

##### 4.1 Experimental Results for the Smooth Channel

The local Sherwood number ratio results for the smooth channel are shown in Figures 4, 5, and 6 for the three Reynolds numbers studied. In Figure 4, the  $Sh/Sh_0$  data along the entire test channel are shown, while in Figures 5 and 6, only the data in the before-turn region, in the turn region, and in the after-turn region are plotted so that the effect of the turn on the  $Sh/Sh_0$  can be examined closely. In this paper, the before-turn and after-turn regions refer to the sections of the test channel between  $X/D = 9$  and 12, and  $X/D = 14$  and 17 (3D upstream and 3D downstream of the turn), respectively.

Attention is first focused on the  $Sh/Sh_0$  distribution on the top wall in Figure 4. In the entrance section, the Sherwood number ratio decreases monotonically with increasing axial distance until it attains

the value of one at  $X/D \approx 10$ . The  $Sh/Sh_0$  distribution compares well with that for a straight smooth channel of large aspect ratio by Sparrow and Cur (1982).

Entering the turn region, the  $Sh/Sh_0$  increases with a rapid increase along the outer line. The increase is believed to be the result of the secondary flow induced by the turn. The dip in the  $Sh/Sh_0$  distribution along the outer line at  $X/D \approx 12.5$  indicates that there is a low mass transfer zone at the outside corner of the turn region. The outer-line  $Sh/Sh_0$  then increases gradually and reaches a maximum at the end of the turn ( $X/D \approx 14.5$ ). The large  $Sh/Sh_0$  values near the outer wall at the end of the turn are caused by the flow being forced outward by the sharp turn.

The low Sherwood number ratios along the inner line at  $X/D \approx 13.5$  are due to the flow separation at the tip of the inner wall. The downturn of the  $Sh/Sh_0$  distribution along the center line at  $X/D \approx 14$  can also be attributed to the flow separation. The large values of the  $Sh/Sh_0$  at  $X/D \approx 15$  along the inner line are due to the flow reattachment and the flow being pushed back toward the inner wall after the turn. In general, the top-wall  $Sh/Sh_0$  values in the after-turn region are much higher than those in the before-turn region.

Leaving the after-turn region, the top-wall  $Sh/Sh_0$  drops gradually. The flow becomes almost redeveloped near the end of the second straight section of the test channel.

Attention is now turned to the  $Sh/Sh_0$  distributions on the inner wall and on the outer wall. In the before-turn region, the values of  $Sh/Sh_0$  on both the inner and outer walls are about one. In the turn region, the outer-wall  $Sh/Sh_0$  increases gradually around the turn. In

the after-turn region, the  $Sh/Sh_0$  along the outer wall is high at  $X/D \approx 14$ . The flow is being forced toward the outer wall at the end of the turn. Further downstream, the outer-wall  $Sh/Sh_0$  reaches a minimum at  $X/D \approx 15$  and then a peak at  $X/D \approx 16$ , showing that the flow is being pushed away from the outer wall and then back toward the outer wall again.

The effect of the flow separation (at the tip of the inner wall) and reattachment on the flow field can be seen very clearly in the inner-wall  $Sh/Sh_0$  distribution in the after-turn region. The inner-wall  $Sh/Sh_0$  distribution is initially very low at  $X/D \approx 14.5$  and has a high peak at  $X/D \approx 15.5$ .

The inner-wall and outer-wall  $Sh/Sh_0$  values in the after-turn region are generally higher than those in the before-turn region. Downstream of the after-turn region, the  $Sh/Sh_0$  drops gradually as the effect of the turn on the flow diminishes. In the downstream straight section of the test channel, the criss-crossing pattern of the  $Sh/Sh_0$  distribution shows that the flow is being pushed toward the inner wall and the outer wall alternately.

The  $Sh/Sh_0$  distribution for  $Re = 15,000$  presented in Figure 5 exhibits the same general trends as that for  $Re = 30,000$ . Again, in the turn region, low  $Sh/Sh_0$  zones on the top wall are evident at the outside corner at  $X/D \approx 12.5$  (due to flow recirculation) and near the tip of the inner wall at  $X/D \approx 13.0$  (due to flow separation).

In the after-turn region, the  $Sh/Sh_0$  distributions are very high near the flow reattachment zone on the inside of the top wall and on the inner wall at  $X/D \approx 15.5$ . The inner-line  $Sh/Sh_0$  on the outer wall drops to a minimum at  $X/D \approx 15.5$  and reaches a peak at  $X/D \approx 16$ , showing that

the flow may be forced away from the outer wall and the inner wall alternately in the after-turn region, as in the case of  $Re = 30,000$ .

The  $Sh/Sh_0$  distribution for  $Re = 60,000$  (Figure 6) is only slightly different from those for  $Re = 30,000$  and  $15,000$ . Just before entering the turn region ( $X/D \approx 11.5$ ), the inner-wall  $Sh/Sh_0$  increases while the outer-wall  $Sh/Sh_0$  decreases to below one. The flow being forced inward due to the turn is more evident in this case than in the two previous cases.

The recirculation zone at the outside corner of the turn at  $X/D \approx 12.5$  as well as the flow reattachment zone on the inner wall and on the inside of the top wall at  $X/D \approx 15.5$  can be identified very easily. In the turn region, the inner-line  $Sh/Sh_0$  on the top wall remains quite constant. Otherwise, the  $Sh/Sh_0$  distribution for  $Re = 60,000$  is similar to those for the two low Reynolds numbers studied.

## 4.2 Experimental Results for the Rib-Roughened Channel

### 4.2.1 Local Mass Transfer Data

The experimental results for the rib-roughened channel with  $e/D = 0.063$ ,  $F/e = 10$ , and  $\alpha = 90^\circ$  are shown in Figures 7, 8, and 9. Firstly, the  $Sh/Sh_0$  distribution for  $Re = 60,000$  shown in Figure 7 will be examined. In the entrance section of the test channel, the axial  $Sh/Sh_0$  distribution on the top wall decreases with increasing distance, and settles into a periodic pattern with a small spanwise variation, just before entering the sharp turn. In the periodic region, the maximum  $Sh/Sh_0$  value between adjacent ribs is approximately equal to 3. The axial location where the value of  $Sh/Sh_0$  is maximum (due to flow reattachment) is about 2 to 3 times the rib-height downstream of a rib. At  $X/D \approx 11$ , the top-wall  $Sh/Sh_0$  increases with a faster increase along

the outer-line than along the inner-line as the flow begins to turn inward.

In the turn region, the top-wall  $Sh/Sh_0$  is relatively low since there is no rib in the region. In the after-turn region, the top-wall  $Sh/Sh_0$  distribution is generally higher than that in the before-turn region. There is an increase in the  $Sh/Sh_0$  in the spanwise direction toward the outer wall. Further downstream of the turn, the peak between adjacent ribs in the  $Sh/Sh_0$  distribution decreases gradually and the spanwise variation becomes smaller. The  $Sh/Sh_0$  becomes periodic again near the end of the second straight section of the channel.

In the before-turn region, the  $Sh/Sh_0$  distribution on the inner wall is about the same as that on the outer wall with the inner-line  $Sh/Sh_0$  values on each wall slightly higher than the corresponding center-line  $Sh/Sh_0$  values (due to the proximity of the ribs on the top wall to the inner line on each wall). The outer-wall Sherwood number ratios in the turn region are generally higher than those in the before-turn region.

After the turn, the side-wall Sherwood number ratios remain as high as those in the turn region, with the values on the inner-wall slightly higher than those on the outer wall. The initial low values of the inner-wall  $Sh/Sh_0$  at  $X/D \approx 14.5$  are due to the flow separation at the tip of the inner wall. The flow reattaches at  $X/D \approx 15$ , resulting in the peak in the inner-wall  $Sh/Sh_0$  distribution. In the downstream straight section of the channel, the inner-wall and the outer-wall distributions cross several times more. It appears that the flow is being pushed toward the inner wall and the outer wall alternately as a result of the turn.

In Figures 8 and 9, the  $Sh/Sh_0$  distributions are shown for  $Re = 30,000$  and  $15,000$ , respectively. Only the  $Sh/Sh_0$  data in the before-turn, the turn, and the after-turn regions are presented. As in the previous case, the top-wall  $Sh/Sh_0$  distribution is periodic in the before-turn region with an increasing spanwise  $Sh/Sh_0$  variation just before entering the turn region. A close examination of the figures reveals that, for  $Re = 15,000$ , the increase of the spanwise  $Sh/Sh_0$  variation begins earlier than that in the higher Reynolds number case. Comparing Figures 7, 8, and 9, there is a definite increase in the spanwise  $Sh/Sh_0$  variation in the after-turn region as the Reynolds number decreases. For all three Reynolds numbers, the after-turn top-wall Sherwood number ratios near the outer wall are higher than those near the inner wall.

#### Effect of Rib Spacing

The experimental results for a ribbed channel with  $e/D = 0.063$ ,  $P/e = 20$ , and  $\alpha = 90^\circ$  are shown in Figure 10 for  $Re = 30,000$ . The top-wall  $Sh/Sh_0$  distribution has many of the characteristics of that for a ribbed channel case with a smaller rib spacing of  $P/e = 10$ . The effect of increasing the rib spacing ( $P/e$ ) on the  $Sh/Sh_0$  distribution around a sharp  $180^\circ$  turn is the overall lower  $Sh/Sh_0$  values. In the before turn region, the top-wall  $Sh/Sh_0$  distribution is axially periodic with a relatively small spanwise variation. The after-turn, top-wall  $Sh/Sh_0$  distribution is generally higher than that in the before-turn region with the larger values of the  $Sh/Sh_0$  along the outer line. As the peak between adjacent ribs in the after-turn  $Sh/Sh_0$  distribution drops gradually with increasing axial distance, the spanwise variation decreases. The peak in the outer-line, top-wall  $Sh/Sh_0$  distribution for

$P/e = 20$  drops in the streamwise direction slightly faster than that for  $P/e = 10$ .

#### Effect of Rib Height

The effect of the height of the ribs on the heat transfer around a sharp turn is studied by examining Figures 8 and 11, in which the  $Sh/Sh_0$  distributions for  $e/D = 0.063$  and  $0.094$ , respectively, are shown. The top-wall  $Sh/Sh_0$  distribution for  $e/D = 0.094$  is higher than that for  $e/D = 0.063$  around the sharp turn. In both cases, the peaks in the top-wall  $Sh/Sh_0$  distributions in the after-turn region drop with increasing axial distance at about the same rate.

The spanwise variation of the after-turn top-wall  $Sh/Sh_0$  for ribs with a large  $e/D$  is smaller than that for ribs with a small  $e/D$ .

On the inner and outer walls, the  $Sh/Sh_0$  distributions for  $e/D = 0.094$  are again higher than those for  $e/D = 0.063$  around the turn. In the after-turn region, the inner-wall and outer-wall Sherwood number ratios for  $e/D = 0.094$  stay about constant with the inner-wall  $Sh/Sh_0$  values higher than the outer-wall values. There is no crossing of the inner-wall and the outer wall  $Sh/Sh_0$  distributions in the  $e/D = 0.094$  case. It appears that the larger ribs keep the flow from being deflected laterally downstream of the turn.

#### Effect of Rib Angle on Local Sherwood Number Ratio

The distributions of the ribbed-wall Sherwood number ratio along three axial lines for  $\alpha = 90^\circ$  and for  $Re = 30,000$  are shown in Figure 12. The periodic nature of the distributions in the entrance duct is evident. The Sherwood number ratios attain their maximum values at the points of flow reattachment, which occur slightly upstream of the mid points between adjacent ribs. The variations of the Sherwood number

ratio in the spanwise direction are very small compared with the axial variations.

In the turn region, where there is no rib on either the top wall or the bottom wall, the Sherwood number ratios along the outer line are higher than those along the inner line. The trend carries onto the after-turn region, where the ribbed-wall Sherwood number ratios near the outer wall are higher than those near the inner wall. The low ribbed-wall Sherwood number ratios near the inner wall are the results of the flow separation at the tip of the inner wall. The strong lateral pressure gradient due to the sharp turn forces the main flow to impinge onto the outer wall. The flow then gets pushed back toward the inner wall, resulting in the high ribbed-wall  $Sh/Sh_0$  near the outer wall. In general, the values of the Sherwood number ratios after the turn are greater than those before the turn.

Further downstream of the turn, as the effect of the turn on the flow field vanishes gradually, both the peak Sherwood number ratio and the spanwise  $Sh/Sh_0$  variation decrease with increasing axial distance, until the axial  $Sh/Sh_0$  distributions become periodic again.

The axial distributions of the ribbed-wall, inner-wall, and outer-wall Sherwood number ratios for angles-of-attack of  $60^\circ$  and  $45^\circ$  are shown in Figures 13 and 14, respectively. The Reynolds number is 30,000 in both cases. Selected segments of the axial distributions before and after the turn from Figures 13 and 14 are replotted on an enlarged scale in Figures 15a and 15b. These figures facilitate the close examination of the effects of the rib angle and the sharp turn on the local ribbed-wall  $Sh/Sh_0$  in the before-turn and after-turn regions. In Figures 15a and 15b, the axial locations of the measurement stations relative to the

ribs are also illustrated.

For  $\gamma = 60^\circ$ , the magnitude of the variations of the before-turn top-wall  $Sh/Sh_0$  in the spanwise direction is comparable to those of the axial periodic  $Sh/Sh_0$  distributions. The values of the before-turn  $Sh/Sh_0$  along the outer line are always greater than the corresponding values along the inner line. These lateral variations of the ribbed-wall  $Sh/Sh_0$  in the before-turn region are due to the secondary flow along the rib axes toward the inner wall.

In the turn, the values of  $Sh/Sh_0$  are lower than those before the turn with  $Sh/Sh_0$  along the outer line generally higher than those along the center line and the inner line.

After the turn, the peak Sherwood number ratios along the outer line decrease significantly from the before-turn values, meanwhile, the decreases (from the before-turn values) of the peak  $Sh/Sh_0$  along the center line and along the inner line are successively lower than those along the outer line. The spanwise variations of  $Sh/Sh_0$  are relatively small after the turn. This may be caused by the complicated interaction between the main flow, which is forced toward the inner wall due to the turn (as described earlier), and the secondary flow along the rib axes toward the outer wall.

For  $\gamma = 45^\circ$ , the top-wall  $Sh/Sh_0$  distributions before the turn are similar to those for  $\gamma = 60^\circ$ . Again, the Sherwood number ratios along the outer line are higher than those along the center line, which, in turn, are higher than those along the inner line. The Sherwood number ratio is relatively uniform in the turn. The after-turn values of  $Sh/Sh_0$  are about the same as those in the before-turn region.

Attention will now be turned to the top of Figures 13 and 14, where

the axial inner-wall and the outer-wall Sherwood number distributions are given. For  $\alpha = 60^\circ$ , the spanwise variations of the before-turn  $Sh/Sh_0$  on the inner (divider) wall are much larger than those on the outer wall. The before-turn Sherwood number ratios along the inner line on the inner wall are much greater than those along the center line on the inner wall, while on the outer wall, the center-line  $Sh/Sh_0$  were only slightly higher than the inner-line  $Sh/Sh_0$ . The secondary flow created by the oblique ribs impinges onto the inner wall, resulting in the high  $Sh/Sh_0$  on the inner wall near the ribbed walls. For  $\alpha = 45^\circ$ , the before-turn  $Sh/Sh_0$  exhibit the same trends except that the spanwise  $Sh/Sh_0$  variations on the inner wall are not as large as those for  $\alpha = 60^\circ$ .

After the turn, the inner-wall  $Sh/Sh_0$  for both  $\alpha = 60^\circ$  and  $\alpha = 45^\circ$  are large compared to the corresponding outer-wall  $Sh/Sh_0$ . The high  $Sh/Sh_0$  on the inner wall is believed to be caused by flow reattachment along with the main flow, which is being forced toward the inner wall due to the turn. On the outer wall, the after-turn  $Sh/Sh_0$  along the inner line are higher than those along the center line for  $\alpha = 60^\circ$ . However, the reverse is true in the case of  $\alpha = 45^\circ$ .

#### Effect of Reynolds Number

The effect of the Reynolds number on the local Sherwood number will now be examined. Experimental data for  $\alpha = 60^\circ$  and  $45^\circ$  and for  $Re = 15,000$  and  $60,000$  are presented in Figures 16 through 19.

Attention is focused first on Figures 16 and 17, along with Figure 13. The top-wall Sherwood number ratios in all three cases are very similar. The spanwise top-wall  $Sh/Sh_0$  variations decrease with increasing Reynolds number. Before the turn, there are much larger

spanwise  $Sh/Sh_0$  variations on the inner wall than on the outer wall for all Reynolds numbers. However, the differences are less evident in the case of  $Re = 15,000$ . After the turn, the inner-wall Sherwood number ratios are always higher than the corresponding outer-wall values and the differences are smaller at higher Reynolds numbers.

Comparing Figures 18 and 19 with Figure 14, it can be seen that the spanwise variations of the before-turn, top-wall  $Sh/Sh_0$  are again very large at low Reynolds numbers. The differences between the before-turn  $Sh/Sh_0$  variations on the inner wall and those on the outer wall are most pronounced at  $Re = 15,000$ .

In general, the flow Reynolds number has only a modest effect on the local Sherwood number ratio.

#### 4.2.2 Average Mass Transfer Data and Correlations

##### Results for Smooth Channel and for Transverse Ribs ( $\alpha = 90^\circ$ )

The local Sherwood number ratios were averaged over various segments of the interior channel surfaces in the before-turn region, in the turn region, and in the after-turn region. The averaging of the local Sherwood number ratios was area-weighted. A typical set of  $\bar{Sh}/Sh_0$  results for  $Re = 30,000$  and  $\alpha = 90^\circ$  is given in Figure 20. In the figure, the top-wall, the outer-wall, and the inner-wall average Sherwood number ratios for the smooth and roughened channel cases studied are shown in three separate charts.

Figure 20 shows that the present  $Sh/Sh_0$  data for the smooth channel are always lower than those for the rib-roughened channel. For instance, the top-wall  $Sh/Sh_0$  values for the smooth channel in the before-turn region, in the turn region, and in the after-turn region are 1.1, 1.7, and 2.05, respectively. The corresponding  $Sh/Sh_0$  values for a

typical roughened channel with  $P/e = 10$ ,  $e/D = 0.063$ , and  $\alpha = 90^\circ$  are 2.6, 2.55, and 3.5. Increasing the rib height results in a higher  $\bar{Sh}/Sh_0$  around the turn due to the higher turbulence level in the flow for the larger rib case. However, increasing the rib pitch lowers the  $\bar{Sh}/Sh_0$  around the turn because of the longer boundary layer between adjacent ribs downstream of the reattachment zone.

The after-turn  $\bar{Sh}/Sh_0$  values are always higher than the corresponding before-turn values as a result of the sharp turn. For the smooth channel, the top-wall  $\bar{Sh}/Sh_0$  in the turn region is more than fifty percent higher than that in the before-turn region. However, for the roughened channel cases, the top-wall  $\bar{Sh}/Sh_0$  values in the turn region are slightly lower than the respective before-turn  $\bar{Sh}/Sh_0$  values because there is no rib on the top-wall in the turn region.

In all of the cases studied, the values of the outer-wall  $\bar{Sh}/Sh_0$  in the turn region are only slightly different from the corresponding after-turn values.

The  $\bar{Sh}/Sh_0$  data for both the smooth and roughened channels were found to be correlated well by the following equation:

$$\bar{Sh}/Sh_0 = a Re^b [(e/D)/0.063]^m \cdot [(P/e)/10]^n, \quad (8)$$

with the numerical values of  $a$ ,  $b$ ,  $m$ , and  $n$  listed in Table 2. Equation (8) correlates all of the  $\bar{Sh}/Sh_0$  data of the present investigation to within  $\pm 6$  percent. Readers should be cautioned that equation (8) applies only to a smooth channel or a ribbed channel with a rib angle-of-attack of  $90^\circ$ . Correlations for other angle-of-attack cases can be found in equation (9). In Figures 21a and 21b, the present top-wall  $\bar{Sh}/Sh_0$  data in the before-turn and the after-turn regions for both the

smooth and roughened channels are plotted against the flow Reynolds number along with the correlation of equation (8).

#### Results for Angled Ribs ( $\alpha = 90^\circ$ , $60^\circ$ , and $45^\circ$ )

For all the cases studied, the local Sherwood number ratios for individual segments of the channel walls before the turn, in the turn, and after the turn were averaged. Typical average Sherwood number ratios, those for  $Pe = 10,000$ , are shown in Figures 22a and 22b. In Figure 22a, the average Sherwood number ratios ( $Sh/Sh_0$ ) are plotted as functions of the rib angle. Before the turn, the top-wall  $Sh/Sh_0$  are much greater than the outer-wall  $Sh/Sh_0$  and the inner-wall  $Sh/Sh_0$  for all three angles-of-attack of  $90^\circ$ ,  $60^\circ$ , and  $45^\circ$ . The top-wall  $Sh/Sh_0$ , the outer-wall  $Sh/Sh_0$ , and the inner-wall  $Sh/Sh_0$  for  $\alpha = 60^\circ$  are all higher than their counterparts for  $\alpha = 90^\circ$  and  $\alpha = 45^\circ$ .

After the turn, the inner-wall  $Sh/Sh_0$  are higher than the outer-wall  $Sh/Sh_0$  for all three rib angles. Also, the top-wall  $Sh/Sh_0$  for  $\alpha = 60^\circ$  decreases significantly after the turn from its before-turn value while those for  $\alpha = 90^\circ$  and  $45^\circ$  increase after the turn from their corresponding before-turn values. These trends are also evident in Figure 22b, where the  $Sh/Sh_0$  results are replotted to show the effect of the sharp  $180^\circ$  turn on the average Sherwood number ratios for the three rib angles-of-attack studied.

The average Sherwood number ratios for the various segments of the channel walls were found to be correlated well with the Reynolds number and the rib angle by the following equation

$$Sh_{avg} = C_1 Re^{C_2} \tan^{C_3} \alpha, \quad (9)$$

where  $C_1$ ,  $C_2$ , and  $C_3$  are constant coefficients. The numerical values of

these coefficients are listed in Table 3. Equation (9) with coefficients from Table 3 correlate the experimental data of the present study to within  $\pm 6$  percent. It should be noted that equation (9) applies to  $e/D = 0.063$  and  $P/e = 10$  only. Correlations for the cases of other  $e/D$  and  $P/e$  ratios can be found in equation (8).

Figure 23a shows  $(\bar{Sh}/Sh_0)(90^\circ/\alpha)^C$  as a function of the flow Reynolds number. The experimental data points shown in the figure are the top-wall  $\bar{Sh}/Sh_0$  obtained in the present study. The figure shows that the present experimental before-turn and after-turn results are well represented by the equations.

The Sherwood number ratios for all of the surfaces in and around the  $180^\circ$  turn were averaged. The overall average Sherwood number ratios  $(\bar{\bar{Sh}}/Sh_0)$  for the three rib angles studied are plotted versus the flow Reynolds number in Figure 23b. The overall Sherwood number ratio is independent of the rib angle but decreases slightly with increasing Reynolds number. It was found that the following equation

$$\bar{\bar{Sh}}/Sh_0 = 7.0 Re^{-0.1} \quad (10)$$

correlates the data to within  $\pm 4$  percent.

#### 4.2.3 Comparison with Heat Transfer Data

##### Results for Smooth Channel and for Transverse Ribs ( $\alpha = 90^\circ$ )

The results of the present study will now be compared with published heat transfer data for smooth and roughened channels with  $\alpha = 90^\circ$ . The present smooth channel data are presented in Figure 24a along with the heat transfer data for a smooth two-pass channel of an aspect ratio of 0.4 reported by Metzger and Sahm (1985). In Figure 24a, the present overall Sherwood number ratio in the before-turn, the turn, or

the after-turn region,  $\bar{Sh}/Sh_0$ , is the area-weighted average of the  $Sh/Sh_0$  values on the top and side walls in the respective region. The heat transfer data are based on the Nusselt number-Reynolds number correlations in regions 2, 3, and 4 given by Metzger and Sahm (1985). The Nusselt numbers are converted to the corresponding Sherwood numbers by  $Sh = (Sc/Pr)^{0.4} Nu$ .

Both the present mass transfer data and the published heat transfer data show that, for all three Reynolds numbers, the average Sherwood number ratios in the after-turn region and in the turn region are successively higher than those in the before-turn region. In addition, both the present data and those of Metzger and Sahm (1985) decrease slightly with increasing Reynolds number.

For the typical case of  $Re = 30,000$ , the present mass transfer data in the before-turn region and in the turn region are about 4 and 12 percent higher than the corresponding heat transfer data, while the present  $\bar{Sh}/Sh_0$  in the after turn region is about 9 percent lower. Considering the differences in the channel aspect ratios and in the channel surfaces over which the data are averaged in the two studies, the agreement between the present data and those by Metzger and Sahm (1985) is very good.

In Figure 24b, the present ribbed channel data are compared with the heat transfer data by Han et al. (1985, 1986). The heat transfer data are for the fully developed flow of air in a uniformly heated, straight, square channel with two opposite ribbed walls, and with the same values of  $e/D$ ,  $P/e$ , and  $Re$  as those of the present study. The fully developed Nusselt numbers of the ribbed walls are converted to their corresponding Sherwood numbers. They are then plotted along with

the before-turn, top-wall  $\overline{Sh}/Sh_0$  data of the present study for the three Reynolds numbers of 15,000, 30,000, and 60,000. Figure 24b shows that the present mass transfer data are slightly higher (by up to 10 percent) than the heat transfer data. This may be due to the effect of the turn on the top-wall  $\overline{Sh}/Sh_0$  at the end of the before-turn region.

#### Results for Angled Ribs ( $\alpha = 90^\circ, 60^\circ, \text{ and } 45^\circ$ )

In Figure 25, the averages of the before-turn ribbed-wall Sherwood numbers for all the cases studied were compared with the fully developed average heat transfer data reported by Han et al. (1985, 1986). The average heat transfer data are those for the fully developed flow of air in a uniformly heated, straight, square channel with two opposite ribbed walls, and with the same values of  $e/D$ ,  $P/e$ ,  $\alpha$ , and  $Re$  as those of the present study. The Nusselt numbers from the heat transfer studies were converted to their corresponding Sherwood numbers.

It can be seen from Figure 25 that the present mass transfer results compared very well with the published heat transfer data in most cases. The deviations between the heat transfer and mass transfer data are less than 10 percent, except for the case of  $\alpha = 45^\circ$  and  $Re = 60,000$ , the deviation of which is 14 percent. The good agreement between the heat and mass transfer data reaffirms that the naphthalene sublimation technique is a reliable tool for the determination of highly localized distributions of the heat transfer coefficient in complicated channel flows, such as those encountered in the present study. The published heat transfer data in NASA CR-4015 (Han 1986) shows an incorrect rib orientation for the square duct. A published errata gives the correct orientation.

## 5.0 PRESSURE DROP MEASUREMENT

### 5.1 Test Section and Data Analysis

A schematic diagram of the test section for pressure drop/friction factor experiments is shown in Figure 26. The flow geometry of this apparatus models situations that exist in actual turbine engine airfoils. The internal geometry of the test section and the construction were very similar to that of the mass transfer test section described earlier. The only difference was of the material used for construction. In this case, Plexiglas was used instead of aluminum.

To measure the pressure drop, twenty (20) pressure taps (1/32-in) in all were drilled in the channel walls at locations shown in Figure 26. Fifteen (15) out of twenty (20) pressure taps were along the outer wall of the test channel with eight (8) taps before the turn and seven (7) taps after the turn region. The remaining five (5) taps were provided on the top wall with two (2) taps each before and after the turn and one (1) in the turn region. The pressure taps number 3, 7, 11, and 15 were thoughtfully used to take into account the difference in pressure drop data at the top wall and the side wall (if any). For the calculations of the pressure drop and friction factor, the average values were considered at these four cross-sectional locations.

For the rough channel tests, the brass ribs were placed and glued onto the top and the bottom walls in the pre-determined fashion as was done in the case of mass transfer test runs.

The pressure drop across the channel section was measured by an inclined or a U-tube manometer. During the experiments, it was noted that the magnitude of the pressure drop was almost the same on the smooth side and the ribbed side walls. Therefore, the pressure drop data

the friction factor calculated were on the basis of the average values. The average friction factor of the present investigation was based on the adiabatic conditions (non-heating test runs).

The Blasius equation,

$$\bar{f}(\text{FD}) = 0.079 \text{ Re}^{-0.25} \quad (11)$$

was used to provide reference values of the friction factor to compare the smooth channel fully-developed results in the two straight sections of the present test channel.

The following equation was used to calculate the friction factors in the fully-developed before and after turn regions of the channel,  $f_{bt}$  and  $f_{at}$ .

$$\bar{f} = \frac{\Delta P}{4(L/D) (G^2/2 g_c)} \quad (12)$$

where,

$L$  = length of the test channel corresponding to the pressure drop,  $\Delta P$ ,  
 $L$  = 6.25 inches for before-turn fully-developed region [Tap 3 to 7], and  
 $L$  = 5.00 inches for after-turn fully-developed region [Tap 14 to 16].

The loss factor due to sudden contraction at the entrance,  $K_c$ , and the loss factor for the turn region,  $K_t$ , was calculated by using the following relation;

$$K_c \text{ (or } K_t) = \frac{\Delta P}{v^2/2g_c} \quad (13)$$

The pressure drop for the entrance loss factor,  $K_c$ , was calculated for 35/16 inches of channel entrance length (Tap 3) and for

the turn loss factor,  $K_t$ , corresponded to 7 inches of channel length (Tap 7 to 14).

For a better comparison, the pressure drop values were non-dimensionalised by the dynamic pressure ( $1/2 \rho V^2$ ) and the plots were drawn between the non-dimensional pressure drop and distance,  $X/D$ .

## 5.2 Results and Discussion

### Pressure Distribution

The non-dimensional pressure drop  $[(P - P_{atm}) / (1/2 \rho V^2)]$  results are plotted against non-dimensional axial distance  $[X/D]$ . Each channel geometry investigated was tested at six flow rates, covering Reynolds numbers from 10,000 to 60,000. A list of pressure drop test runs with all the variable parameters is presented in Appendix C. Figures 27-32 show the plots with different channel/rib geometries in the same order as the list given in Appendix C.

Pressure distributions in all the cases show almost the same trend, that is, the non-dimensional pressure drop increasing with decreasing Reynolds number. The pressure drops (Tap 1,  $X/D = 0.31$ ) sharply at the sudden contraction entrance of the channel to almost the same value in all the cases. The effect of Reynolds number is also very minimal. The pressure then rises by the next tap location ( $X/D = 2.19$ , Tap 2) and then drops in a linear fashion till tap 7 ( $X/D = 10.94$ ). The results show that from  $X/D = 4.69$  (Tap 3) to  $X/D = 10.94$  (Tap 7) can be treated as the fully-developed flow region before the turn. The pressure then rises slightly in the vicinity of the upstream corner of the turn ( $X/D = 11.56$ , Tap 8). A rapid drop in pressure has been seen in the turn region ( $X/D = 11.56$ , Tap 8 to  $X/D = 14.44$ , Tap 10), and just after the turn in the downstream section of the channel ( $X/D = 15.06$ , Tap 11).

The pressure then increases again slightly (except for cases with higher size rib,  $e/D = 0.094$ ), as shown in Figure (32). A linear pressure drop towards the fully-developed region of the downstream section (between  $X/D = 18.8$ , Tap 14 and  $X/D = 23.8$ , Tap 16) is clearly visible.

Examination of the individual pressure distributions for each test reveals that their trends are highly independent of the Reynolds number and the normalized distributions are virtually identical over the entire range of Reynolds number for a given channel geometry.

Figures 33-35 represent the effect of the rib geometry on non-dimensional pressure drop distribution for  $Re = 10,000$ ,  $Re = 30,000$ , and  $Re = 60,000$ , respectively. Again, the results are almost independent of the Reynolds number. But on looking at these plots individually, it is very clear that the pressure drop in the case of the smooth channel is lowest, maximum pressure drop is attained in the case of the channel with higher rib size ( $e/D = 0.094$ ). In order, the results with higher pitch ( $P/e = 20$ ), angle-of-attack ( $\alpha = 45^\circ$ ), and angle-of-attack ( $\alpha = 60^\circ$ ) show an increase in pressure drop, but remain in between the smooth channel and with  $e/D = 0.094$  cases.

#### Friction Factor and Loss Coefficients

On the basis of the normalized pressure distribution results and to cover the entire test channel under present investigation, the channel was divided into four regions, namely, the entrance region ( $X/D = 0$  to  $4.69$ , Tap 3), the fully-developed before-turn region ( $X/D = 4.69$ , Tap 3 to  $10.94$ , Tap 7), the turn region ( $X/D = 10.94$ , Tap 7 to  $18.8$ , Tap 14), and the fully-developed after-turn region ( $X/D = 18.8$ , Tap 14 to  $23.8$ , Tap 16).

The plots for average fully-developed friction factors,  $f_{bt}$  and  $f_{at}$

vs Reynolds number for the different rib and channel geometries are shown in Figures 36 and 37. The loss coefficients,  $K_C$  and  $K_t$ , for the entrance and the turn regions respectively, are plotted against Reynolds number in Figures 38 and 39.

In Figure 36 for  $\bar{f}_{bt}$ , the friction factor for the smooth channel case differs by 6% from the Blasius equation (11). For  $\alpha = 90^\circ$  and  $\alpha = 60^\circ$ , the friction factor approaches an approximately constant value as the Reynolds number increases, while the friction factor is maximum with higher size rib and minimum with higher rib spacing. The friction factor with  $\alpha = 60^\circ$  is about 45% higher than that with  $\alpha = 90^\circ$ . Also the friction factor with  $\alpha = 45^\circ$  is less than that with  $\alpha = 90^\circ$ , but not by much.

The trend of Figure 37 for  $\bar{f}_{at}$  looks the same as that of  $\bar{f}_{bt}$  in Figure 36, except that the variation is not very smooth and also the values with  $\alpha = 45^\circ$  are lower than that with  $P/e = 20$  at some locations. For the smooth channel case, the friction factor is approximately 100% higher than the values calculated by equation (11). It is interesting to note that the average friction factor for the fully-developed after-turn region is higher than the corresponding fully-developed before-turn region, except in cases with  $\alpha = 60^\circ$  and  $\alpha = 45^\circ$ , in which  $\bar{f}_{at}$  is lower than their respective values of  $\bar{f}_{bt}$ .

The loss coefficient in the entrance section of the channel,  $K_C$ , decreases with increasing Reynolds number, as shown in Figure 38. Figure 39 shows the loss coefficient,  $K_t$ , against Reynolds number for the turn region. It decreases with increasing Reynolds number. The effect of rib geometry on these two loss coefficients are identical as far as the trend and the overall range is concerned. It is noted that,

for  $\alpha = 90^\circ$  and  $P/e = 10$ ,  $K_c$  is lower than with same  $P/e$  but with  $\alpha = 60^\circ$  and  $\alpha = 45^\circ$ . However,  $K_t$  for  $\alpha = 90^\circ$  is higher than that for  $\alpha = 60^\circ$  and  $45^\circ$  for the same  $P/e = 10$ . Both loss coefficients remain maximum with higher rib size in all cases.

For all the cases investigated, the values of all the four friction factors are tabulated in Table 4.

### Correlations

The two fully-developed friction factors,  $\bar{f}_{bt}$  and  $\bar{f}_{at}$ , and the two loss coefficients,  $K_c$  and  $K_t$  were correlated by one single equation of the following form:

$$\bar{f} \text{ (or } K) = a (Re)^b ((P/e)/10)^c ((e/D)/0.063)^m (\alpha/90^\circ)^n \quad (14)$$

where the coefficients,  $a$ ,  $b$ ,  $c$ ,  $m$ , and  $n$ , are given in Table 5. The deviations in equation (14) from the test data are  $\pm 7\%$ ,  $\pm 10\%$  (8% for 95% data points),  $\pm 5.5\%$ , and  $\pm 6.6\%$ , respectively, for  $f_{bt}$ ,  $f_{at}$ ,  $K_c$  and  $K_t$ .

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

The detailed mass transfer distributions around the sharp  $180^\circ$  turns in a smooth channel and in a rib-roughened channel have been studied. The following conclusions can be drawn:

### A. Smooth Channel and Transverse Ribs:

1. For the smooth channel, the heat/mass transfer around the turn is influenced by the flow separation at the tip of the divider (inner) wall and the secondary flow induced by the centrifugal force at the turn. The heat/mass transfer after the turn is higher than that before the turn. The heat/mass transfer in the turn is also high compared with that before the turn except at the first outside corner of the turn.
2. For the rib-roughened channel, the heat/mass transfer around the turn is influenced not only by the flow separation and the secondary flow at the turn, but also by the presence of repeated ribs on the top and bottom walls. The heat/mass transfer coefficients on the smooth side walls and on the rib-roughened top and bottom walls around the turn are larger than the corresponding coefficients for the smooth channel. The axially periodic distribution of the top-wall heat/mass transfer coefficient after the turn is higher than that before the turn with a more noticeable spanwise variation. The inner-wall and outer-wall heat/mass transfer coefficients after the turn are higher than the respective before-turn coefficients.
3. For the range of Reynolds number studied, the average Sherwood number ratios around the sharp turns in the smooth and rib-roughened channels decrease slightly with increasing Reynolds

number. For the ribbed channel, the spanwise variation of the top-wall Sherwood number ratio in the after-turn region increases with decreasing Reynolds number.

4. The heat/mass transfer around the turn in the ribbed channel decreases with increasing rib spacing and increases with increasing rib height.
5. The average Sherwood number ratios for individual wall segments around the turns in the smooth and ribbed channels can be correlated by equation (8) to within  $\pm 6$  percent.
6. The published heat transfer results for straight rib-roughened channels can be applied to the design of the straight section before the first sharp turn in a multipass ribbed cooling passage in a turbine blade.

B. Angled Ribs:

1. Before the turn, the axial distributions of the ribbed-wall Sherwood number are periodic for all three rib angles-of-attack studied. The local ribbed-wall Sherwood numbers for  $\alpha = 60^\circ$  and  $45^\circ$  near the outer wall are higher than those near the inner wall due to the secondary flow along the rib axes. The spanwise Sherwood number variations decrease as the Reynolds number increases. The spanwise variations of the local ribbed-wall Sherwood number for  $\alpha = 90^\circ$  are very small.
2. After the turn, the ribbed-wall Sherwood numbers near the outer wall are higher than those near the inner wall for all three rib angles studied. For  $\alpha = 60^\circ$  and  $45^\circ$ , the spanwise variations of the ribbed-wall Sherwood numbers after the turn are smaller than those before the turn.

3. Before the turn, the average ribbed-wall Sherwood number for  $\alpha = 60^\circ$  is higher than that for  $\alpha = 45^\circ$ , which, in turn, is higher than that for  $\alpha = 90^\circ$ . However, after the turn, the average ribbed-wall Sherwood number for  $\alpha = 90^\circ$  is higher than those for  $\alpha = 45^\circ$  and  $60^\circ$ .
4. For any rib angle-of-attack, the average inner-wall Sherwood number after the turn is always higher than both the average inner-wall Sherwood number before the turn and the average outer-wall Sherwood number after the turn.
5. The average Sherwood number ratios for individual channel surfaces can be correlated with equations in the form of  $Sh/Sh_0 = a Re^b (\alpha/90^\circ)^c$ .
6. The overall average Sherwood number ratio in the region around the sharp turn is independent of the rib angle, but decreases slightly as the Reynolds number increases.
7. The two fully-developed friction factors ( $\bar{f}_{bt}$  and  $\bar{f}_{at}$ ), and the two loss coefficients ( $K_C$  and  $K_t$ ) can be correlated by equation (14).

C. Recommendations:

1. Use naphthalene-coated ribs, instead of using metallic ribs, to study the local heat/mass transfer coefficients in a two-pass rib-roughened channel.
2. Study the effect of the channel aspect ratio on the local heat/mass transfer coefficients in two-pass ribbed channels.
3. Study the three-pass ribbed channels.

## 7.0 REFERENCES

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TABLE 1. LIST OF FRONT-DRAWN TRANSFER TEST RUNS

| STATION | $L/D$  | $P/\rho U^2$ | $e/D$ | $\alpha$ |
|---------|--------|--------------|-------|----------|
| SMOOTH  | 15,000 | —            | —     | —        |
|         | 30,000 | —            | —     | —        |
|         | 60,000 | —            | —     | —        |
| ROUGH   | 15,000 | 10           | 0.063 | 90°      |
|         | 30,000 | 10           | 0.063 | 90°      |
|         | 60,000 | 10           | 0.063 | 90°      |
| ROUGH   | 15,000 | 10           | 0.063 | 60°      |
|         | 30,000 | 10           | 0.063 | 60°      |
|         | 60,000 | 10           | 0.063 | 60°      |
| ROUGH   | 15,000 | 10           | 0.063 | 45°      |
|         | 30,000 | 10           | 0.063 | 45°      |
|         | 60,000 | 10           | 0.063 | 45°      |
| ROUGH   | 15,000 | 20           | 0.063 | 90°      |
| ROUGH   | 15,000 | 10           | 0.034 | 90°      |

NOTE:  $L$  = LENGTH OF TUBES.

SMOOTH = SMOOTH SURFACE,  $e/D = 0$ ,  $\alpha = 0^\circ$ .

ROUGH = SURFACE WITH 100- $\mu$ m (0.004-in.) SAND GRAIN COATING.

$P/\rho U^2$  = PRESSURE LOSS COEFFICIENT.

Table 2. Numerical Values of the Coefficients a, b, m, and n  
in Equation (8)

| Region                         | Surface    | a    | b     | m    | n     |
|--------------------------------|------------|------|-------|------|-------|
| before turn,<br>smooth channel | top wall   | 2.02 | -0.06 | 0    | 0     |
|                                | outer wall | 2.10 | -0.06 | 0    | 0     |
|                                | inner wall | 2.08 | -0.06 | 0    | 0     |
| in turn,<br>smooth channel     | top wall   | 3.21 | -0.06 | 0    | 0     |
|                                | outer wall | 3.23 | -0.06 | 0    | 0     |
| after turn,<br>smooth channel  | top wall   | 3.84 | -0.06 | 0    | 0     |
|                                | outer wall | 3.45 | -0.06 | 0    | 0     |
|                                | inner wall | 4.07 | -0.06 | 0    | 0     |
| before turn,<br>ribbed channel | top wall   | 7.2  | -0.1  | 0.22 | -0.3  |
|                                | outer wall | 4.6  | -0.1  | 0.69 | -0.11 |
|                                | inner wall | 4.6  | -0.1  | 0.53 | -0.15 |
| in turn,<br>ribbed channel     | top wall   | 6.7  | -0.1  | 0.23 | -0.31 |
|                                | outer wall | 7.0  | -0.1  | 0.31 | -0.52 |
| after turn,<br>ribbed channel  | top wall   | 9.3  | -0.1  | 0.13 | -0.49 |
|                                | outer wall | 6.7  | -0.1  | 0.4  | -0.30 |
|                                | inner wall | 7.3  | -0.1  | 0.68 | -0.14 |

TABLE 3. Coefficients a, b, and c in equation (9)

| Region      | Surface    | a   | b    | c if<br>$\alpha \geq 60^\circ$ | c if<br>$\alpha < 60^\circ$ |
|-------------|------------|-----|------|--------------------------------|-----------------------------|
| before turn | top wall   | 7.2 | -0.1 | -0.58                          | -0.059                      |
|             | outer wall | 4.6 | -0.1 | -0.74                          | -0.26                       |
|             | inner wall | 4.8 | -0.1 | -0.63                          | -0.3                        |
| in turn     | top wall   | 6.7 | -0.1 | 0.24                           | 0.02                        |
|             | outer wall | 7.0 | -0.1 | 0.11                           | 0.18                        |
| after turn  | top wall   | 9.3 | -0.1 | 0.4                            | 0.15                        |
|             | outer wall | 6.7 | -0.1 | 0                              | 0.066                       |
|             | inner wall | 7.3 | -0.1 | -0.099                         | -0.077                      |

Table 4 FRICTION AND LOSS FACTORS

| CHANNEL                                           | Re     | $f_{bt}$ | $f_{at}$ | $K_c$  | $K_t$  |
|---------------------------------------------------|--------|----------|----------|--------|--------|
| SMOOTH                                            | 10,000 | 0.0075   | 0.0162   | 1.3200 | 1.6703 |
|                                                   | 20,000 | 0.0064   | 0.0128   | 1.2061 | 1.6631 |
|                                                   | 30,000 | 0.0057   | 0.0117   | 1.1387 | 1.5994 |
|                                                   | 40,000 | 0.0054   | 0.0101   | 1.0934 | 1.5980 |
|                                                   | 50,000 | 0.0051   | 0.0097   | 1.0905 | 1.5841 |
|                                                   | 60,000 | 0.0049   | 0.0097   | 1.0992 | 1.4452 |
| ROUGH<br>P/e=10<br>e/D=0.063<br>$\alpha=90^\circ$ | 10,000 | 0.0319   | 0.0377   | 1.7996 | 2.5754 |
|                                                   | 20,000 | 0.0311   | 0.0352   | 1.7847 | 2.5487 |
|                                                   | 30,000 | 0.0301   | 0.0329   | 1.7042 | 2.4560 |
|                                                   | 40,000 | 0.0303   | 0.0320   | 1.6990 | 2.4223 |
|                                                   | 50,000 | 0.0300   | 0.0323   | 1.6810 | 2.3103 |
|                                                   | 60,000 | 0.0297   | 0.0344   | 1.5725 | 2.2674 |
| ROUGH<br>P/e=10<br>e/D=0.063<br>$\alpha=60^\circ$ | 10,000 | 0.0431   | 0.0431   | 2.1821 | 1.9666 |
|                                                   | 20,000 | 0.0441   | 0.0433   | 2.1498 | 1.8591 |
|                                                   | 30,000 | 0.0436   | 0.0419   | 2.0726 | 1.8090 |
|                                                   | 40,000 | 0.0445   | 0.0404   | 1.9513 | 1.7797 |
|                                                   | 50,000 | 0.0440   | 0.0388   | 1.9181 | 1.6810 |
|                                                   | 60,000 | 0.0440   | 0.0389   | 1.8540 | 1.6380 |
| ROUGH<br>P/e=10<br>e/D=0.063<br>$\alpha=45^\circ$ | 10,000 | 0.0302   | 0.0269   | 1.9935 | 2.1013 |
|                                                   | 20,000 | 0.0309   | 0.0270   | 1.9511 | 2.0078 |
|                                                   | 30,000 | 0.0298   | 0.0252   | 1.8719 | 1.9947 |
|                                                   | 40,000 | 0.0279   | 0.0269   | 1.8739 | 1.9378 |
|                                                   | 50,000 | 0.0268   | 0.0226   | 1.7672 | 1.8266 |
|                                                   | 60,000 | 0.0258   | 0.0232   | 1.6923 | 1.7971 |
| ROUGH<br>P/e=20<br>e/D=0.063<br>$\alpha=90^\circ$ | 10,000 | 0.0259   | 0.0307   | 1.7241 | 2.2414 |
|                                                   | 20,000 | 0.0243   | 0.0270   | 1.7442 | 2.2174 |
|                                                   | 30,000 | 0.0242   | 0.0240   | 1.6114 | 2.1565 |
|                                                   | 40,000 | 0.0256   | 0.0269   | 1.5812 | 2.0522 |
|                                                   | 50,000 | 0.0249   | 0.0269   | 1.5970 | 1.9397 |
|                                                   | 60,000 | 0.0219   | 0.0285   | 1.4976 | 1.9394 |
| ROUGH<br>P/e=10<br>e/D=0.094<br>$\alpha=90^\circ$ | 10,000 | 0.0513   | 0.0539   | 2.3437 | 3.0011 |
|                                                   | 20,000 | 0.0487   | 0.0500   | 2.2715 | 3.0557 |
|                                                   | 30,000 | 0.0479   | 0.0509   | 2.2164 | 2.9352 |
|                                                   | 40,000 | 0.0487   | 0.0505   | 2.1700 | 2.8697 |
|                                                   | 50,000 | 0.0483   | 0.0517   | 2.0690 | 2.7586 |
|                                                   | 60,000 | 0.0473   | 0.0509   | 1.9768 | 2.6507 |

Re = REYNOLDS NUMBER, P/e = PITCH TO FIR HEIGHT RATIO, e/D = FIR HEIGHT TO HYDRAULIC DIAMETER RATIO,  $\alpha$  = FIR ANGLE OF ATTACK

$f_{bt}$  = AVERAGE FRICTION FACTOR BEFORE TURN

$f_{at}$  = AVERAGE FRICTION FACTOR AFTER TURN

$K_c$  = LOSS FACTOR OF CONTRACTION AT THE ENTRY AND

$K_t$  = LOSS FACTOR IN THE TURN

Table 5. coefficients a, b, c, m, and n in equation (14)

| REGION/FACTOR | a      | b     | c     | m     | n<br>if             | n<br>if             |
|---------------|--------|-------|-------|-------|---------------------|---------------------|
|               |        |       |       |       | $\alpha = 60^\circ$ | $\alpha = 60^\circ$ |
| $f_{bt}$      | 0.0432 | 0.034 | 0.342 | 1.173 | 0.865               | 0.105               |
| $f_{at}$      | 0.0476 | 0.032 | 0.37  | 0.99  | 0.447               | 0.46                |
| $K_c$         | 2.54   | 0.04  | -0.05 | 0.595 | 0.435               | 0.12                |
| $K_t$         | 3.25   | 0.029 | 0.215 | 0.42  | 0.75                | 0.32                |

$f_{bt}$  = AVERAGE FRICTION FACTOR BEFORE TURN

$f_{at}$  = AVERAGE FRICTION FACTOR AFTER TURN

$K_c$  = LOSS FACTOR OF CONTRACTION AT THE ENTRANCE

$K_t$  = LOSS FACTOR IN THE TURN

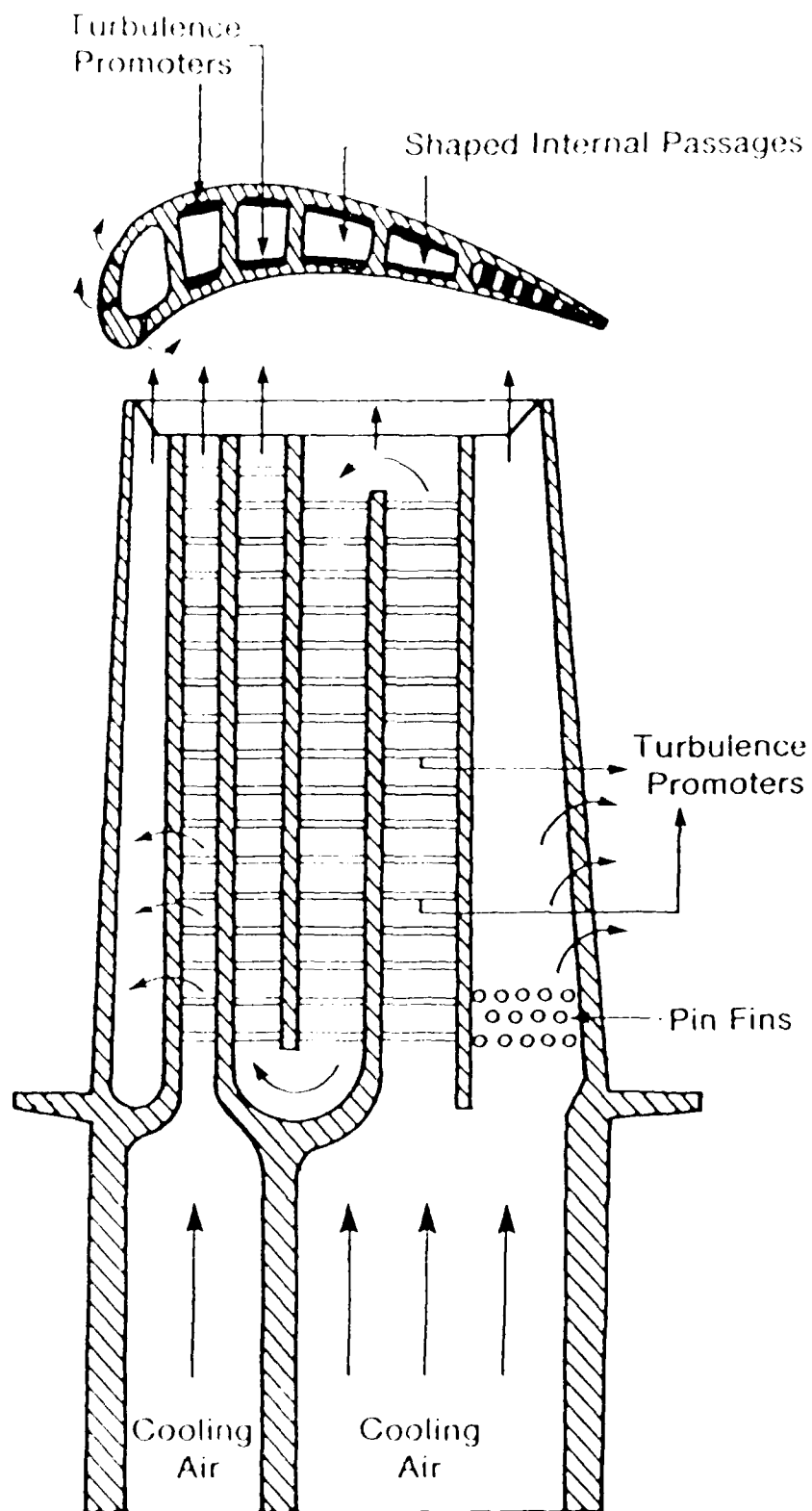


Fig. 1. Cooling concept of a modern multipass turbine blade with ribs at right angle

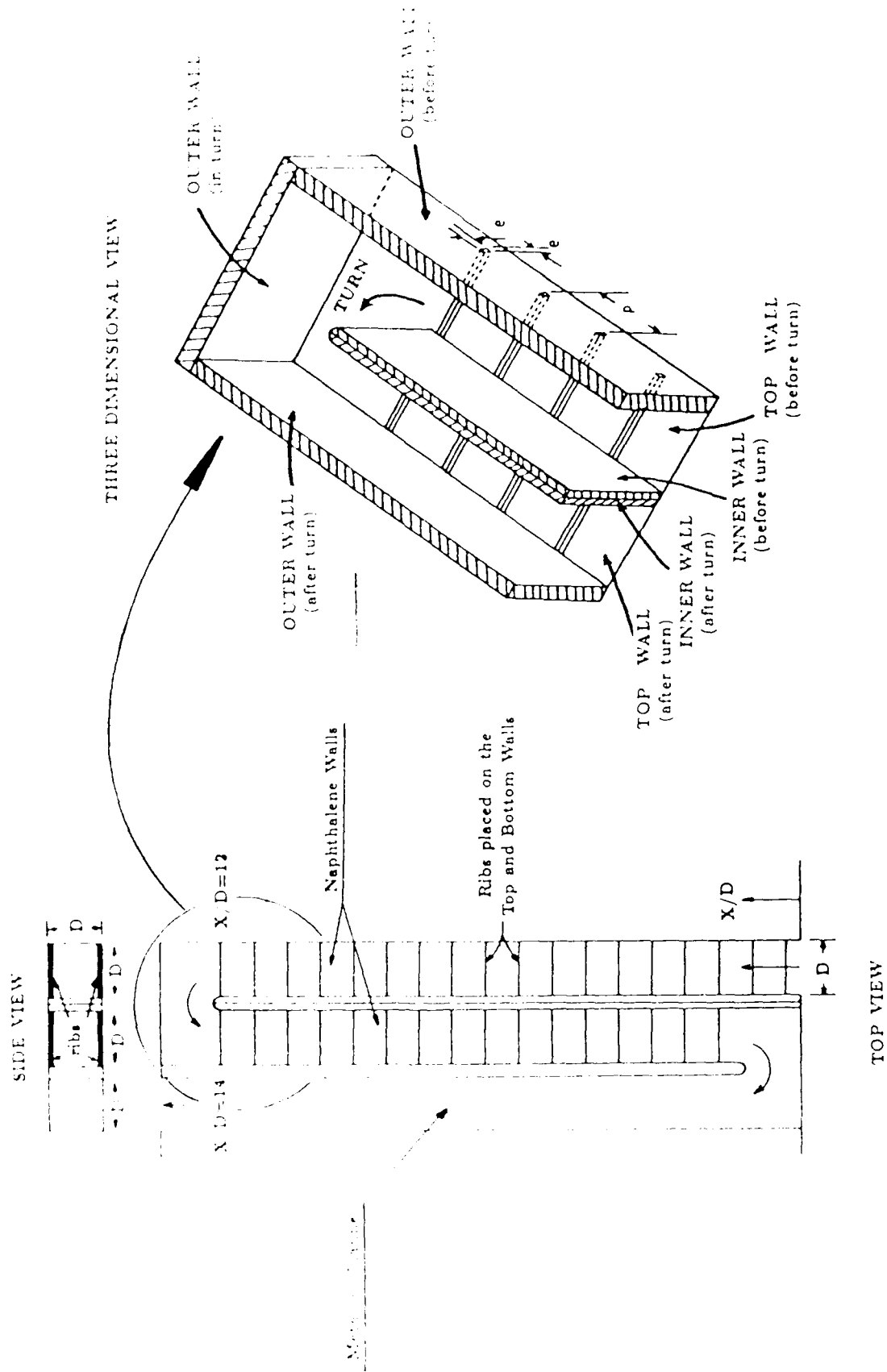


Fig. 2. Sketch of the test section for mass transfer experiments.

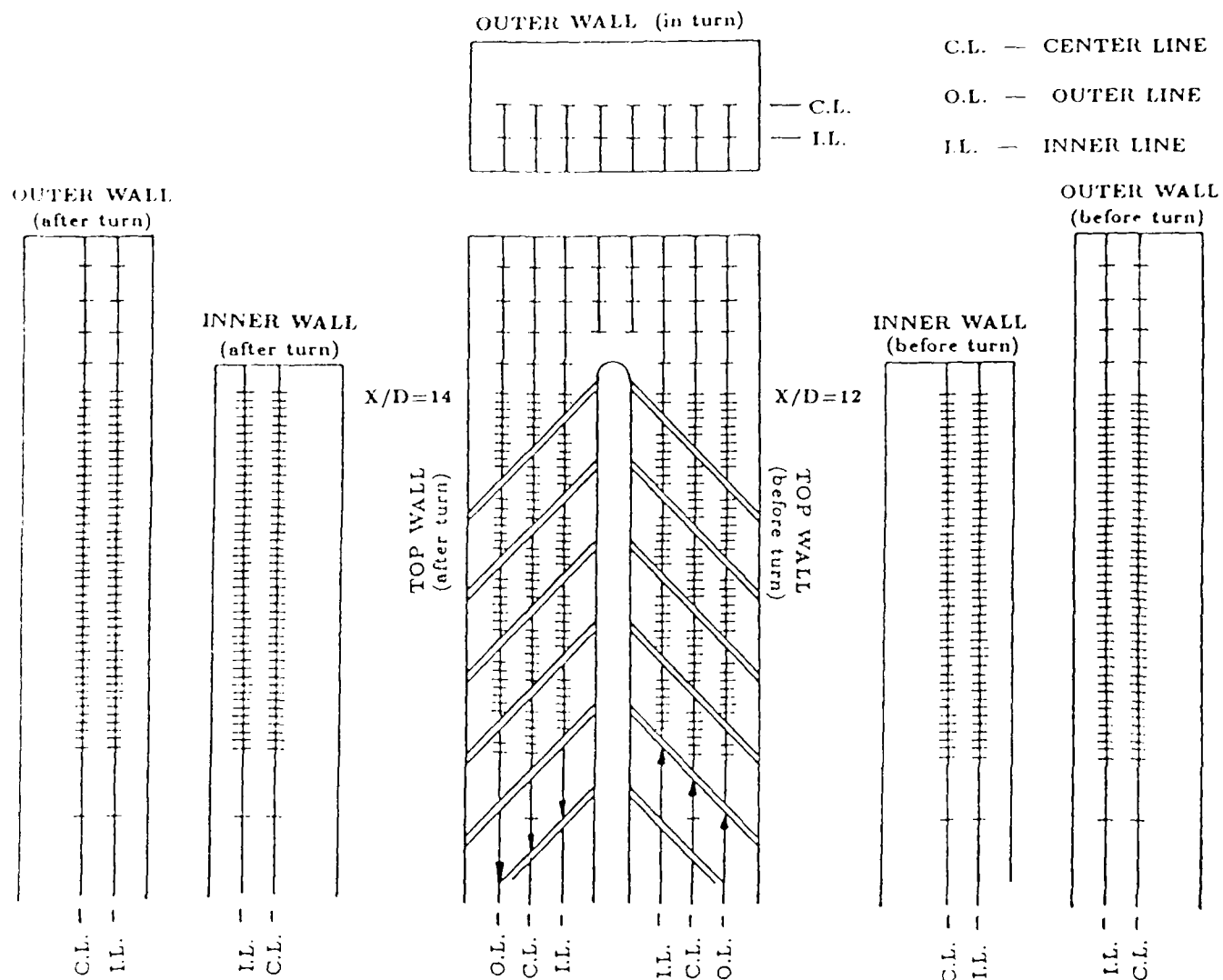


Fig. 3a. Measurement points before, in, and after the turn for a typical test run

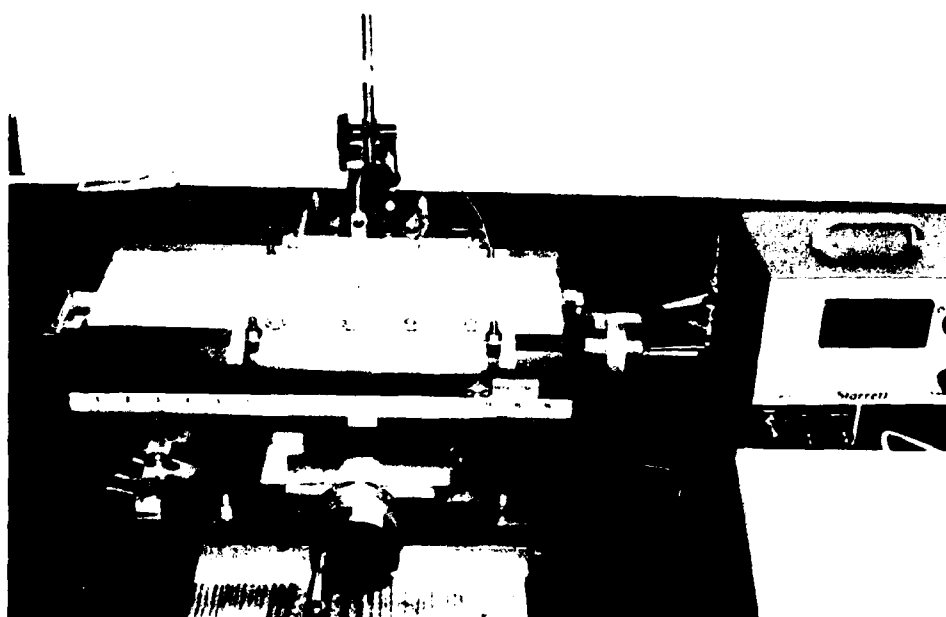
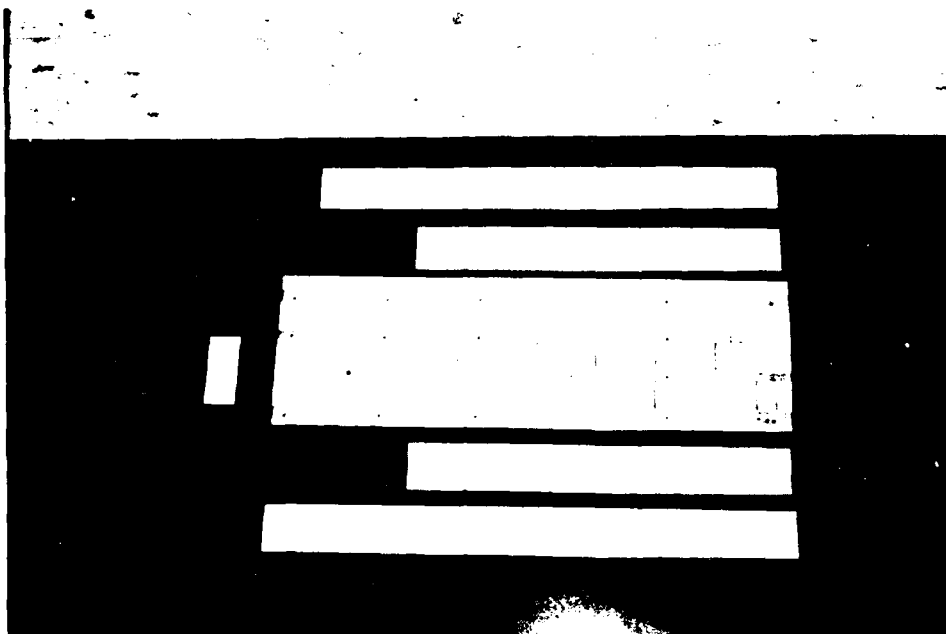


Fig. 3b. Upper Photo - Test Section with Naphthalene Plates  
 Lower Photo - Transversing Table and Instrumentation

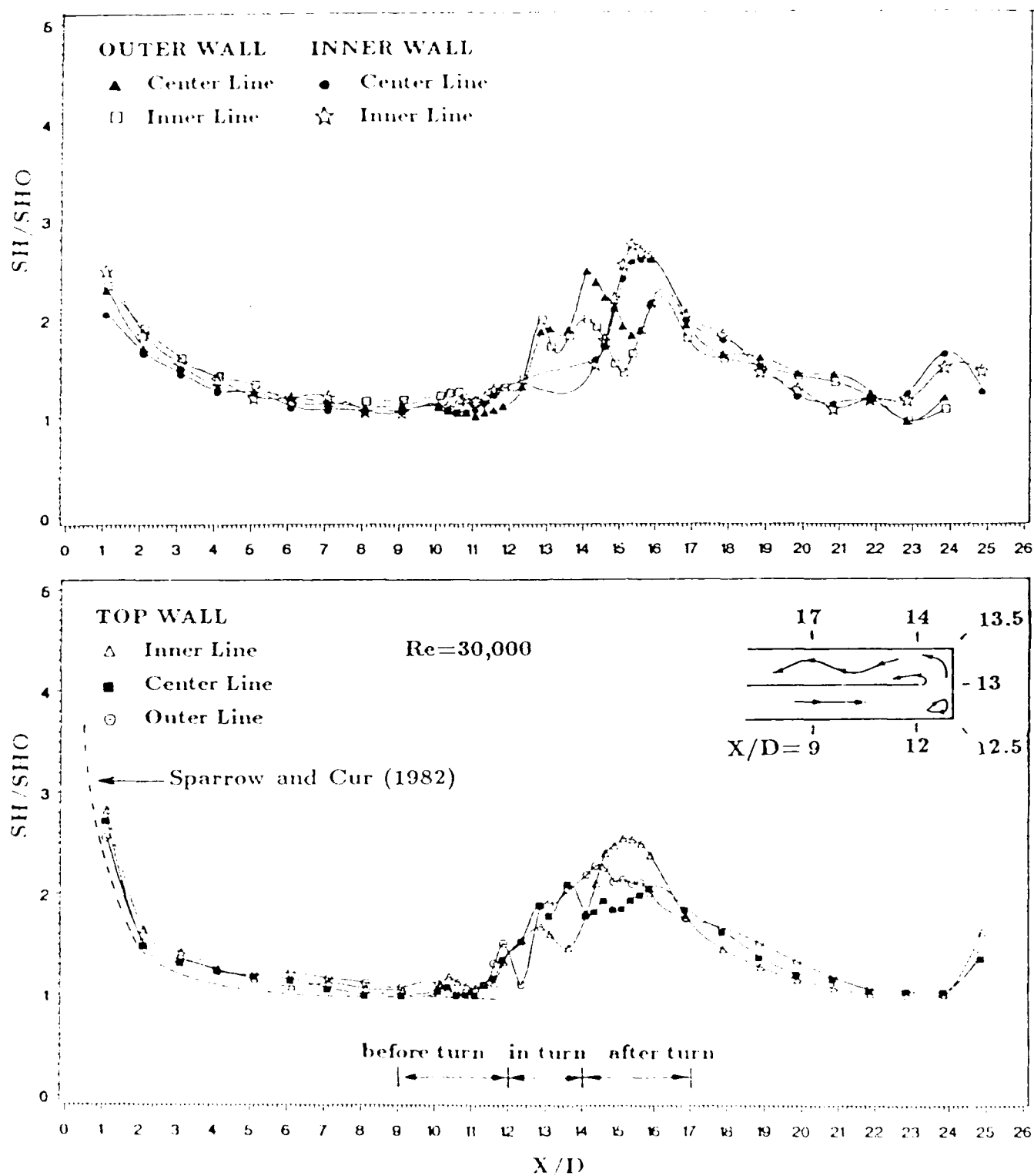


Fig. 4, The Local Sherwood No. Ratio for Smooth Channel with  $Re = 30,000$

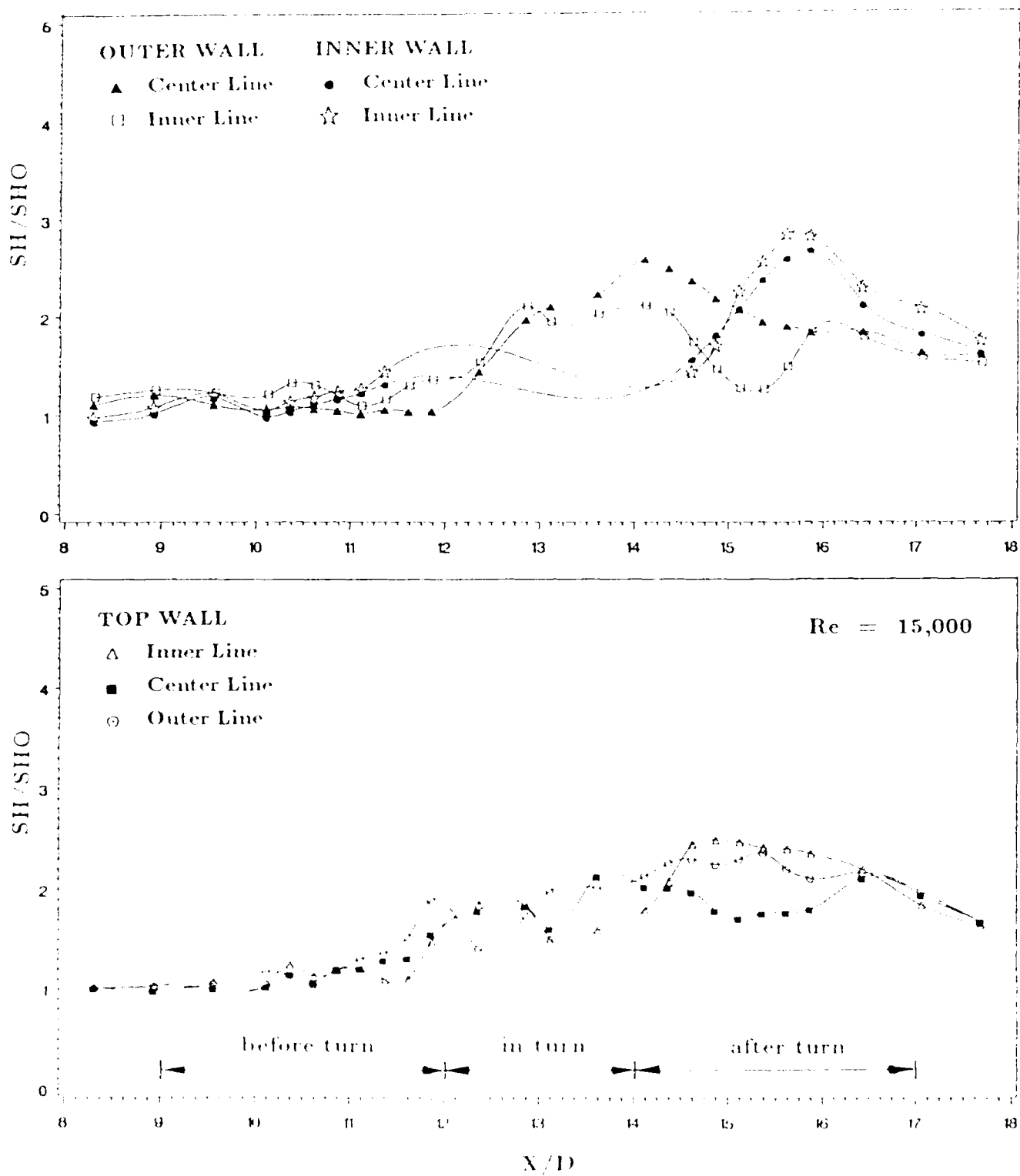


Fig. 5. The Local Sherwood No. Ratio for Smooth Channel with  $Re = 15,000$

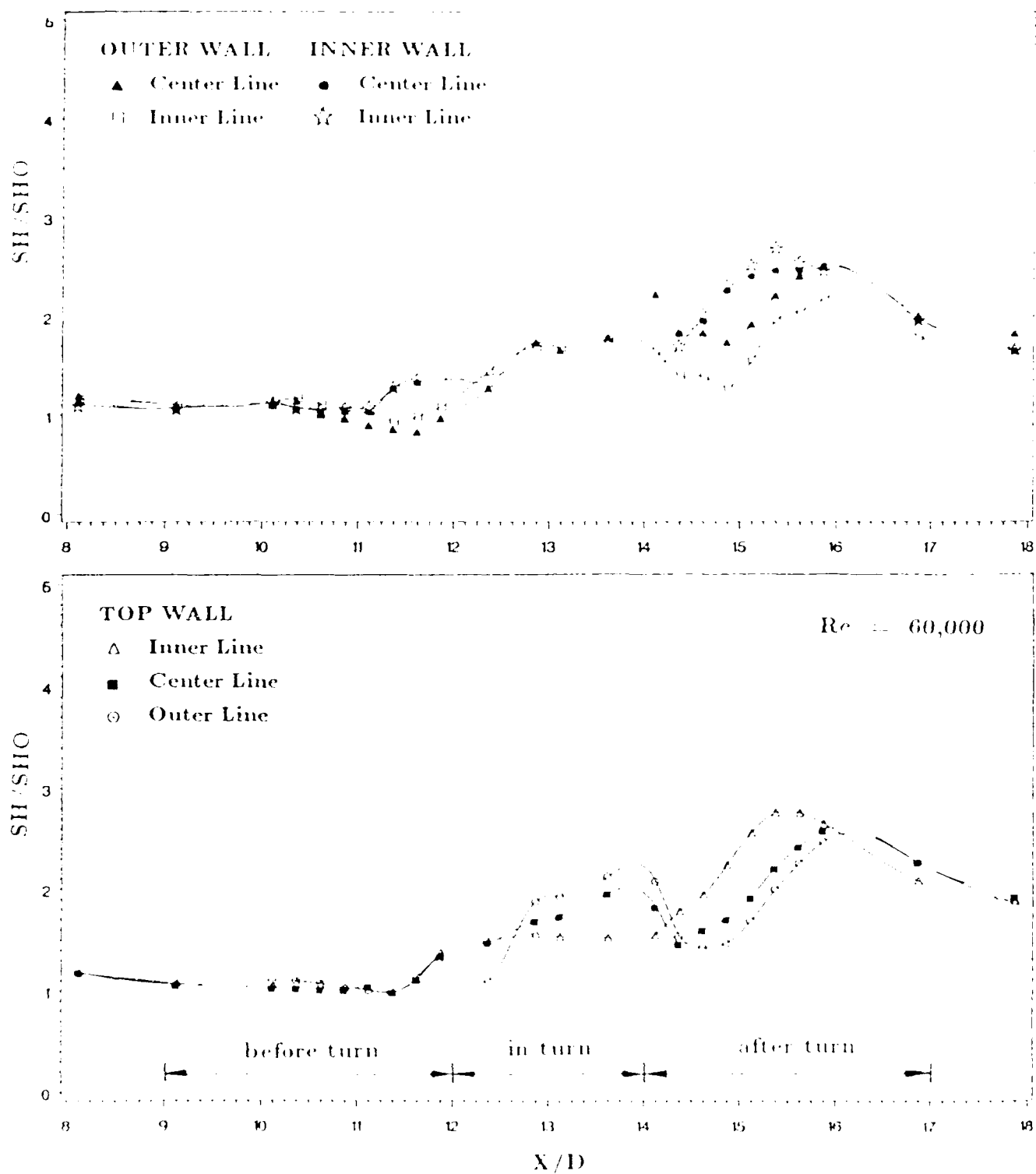


Fig. 6. The Local Sherwood No. Ratio for Smooth Channel with  $Re = 60,000$

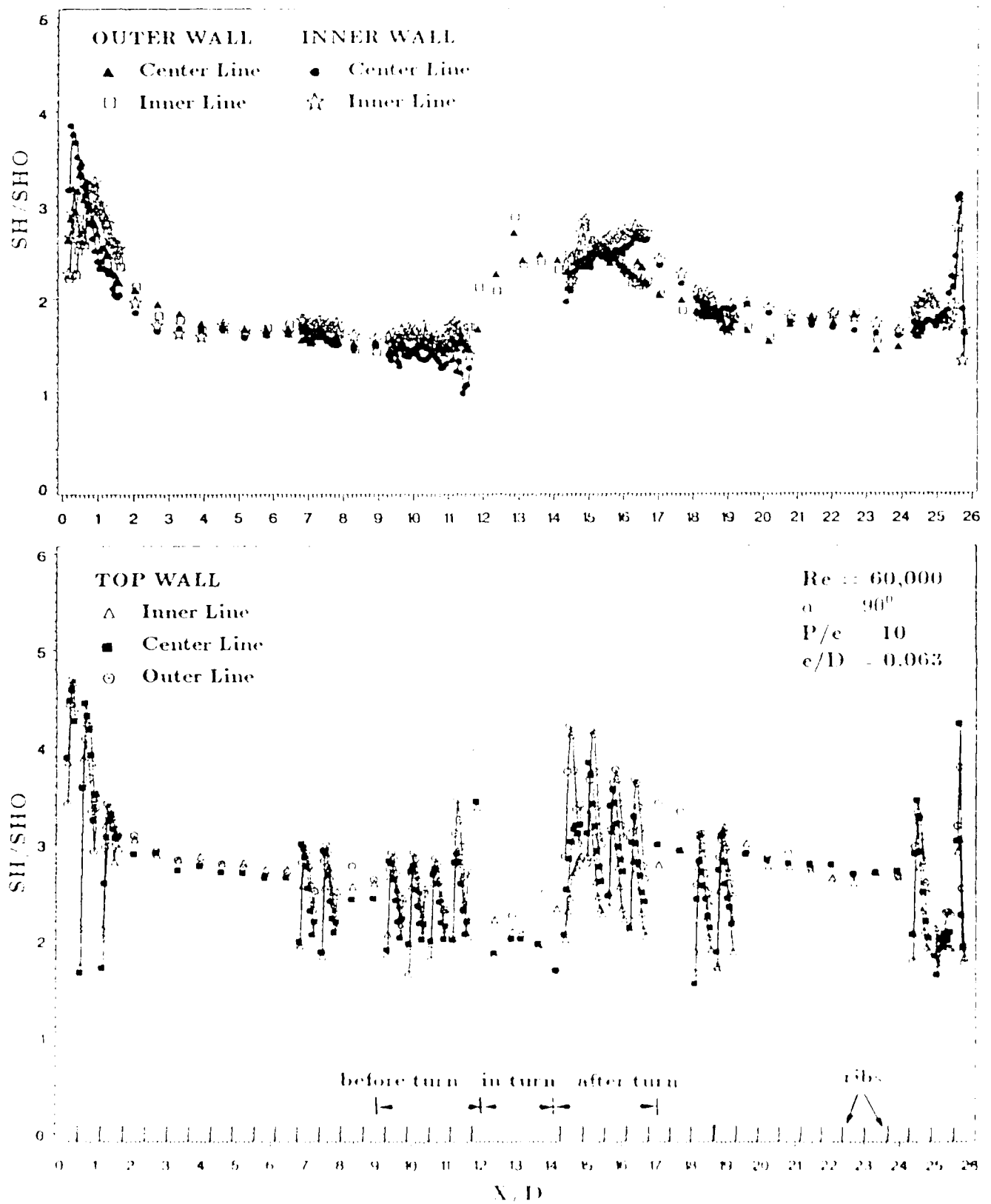


FIG. 7. The Local Sherwood No. Ratio for Ribbed Channel with  $e/D = 0.063$ ,  $P/e = 10$ , and  $Re = 60,000$

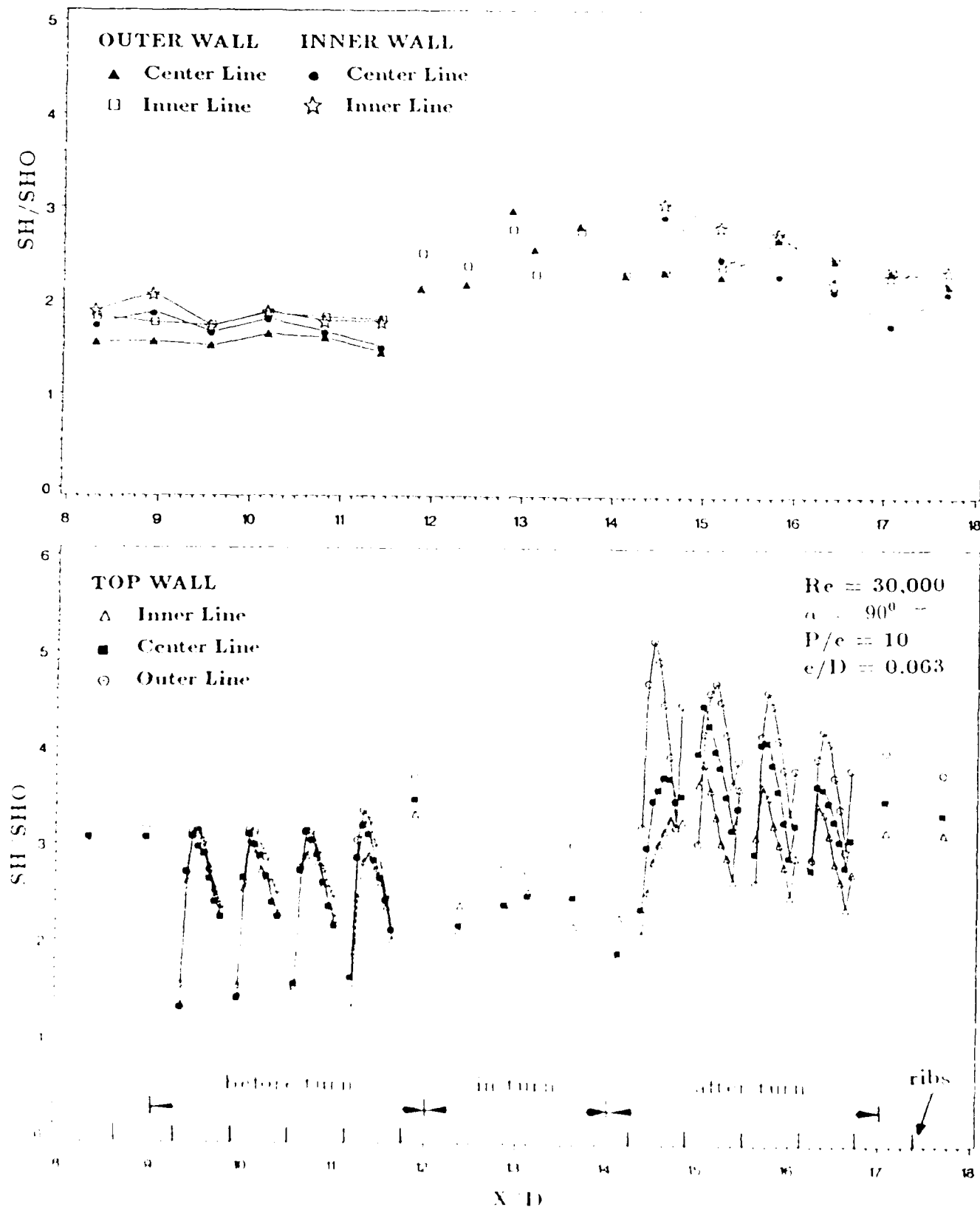


Fig. 8 The Local Sherwood No. Ratio for Ribbed Channel with  $e/D = 0.063$ ,  $P/e = 10$ , and  $Re = 30,000$

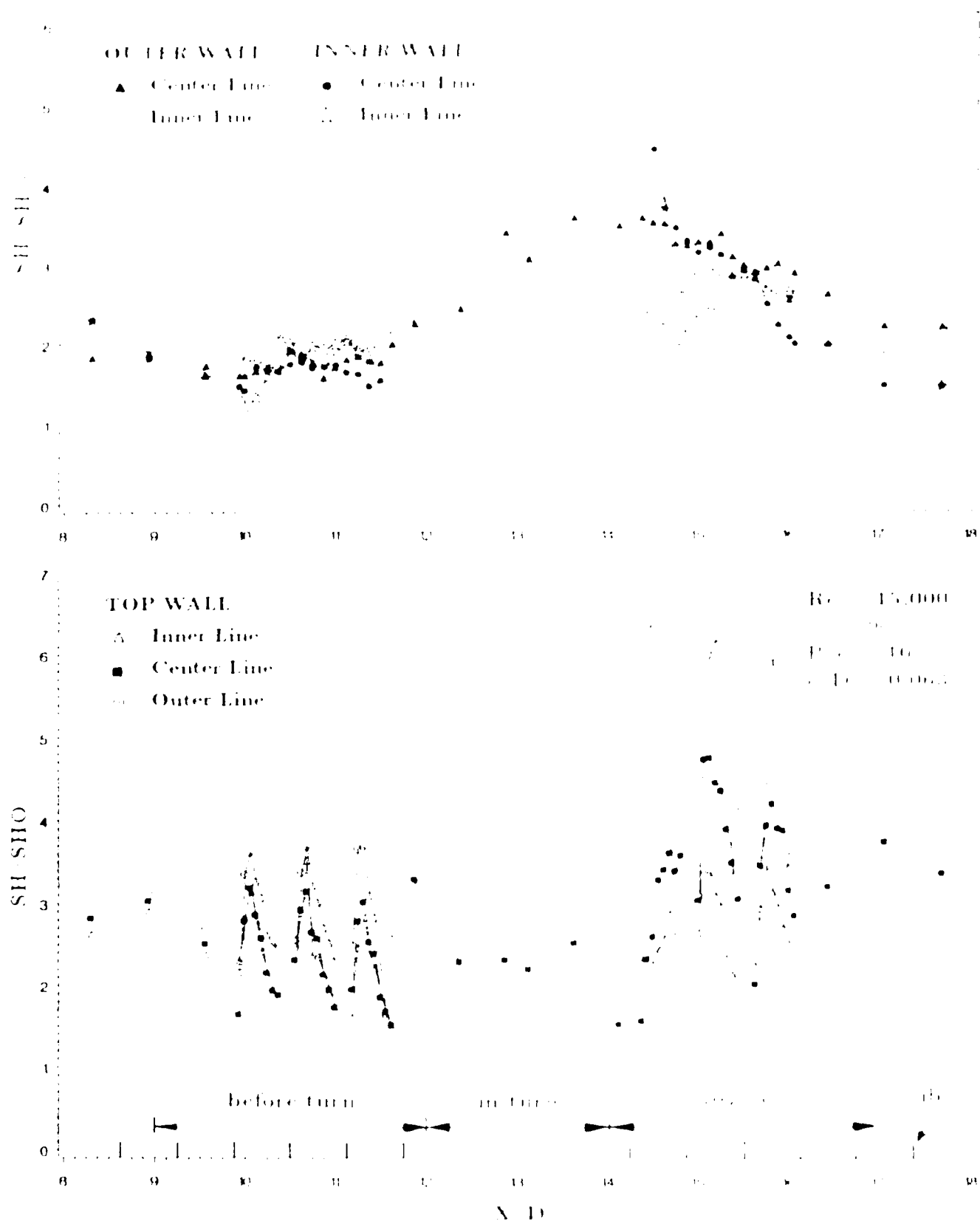


Fig. 9. The Local Sherwood No. Ratio for Ribbed Channel with  $e/D = 0.063$ ,  $Pr = 10$ , and  $Re = 15,000$ .

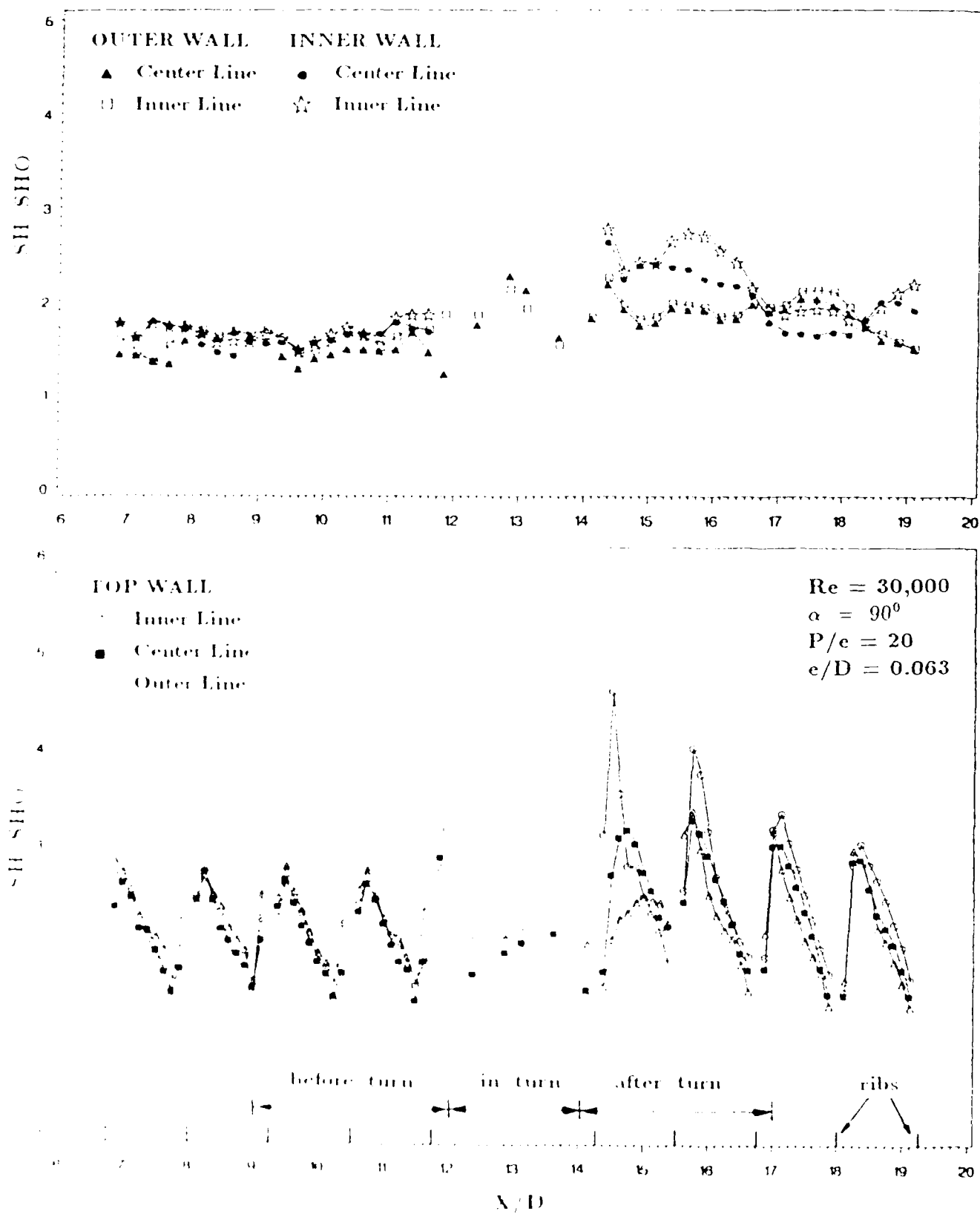


FIG. 2 The Local Sherwood No. Ratio for Ribbed Channel  
 with  $e/D = 0.063$ ,  $P/e = 20$ , and  $Re = 30,000$

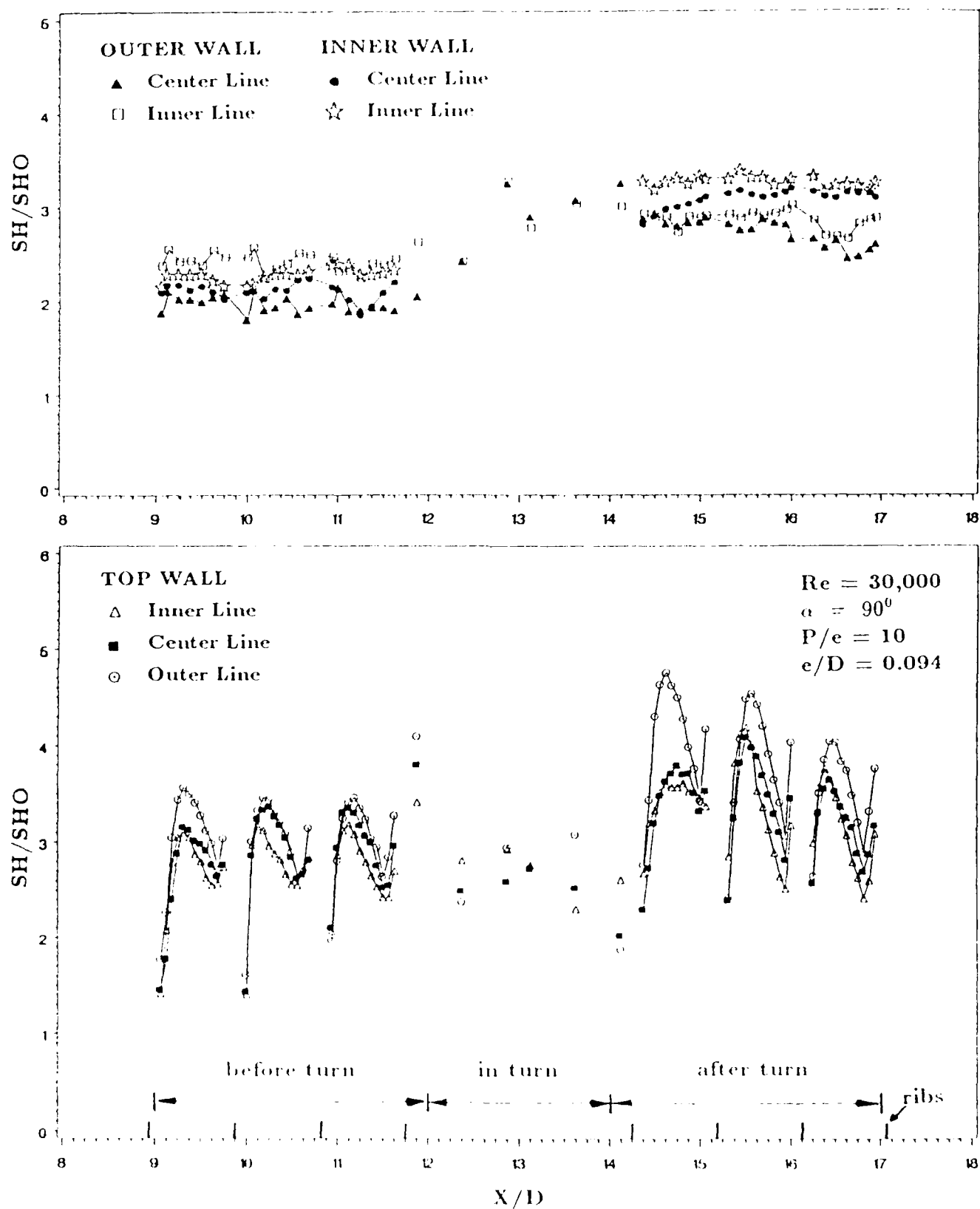


Fig. 11. The Local Sherwood No. Ratio for Ribbed Channel  
 with  $e/D = 0.094$ ,  $P/e = 10$ , and  $Re = 30,000$

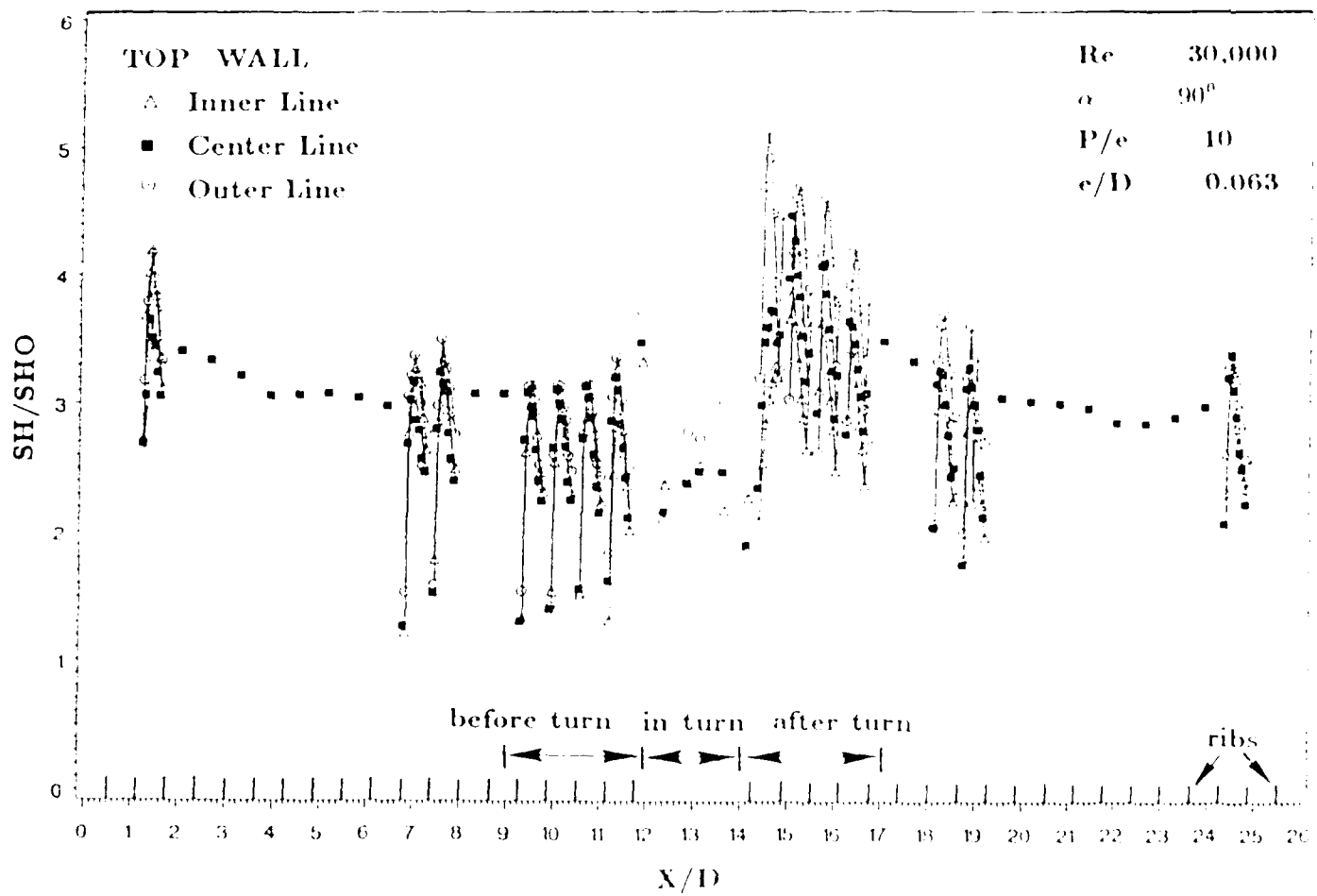


Fig. 12. The local Sherwood no. ratio with  $\alpha = 90^\circ$  and Re = 30,000

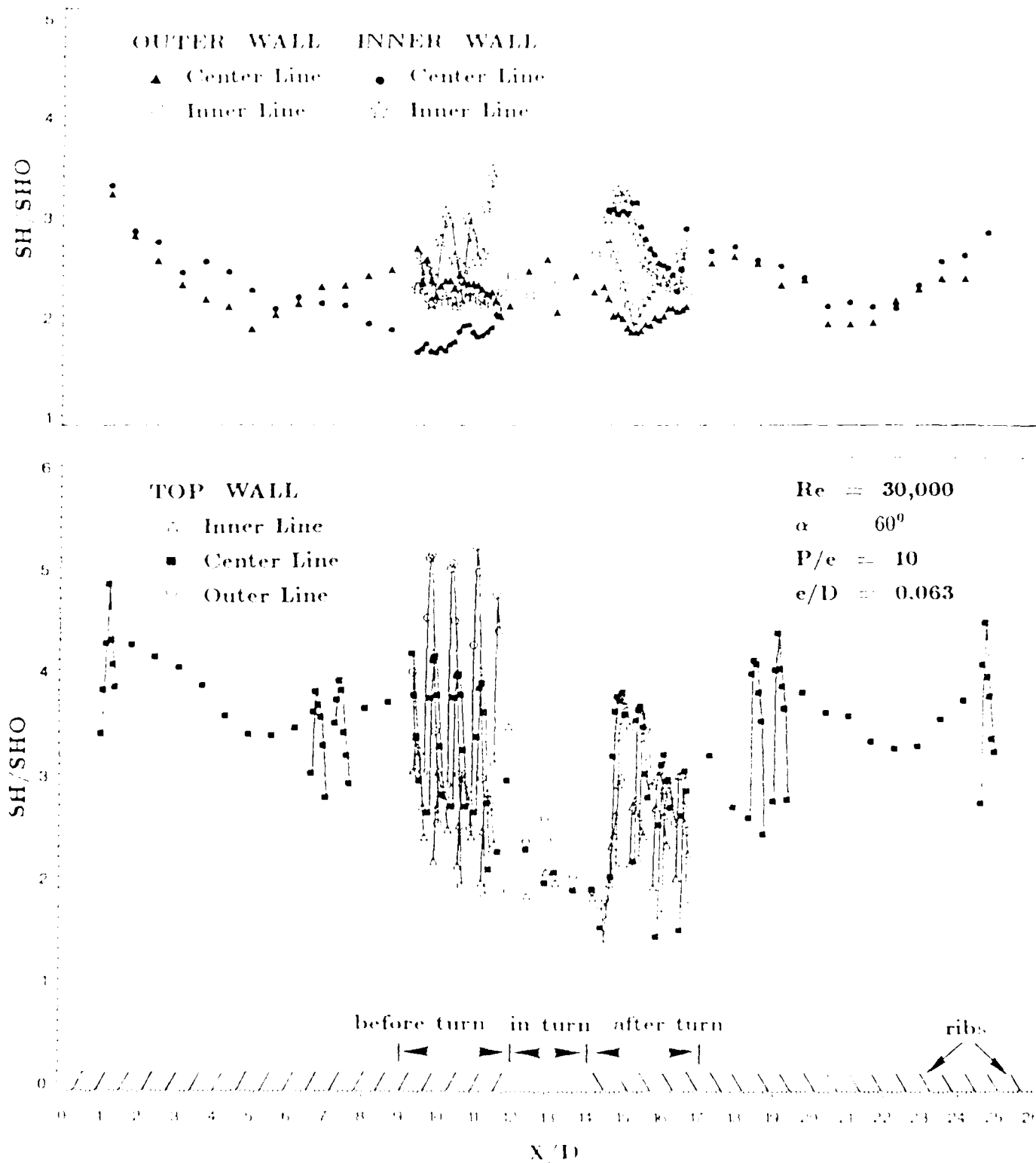


Fig. 13. The local Sherwood no. ratio with  $\alpha = 60^\circ$  and  $Re = 30,000$

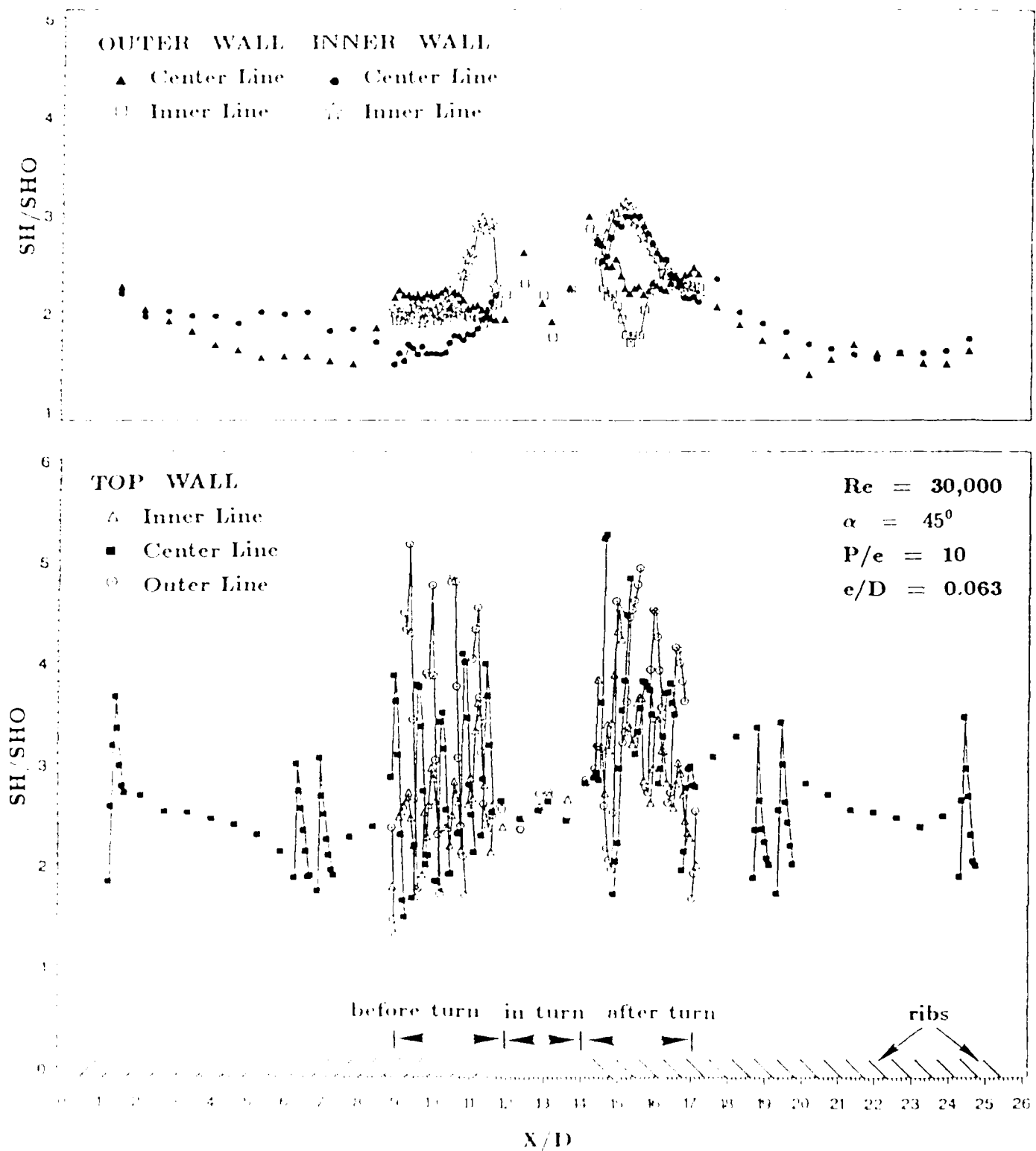
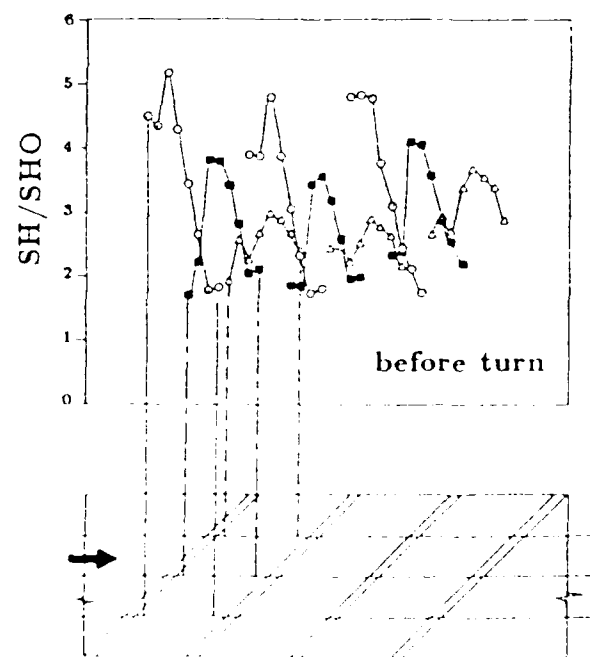
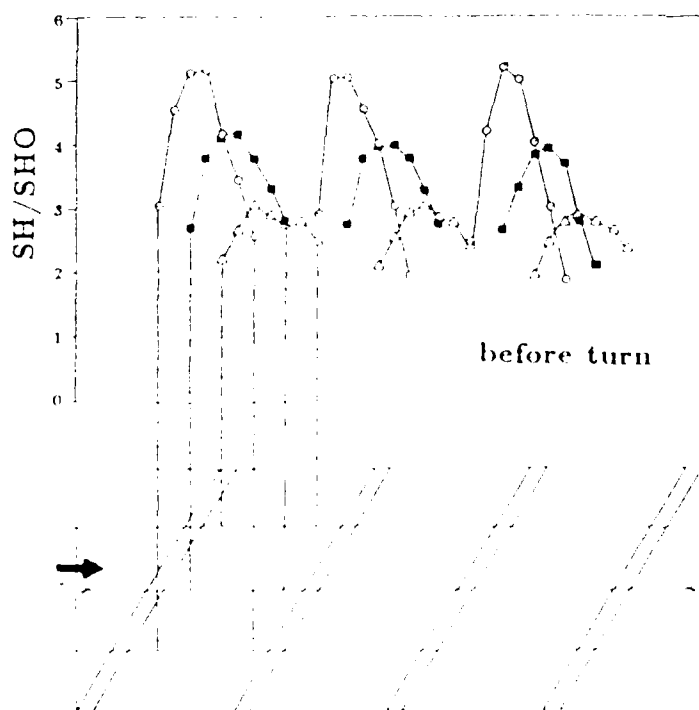
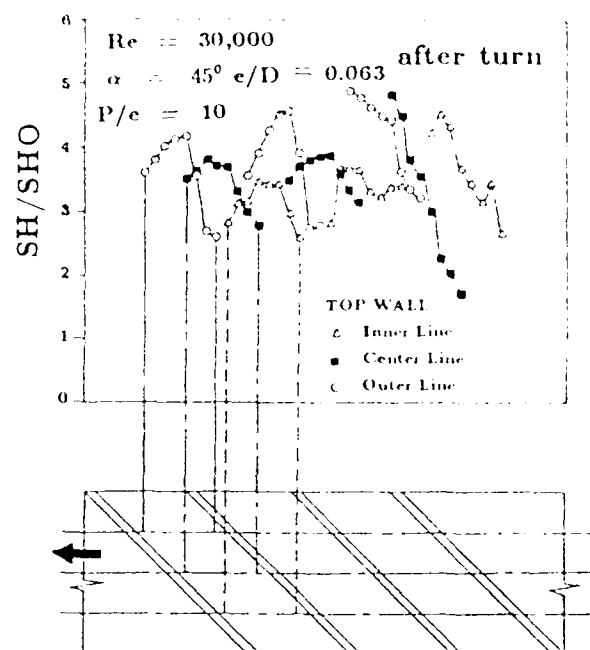
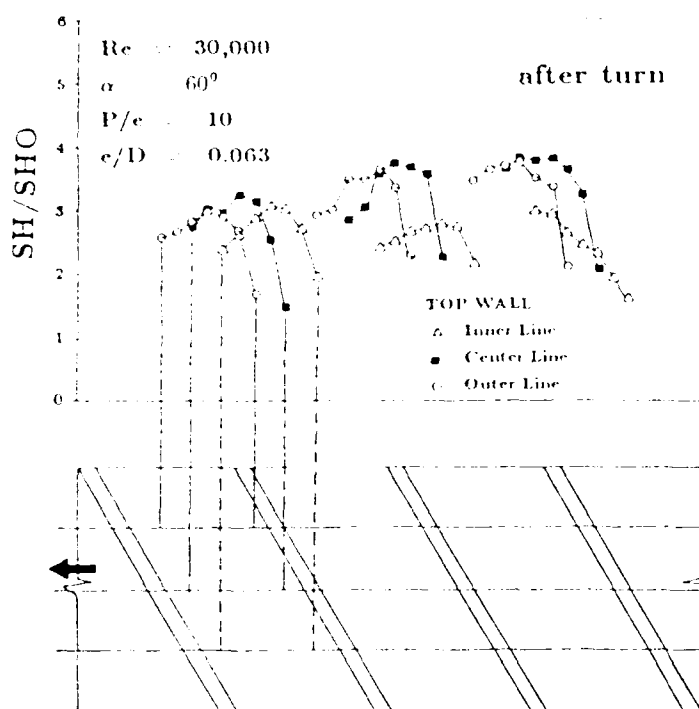


Fig. 14. The local Sherwood no. ratio with  $\alpha = 45^\circ$  and  $Re = 30,000$



(a)

(b)

Fig. 15. The detailed Sherwood no. ratios on the top wall with  $Re = 30,000$ , (a)  $\alpha = 60^\circ$ ; (b)  $\alpha = 45^\circ$

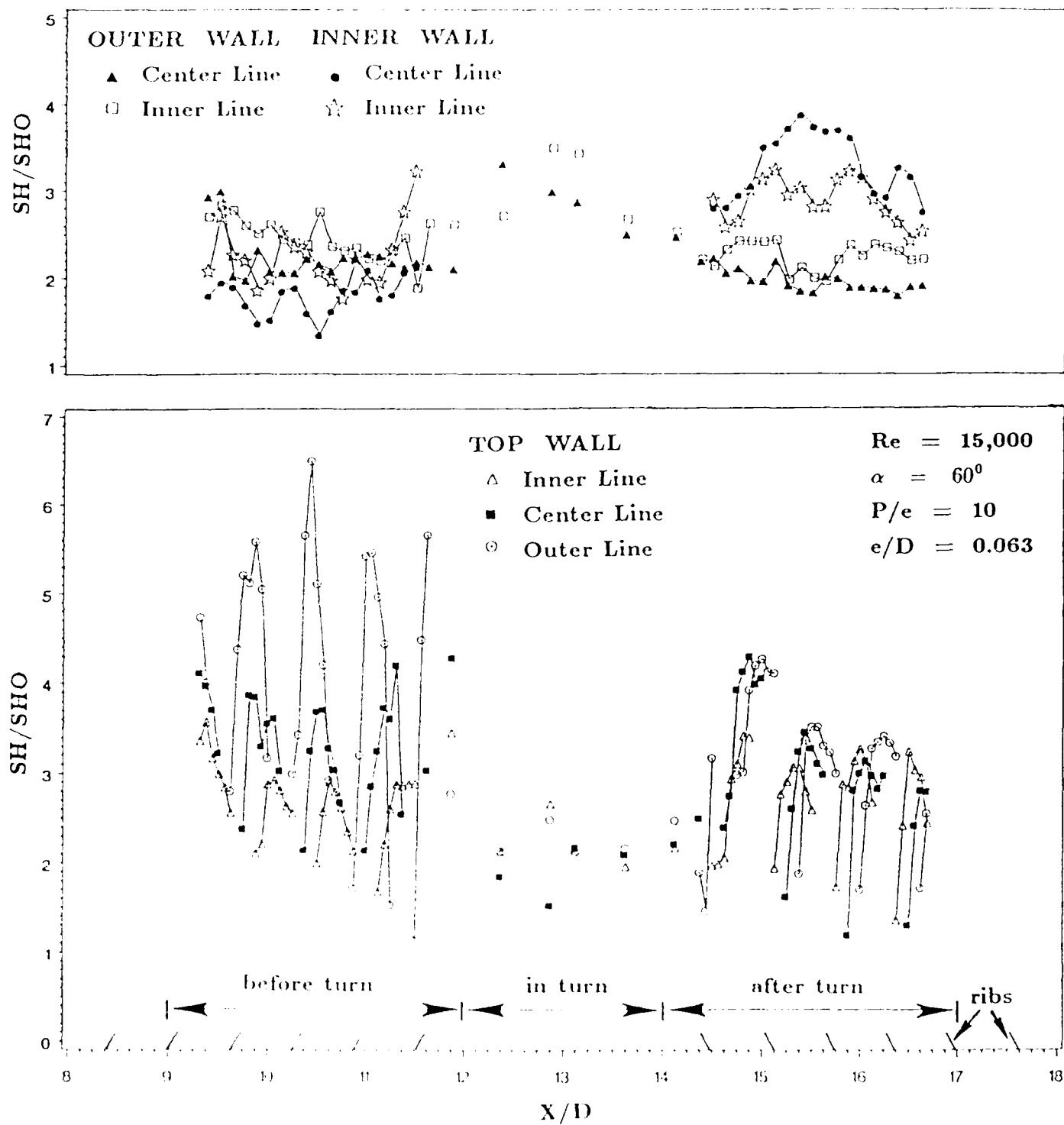


Fig. 16. The local Sherwood no. ratio with  $\alpha = 60^\circ$  and  $Re=15,000$

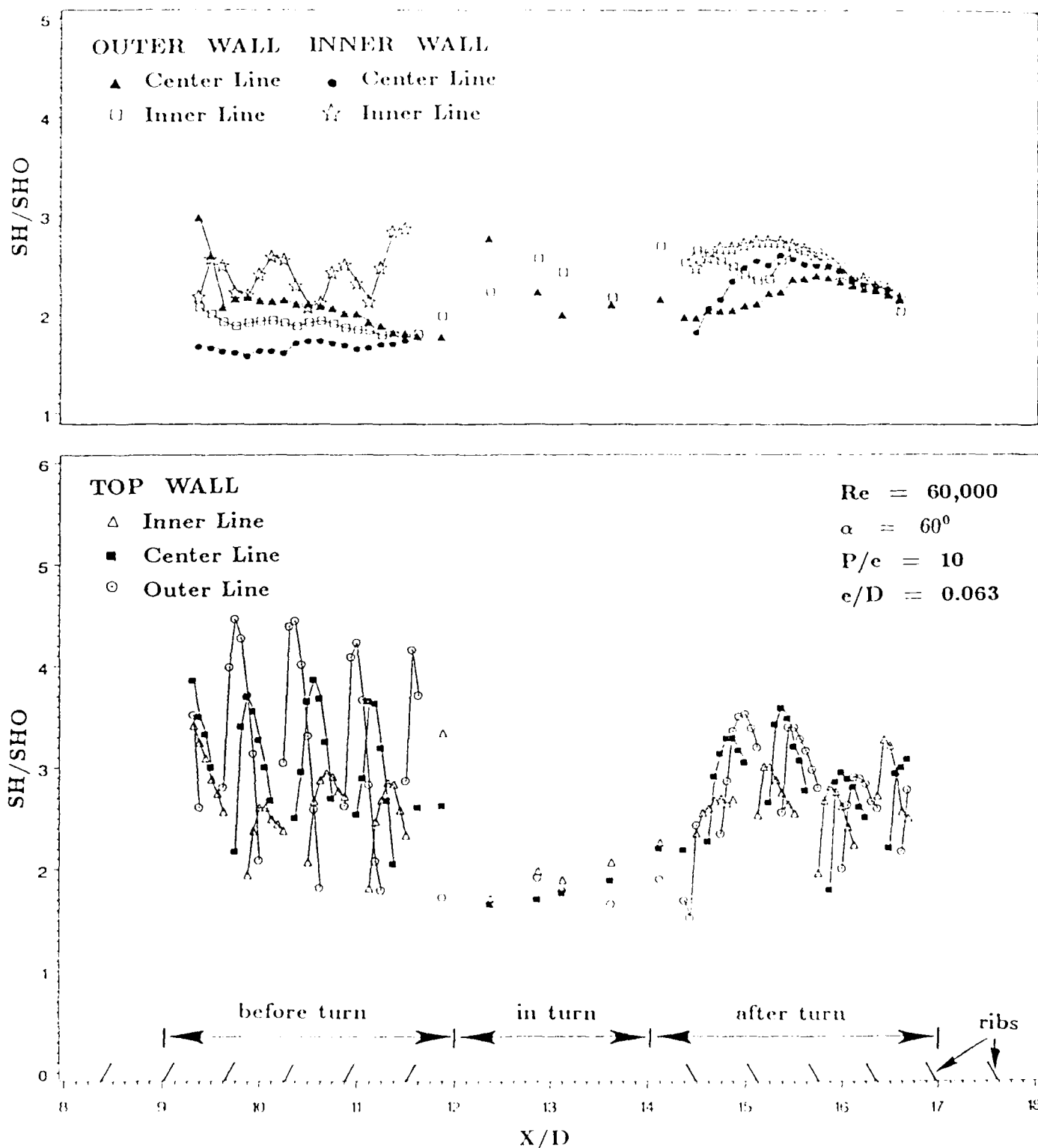


Fig. 17. The local Sherwood no. ratio with  $\alpha = 60^\circ$  and  $Re=60,000$

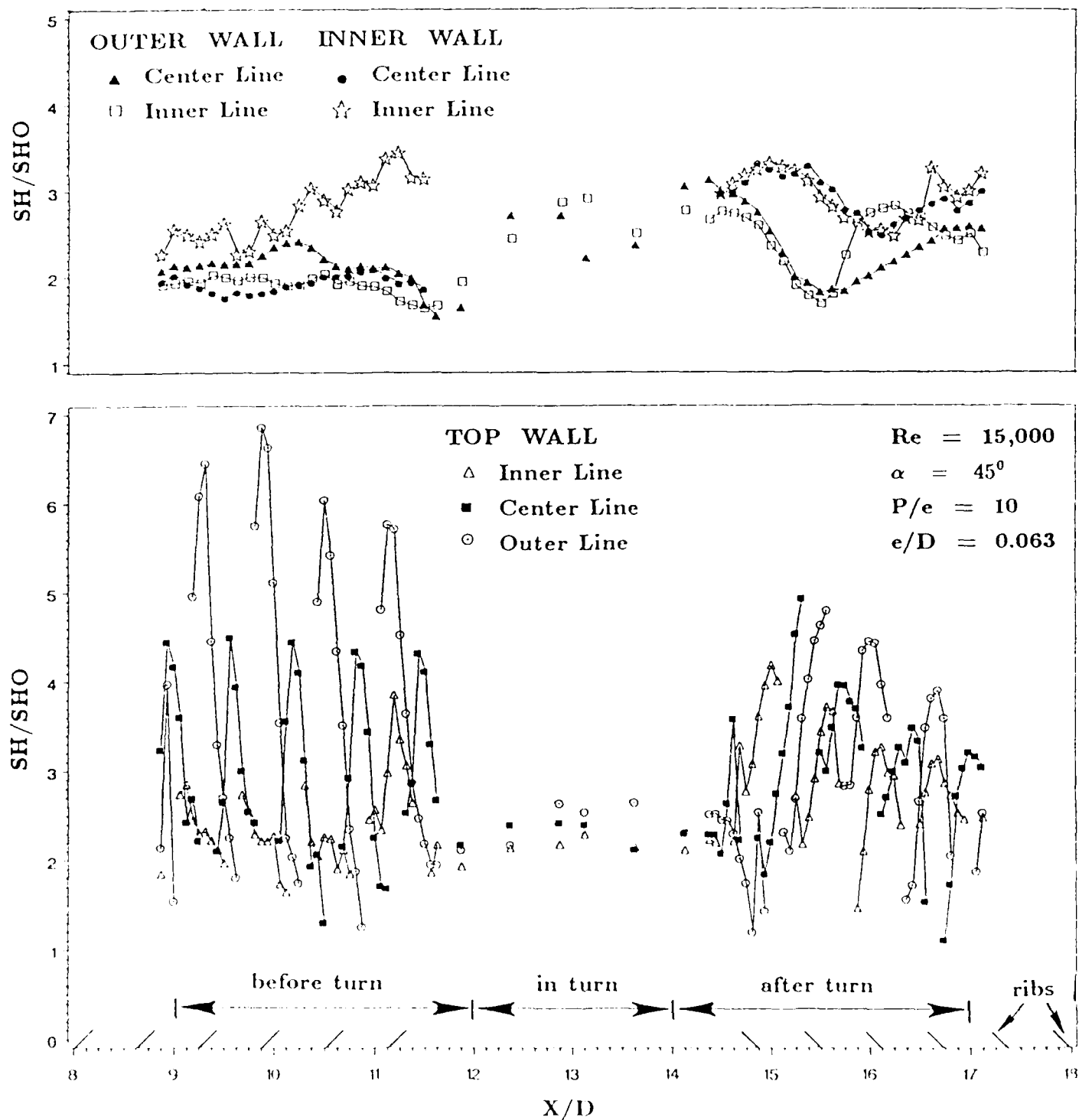


Fig. 18. The local Sherwood no. ratio with  $\alpha = 45^\circ$  and  $Re = 15,000$

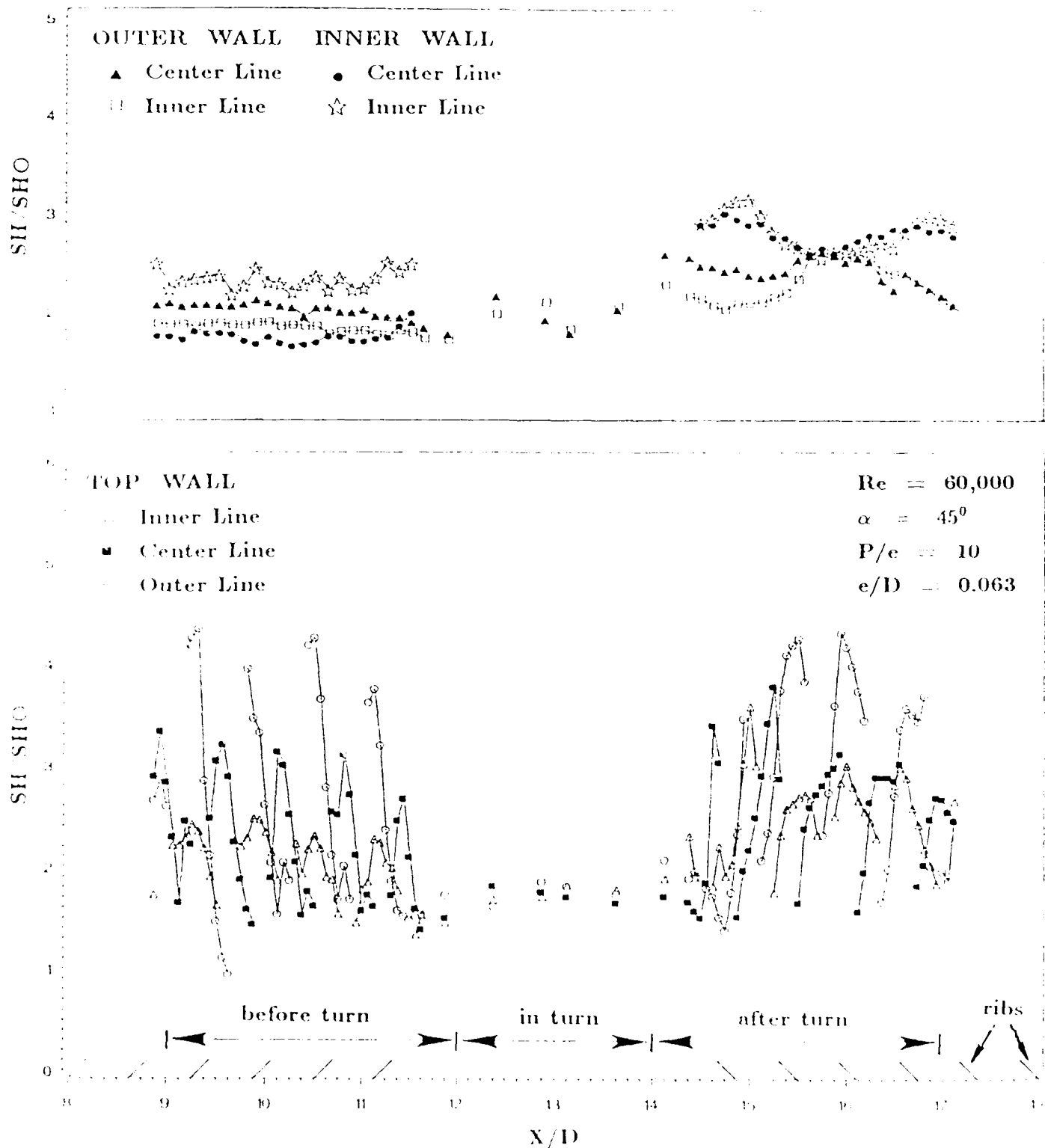


Fig. 19. The local Sherwood no. ratio with  $\alpha = 45^\circ$  and  $Re = 60,000$

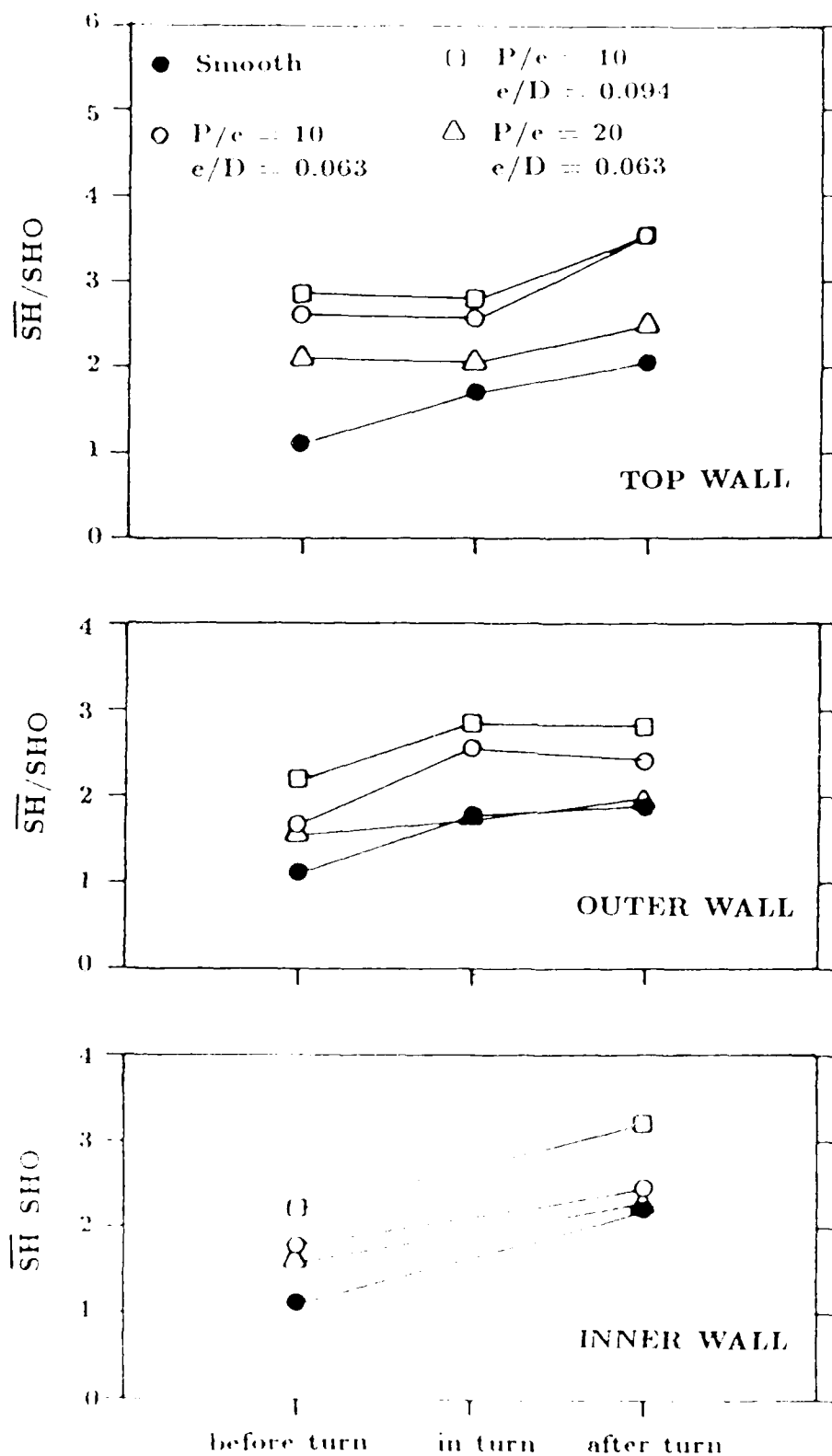


FIG. 20. The Average Sherwood No. Ratio on Each of the Channel Surfaces with  $Re = 50,000$

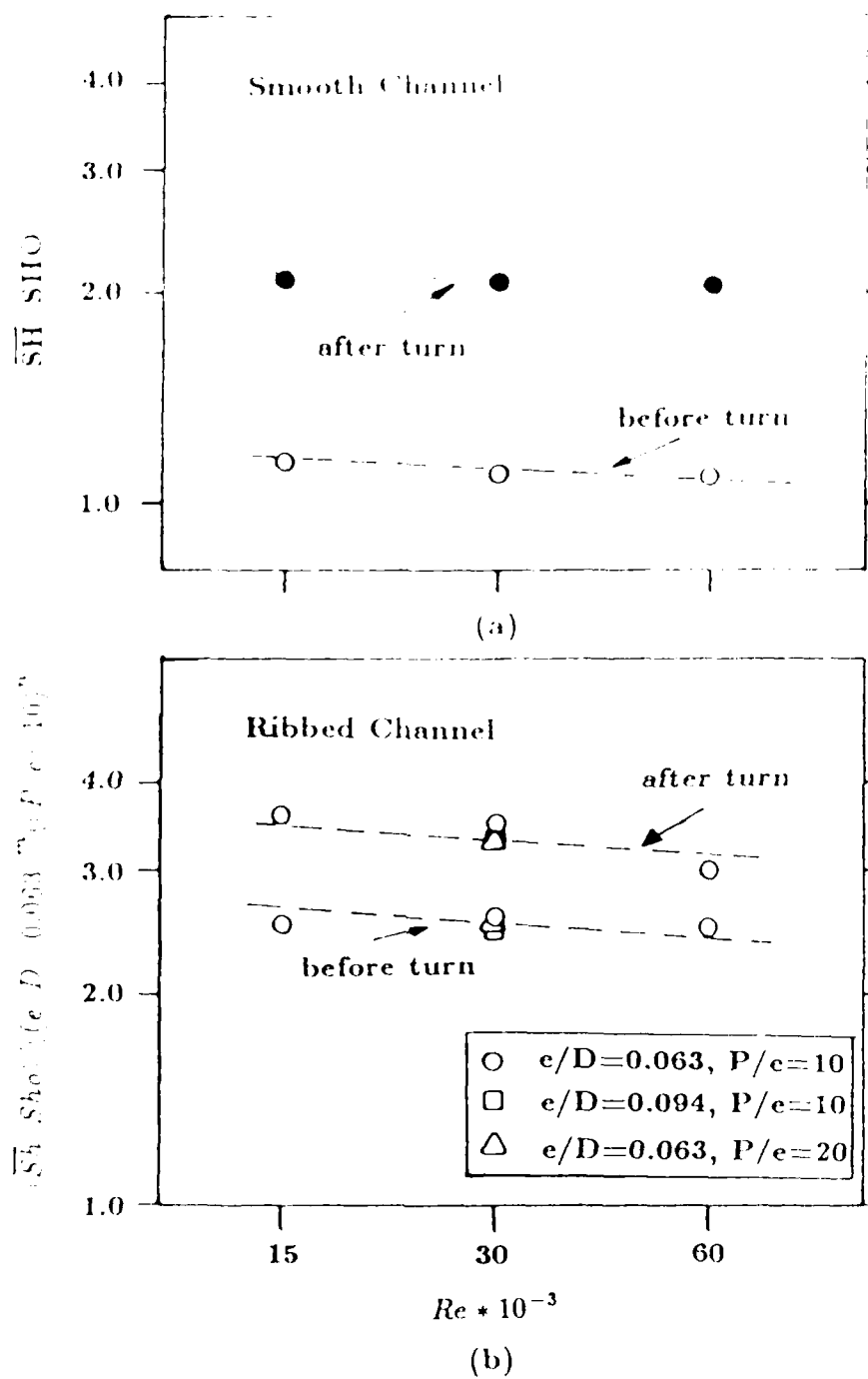


Fig. 21. Correlations of the Average Sherwood No. Ratio on the Top Wall

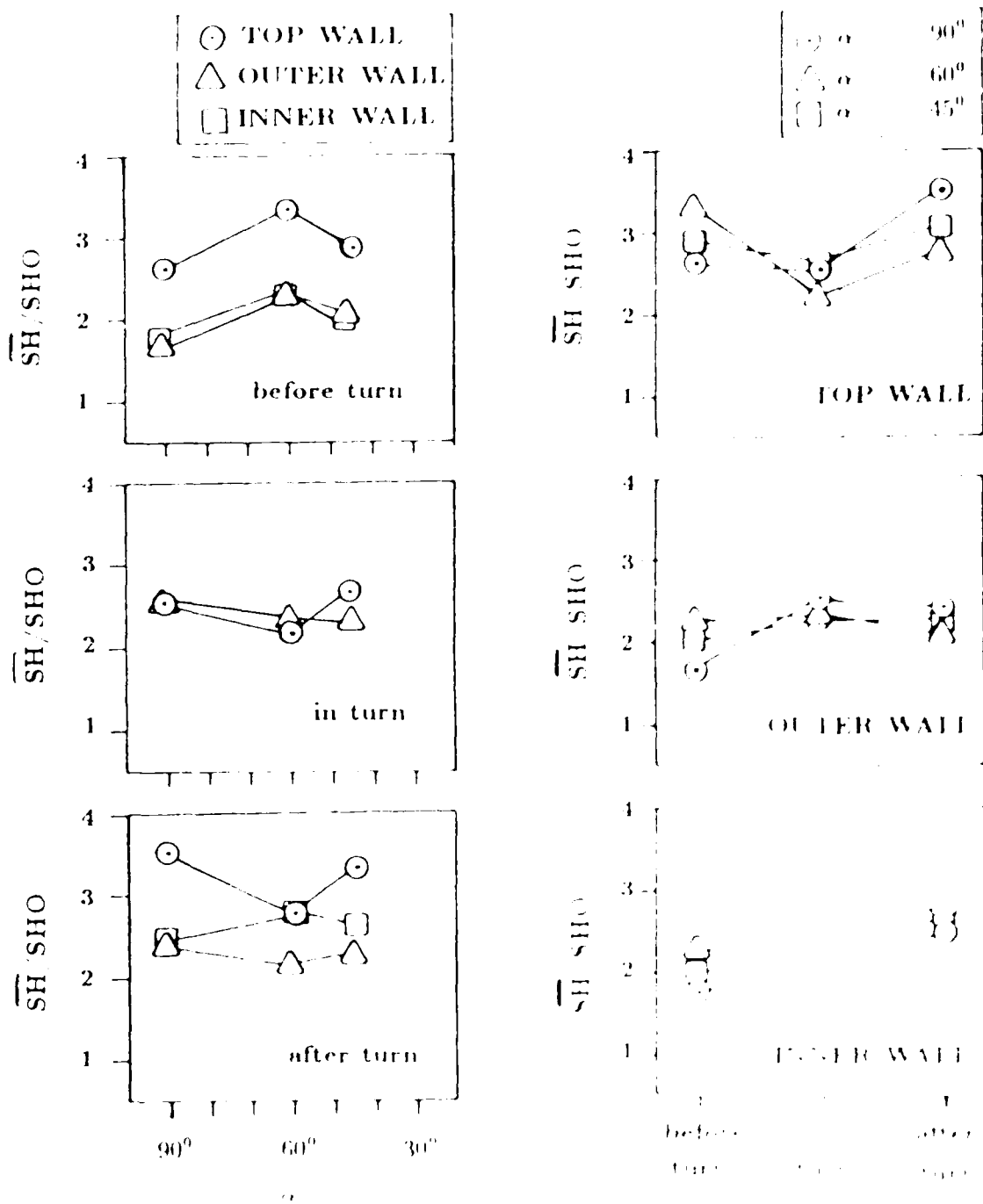


Fig. 22. The average Sherwood no. ratios on each of the channel surface with  $Re = 30,000$ .

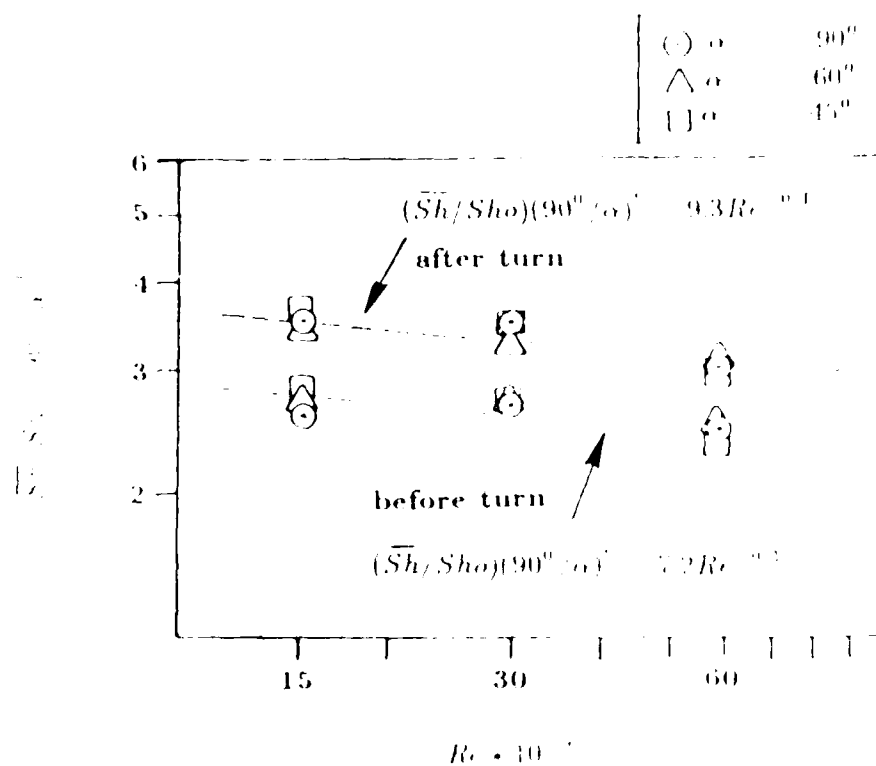


Fig. 25. Correlations of the average Sherwood no. ratio on the top wall with rib angles

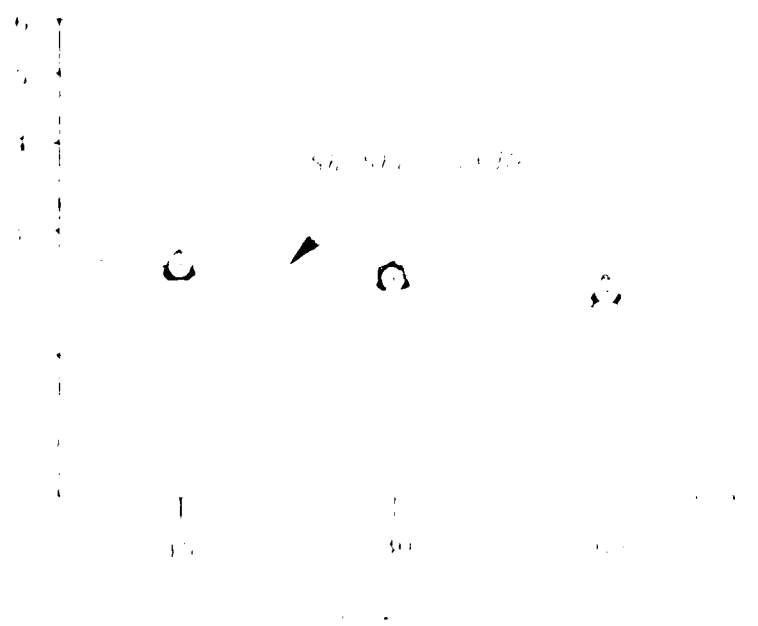


Fig. 26. Correlation of the overall average Sherwood no. ratio on all surfaces with rib angles

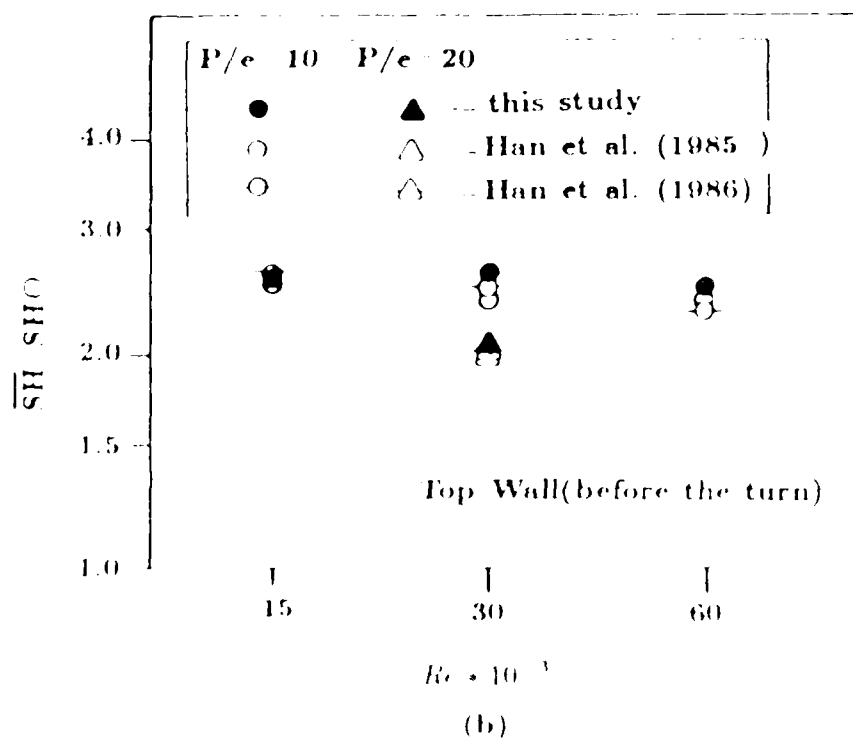
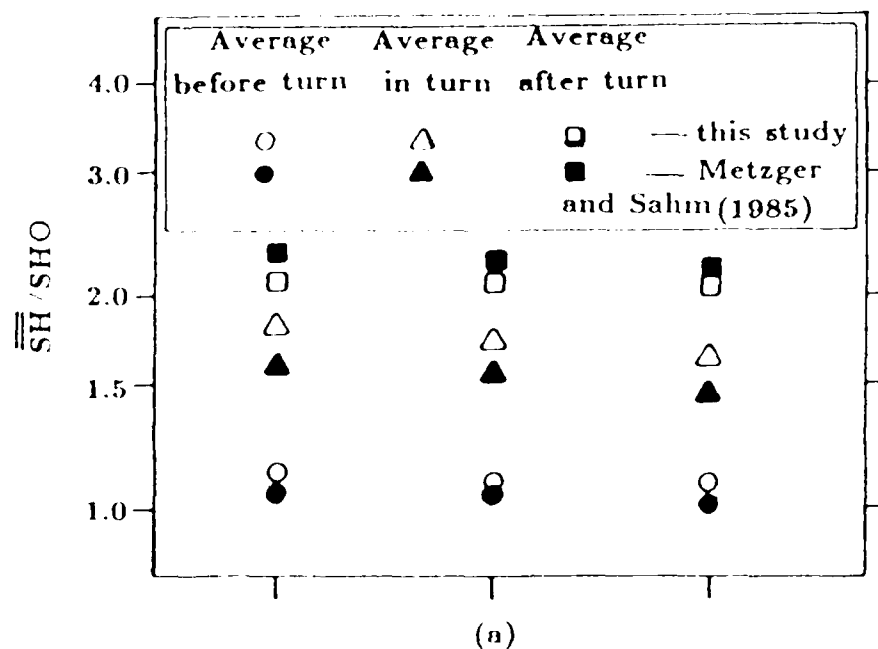


FIG. 24. Comparison between the present result and the published heat transfer data

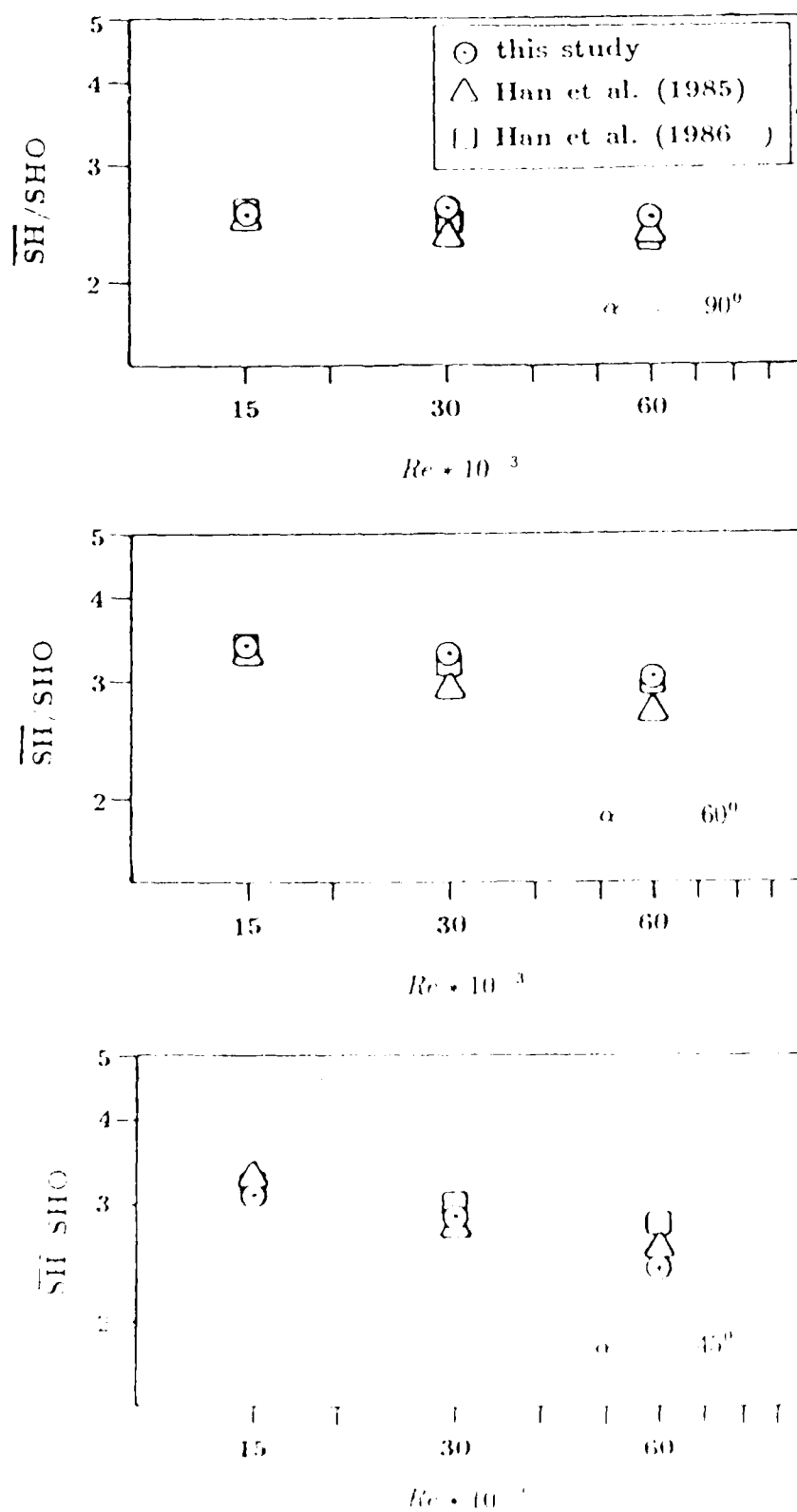
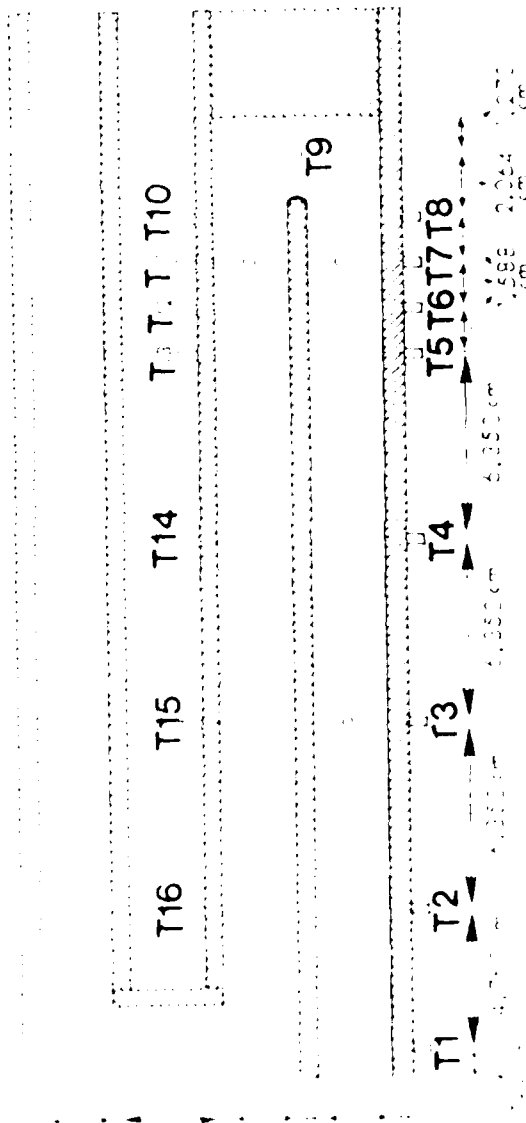


FIG. 25. Comparison between the present results on the top wall (before the turn) and the published heat transfer data

# TOP VIEW



# SIDE VIEW

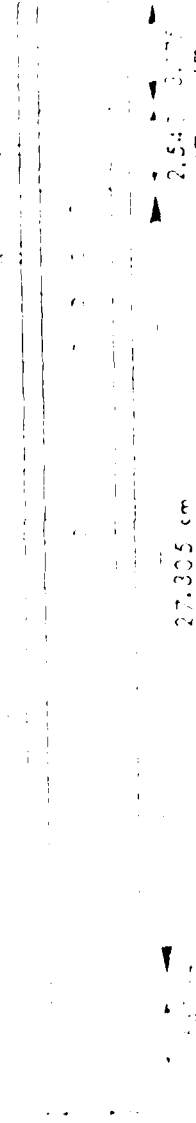


Fig. 46. Schematics of the test section for the pressure drop experiments

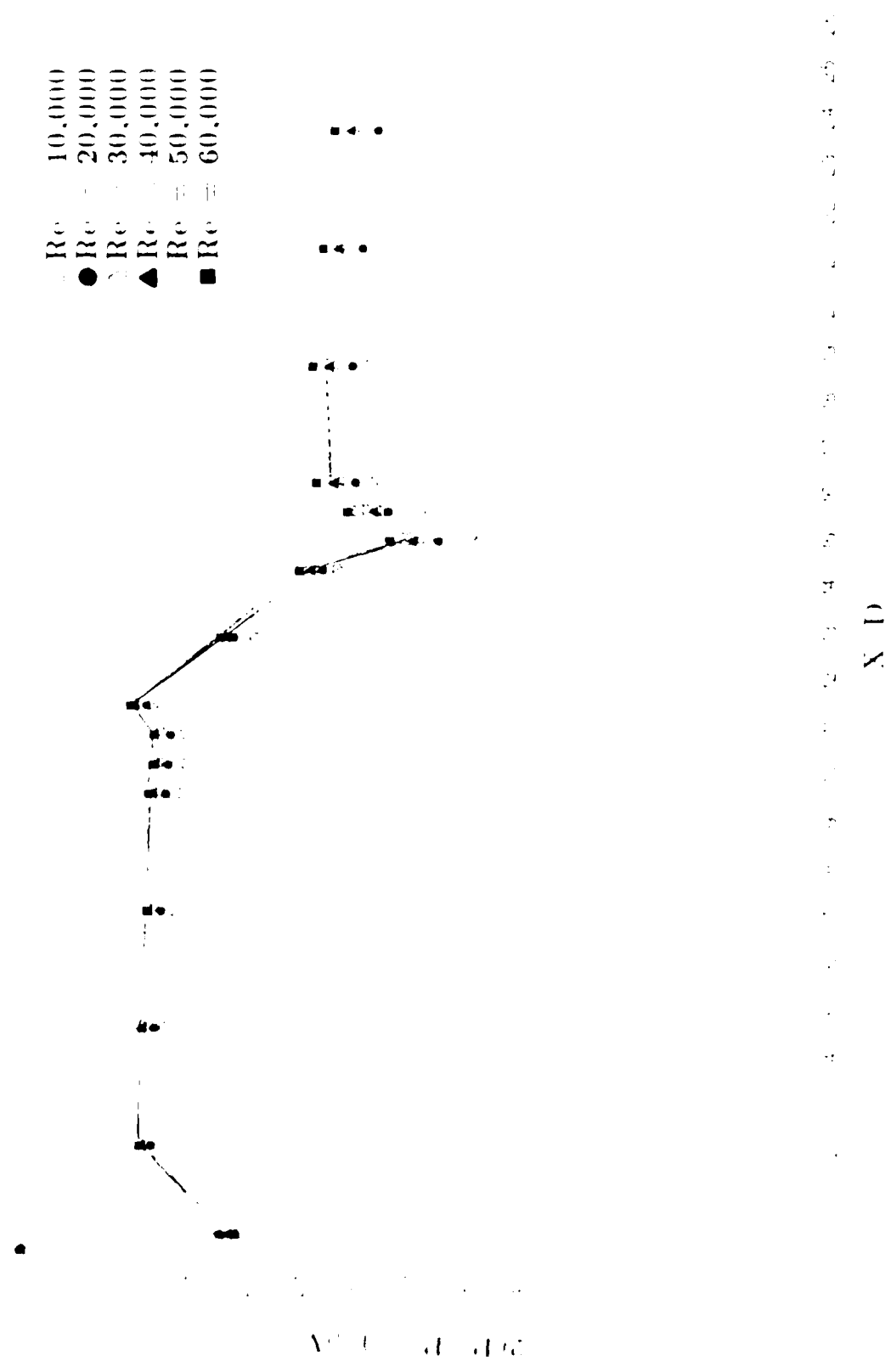


Fig. 27. Dimensionless pressure drop for smooth pipe

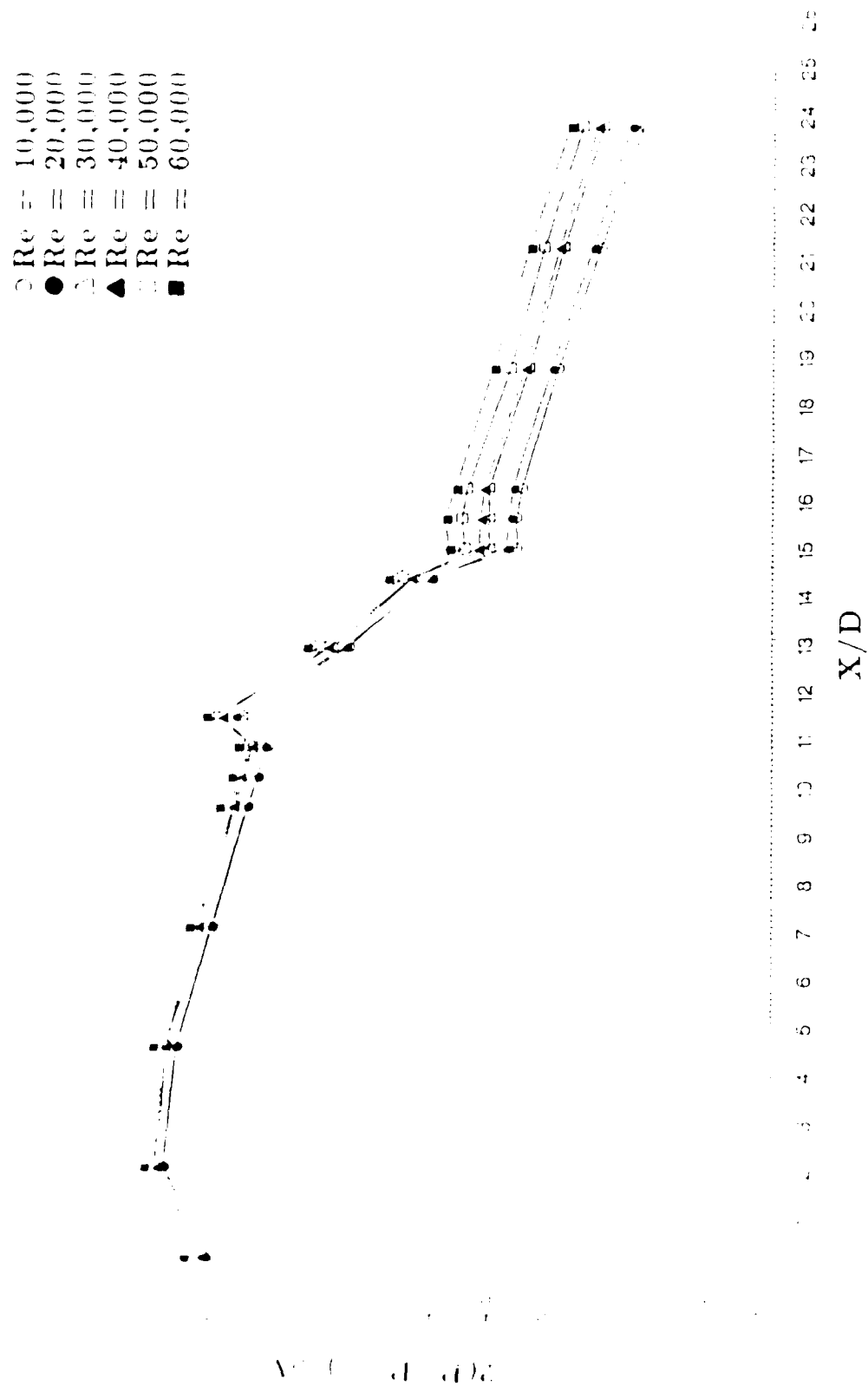


Fig. 28. Dimensionless pressure drop for rough channel  
with  $P/e=10$ ,  $e/D=0.063$ , and  $\alpha = 90^\circ$

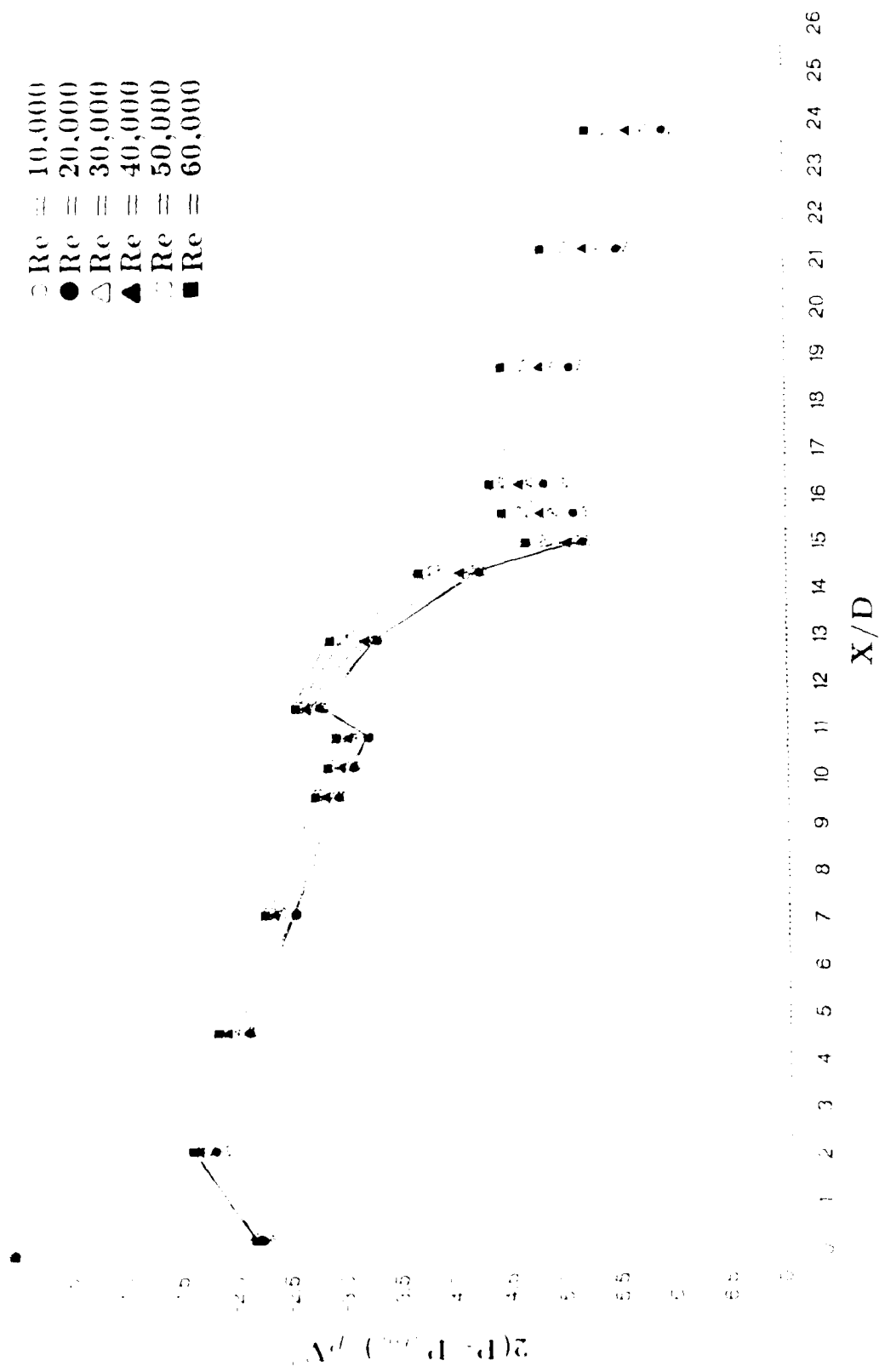


Fig. 29. Dimensionless pressure drop for rough channel  
with  $P/e=10$ ,  $e/D=0.063$ , and  $\alpha=60^\circ$ .

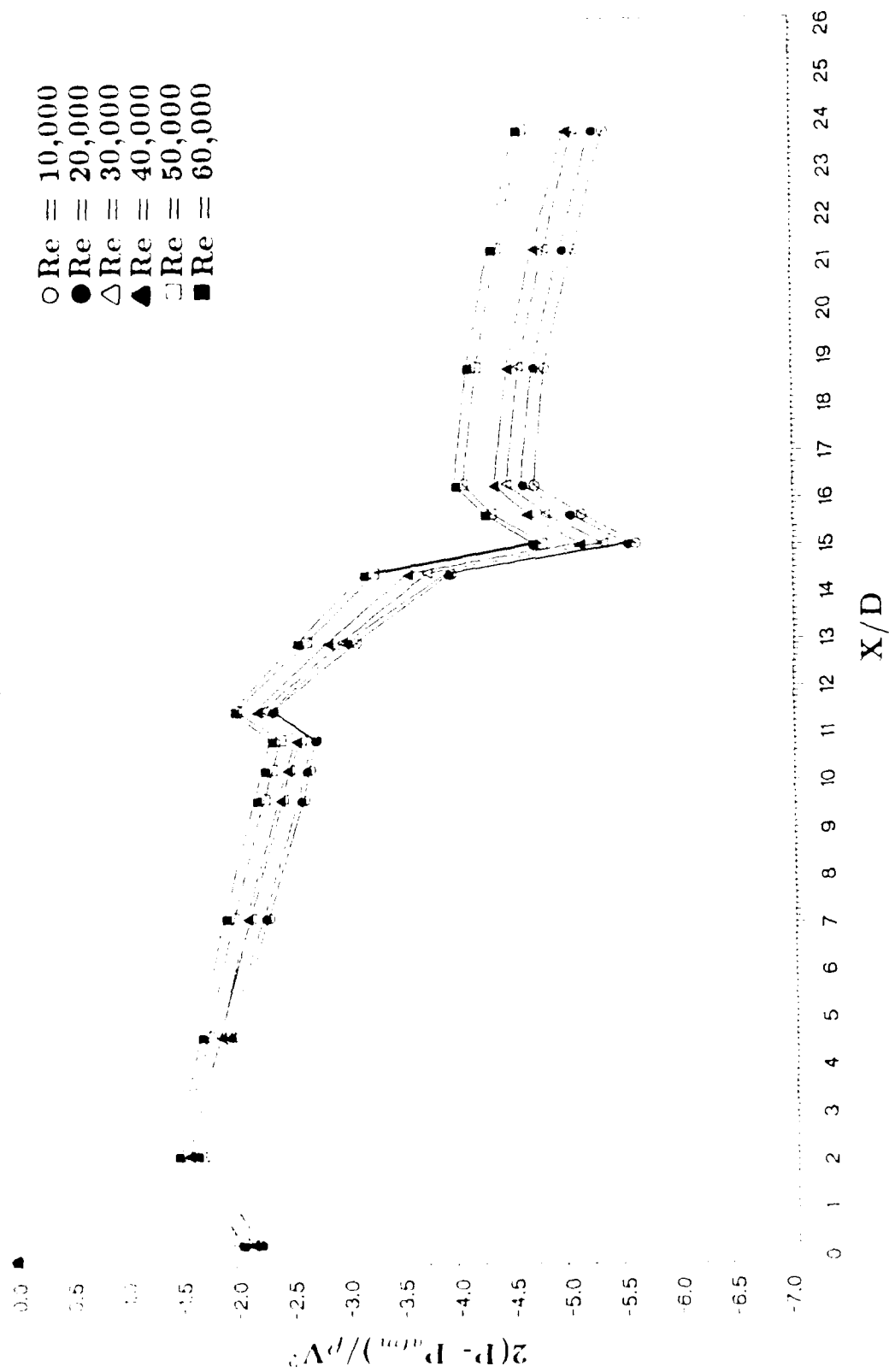


Fig. 30. Dimensionless pressure drop for rough channel  
with  $P/e=10$ ,  $e/D=0.063$ , and  $\alpha = 45^\circ$ .

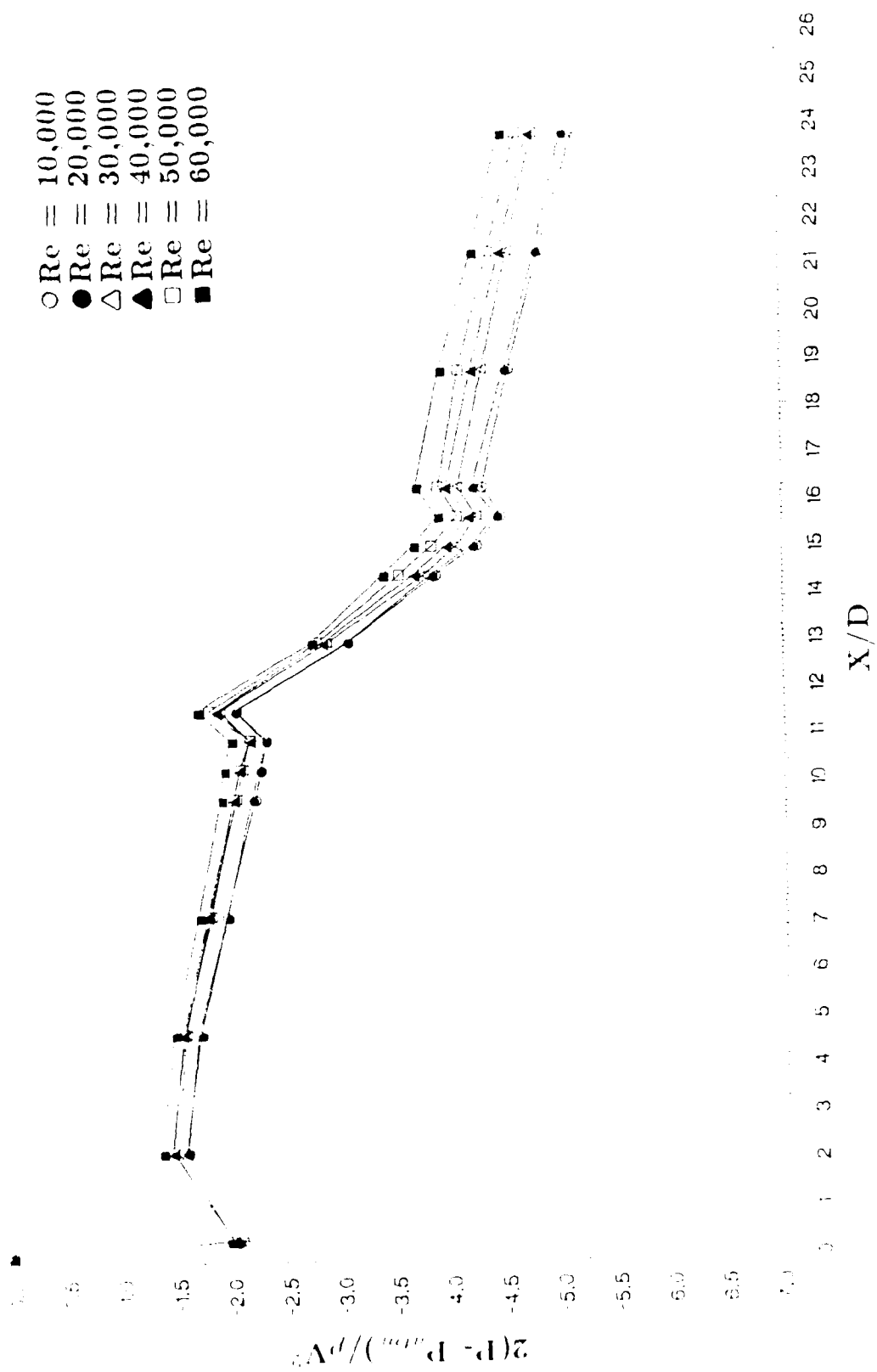


Fig. 31. Dimensionless pressure drop for rough channel  
with  $P/e=20$ ,  $e/D=0.063$ , and  $\alpha = 90^\circ$ .

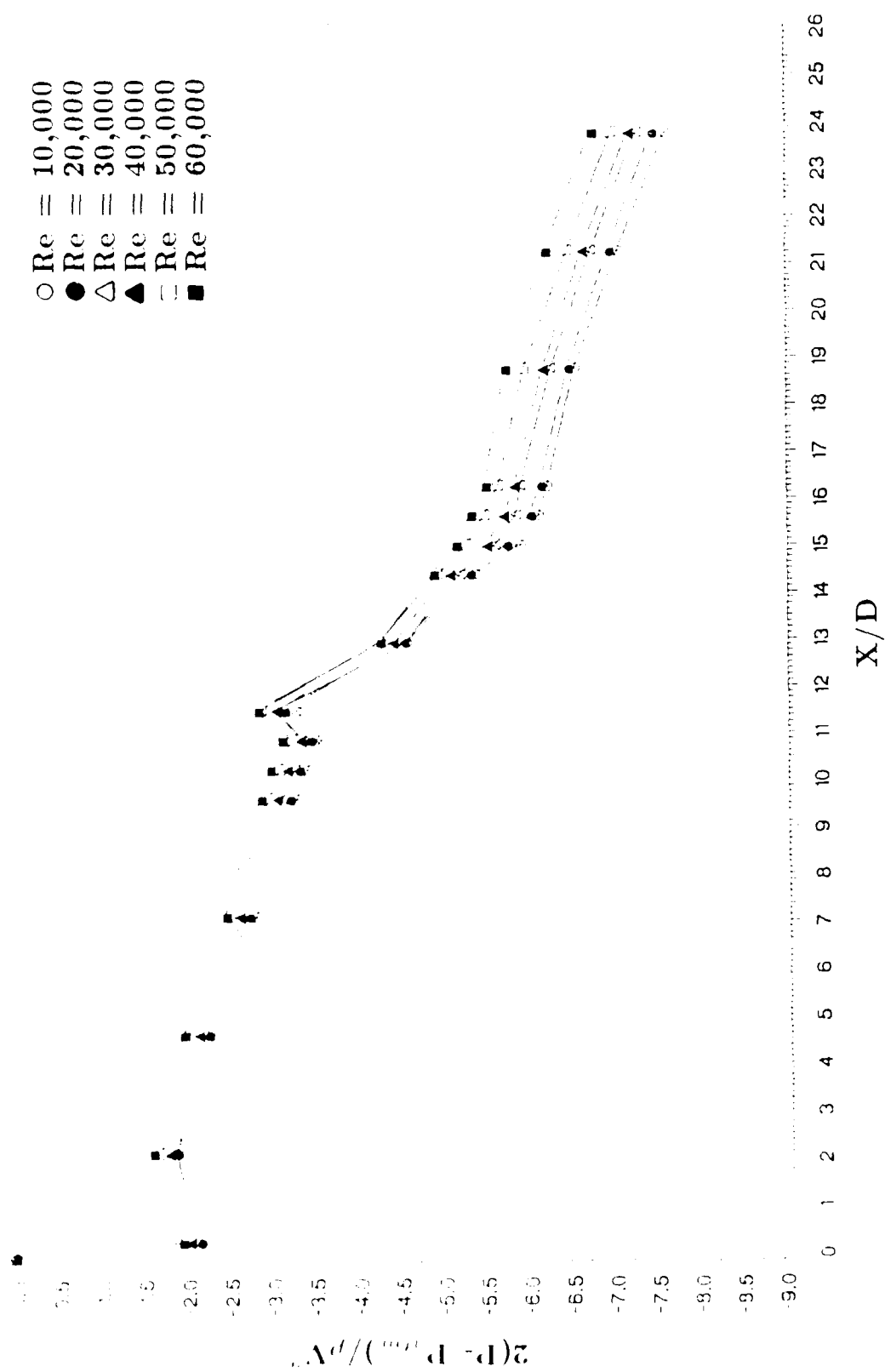


Fig. 32. Dimensionless pressure drop for rough channel  
with  $P/e=10$ ,  $e/D=0.094$ , and  $\alpha = 90^\circ$ .

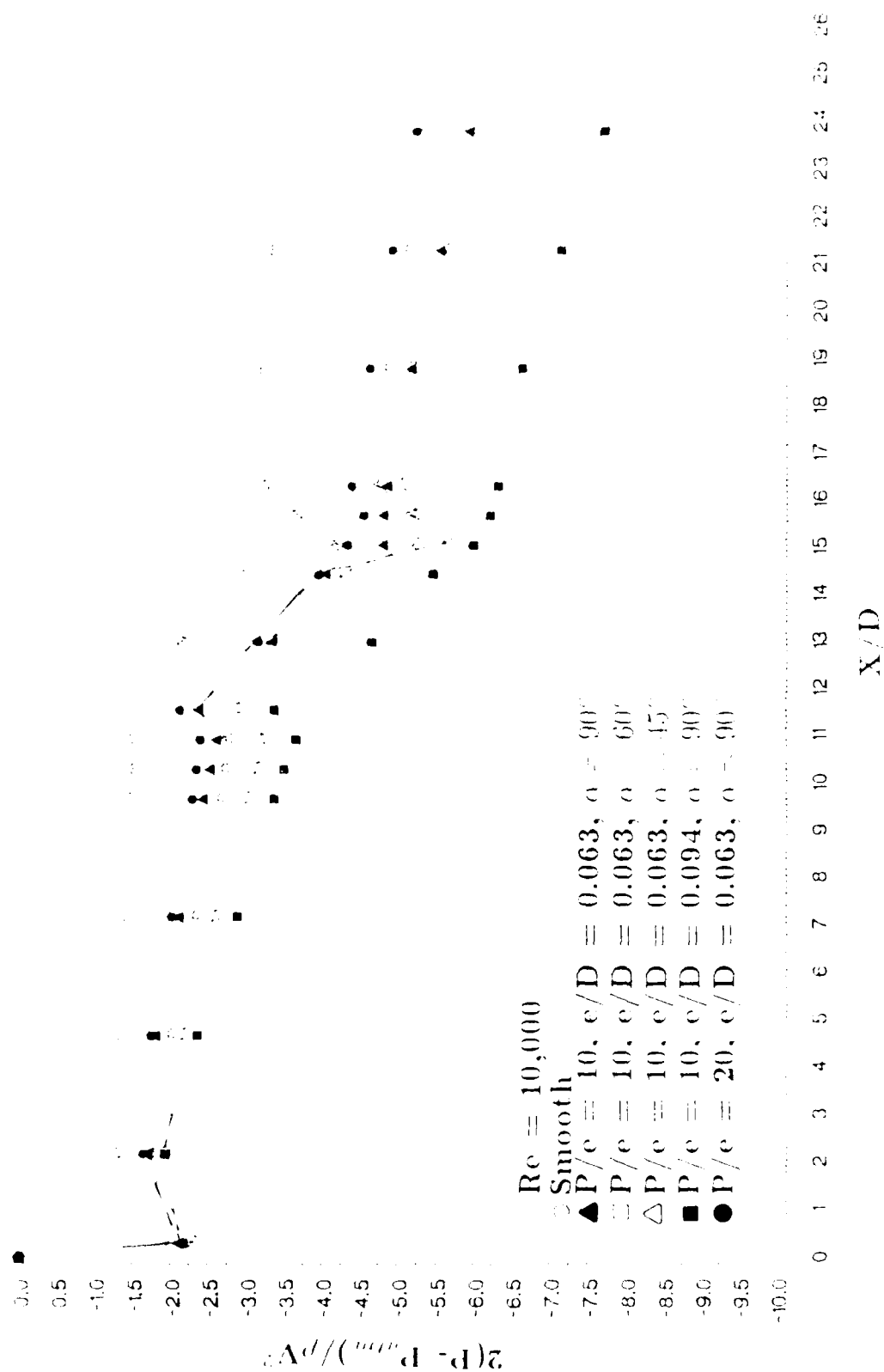


Fig. 33. Dimensionless pressure drop for rough channel  
with Re=10,000.

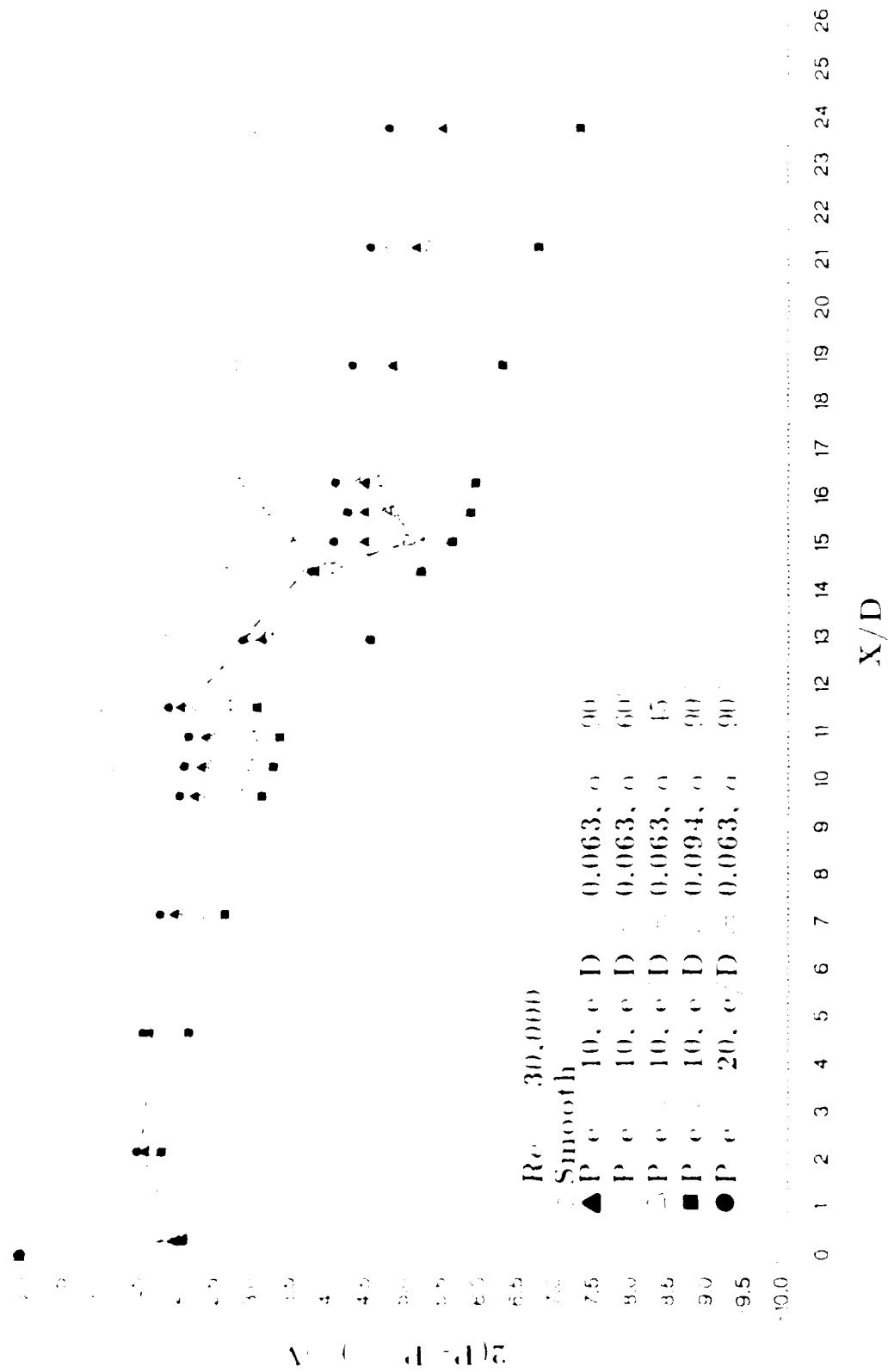
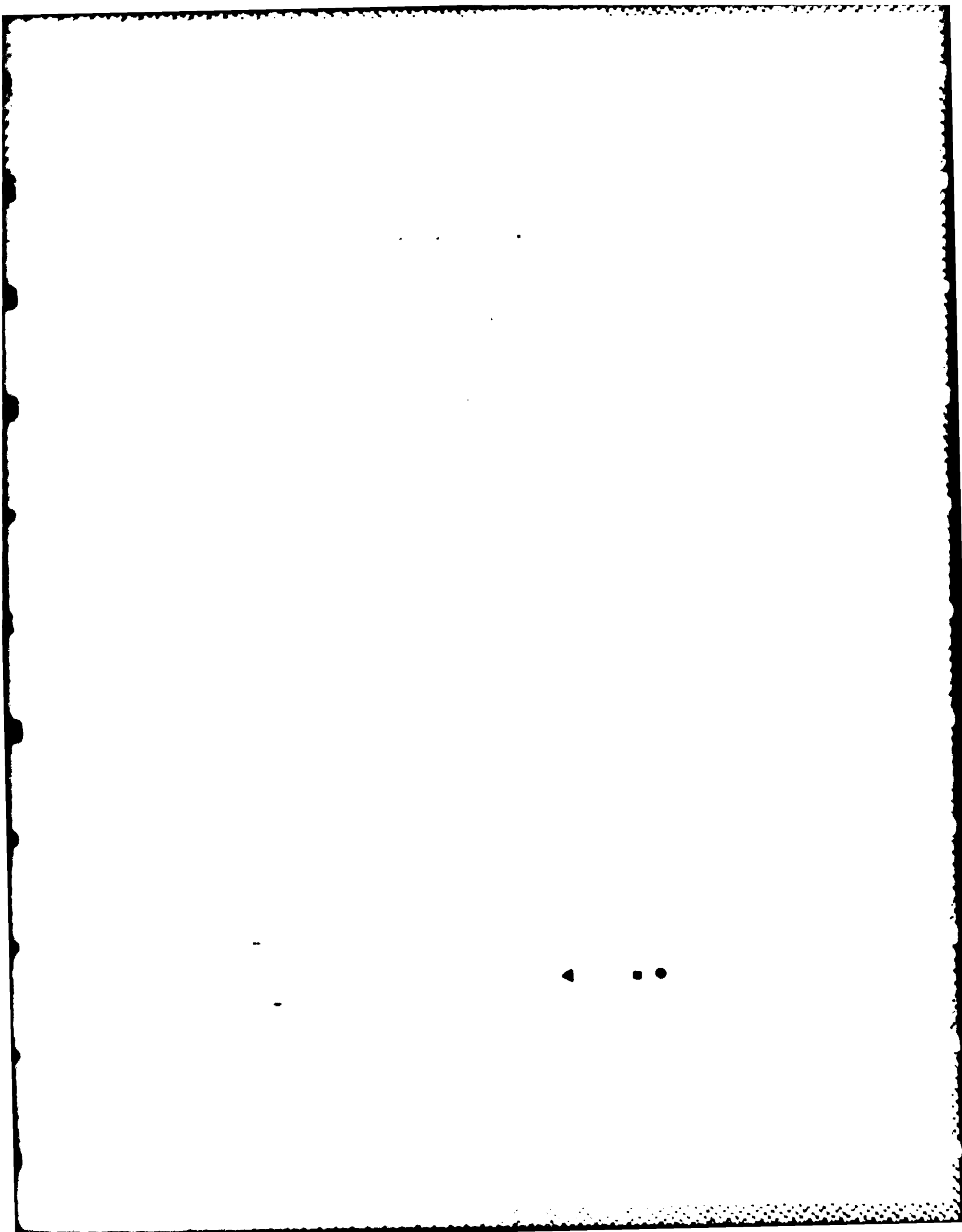


Fig. 34. Dimensionless pressure drop for rough channel  
with  $Re=30,000$ .





1.2

Blind to Equivalency



Re

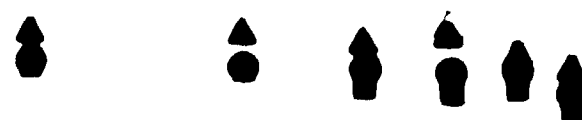
1. The following information is for informational purposes only and should not be used for any other purpose.



Blindfolded - 100% - 100% - 100%

Re-

|   |   |     |     |
|---|---|-----|-----|
| ● | 1 | 100 | 100 |
| △ | 1 | 100 | 100 |
| ▲ | 1 | 100 | 100 |
| ■ | 1 | 100 | 100 |



2

100

Re 10

the end of the calculation.

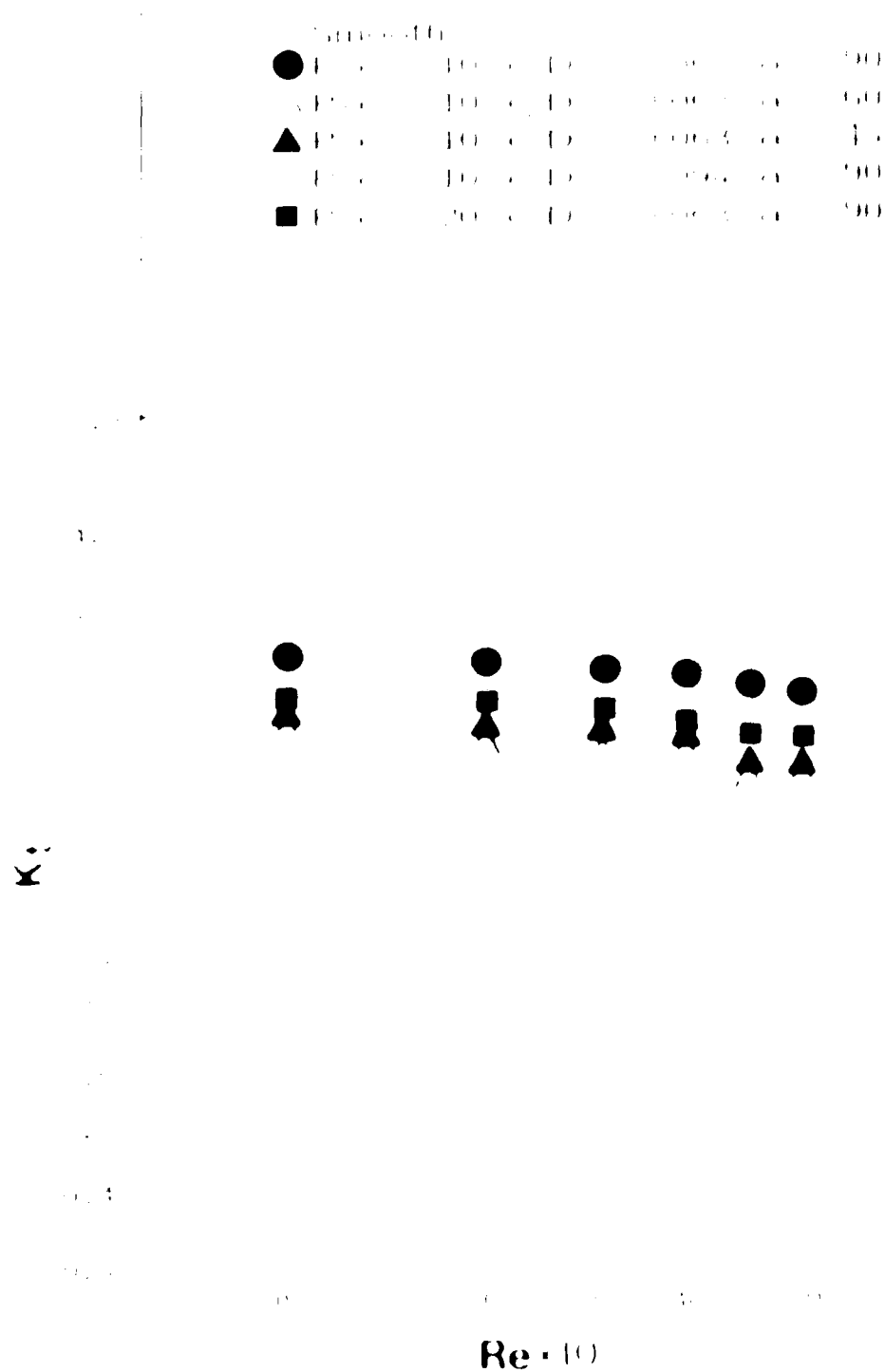
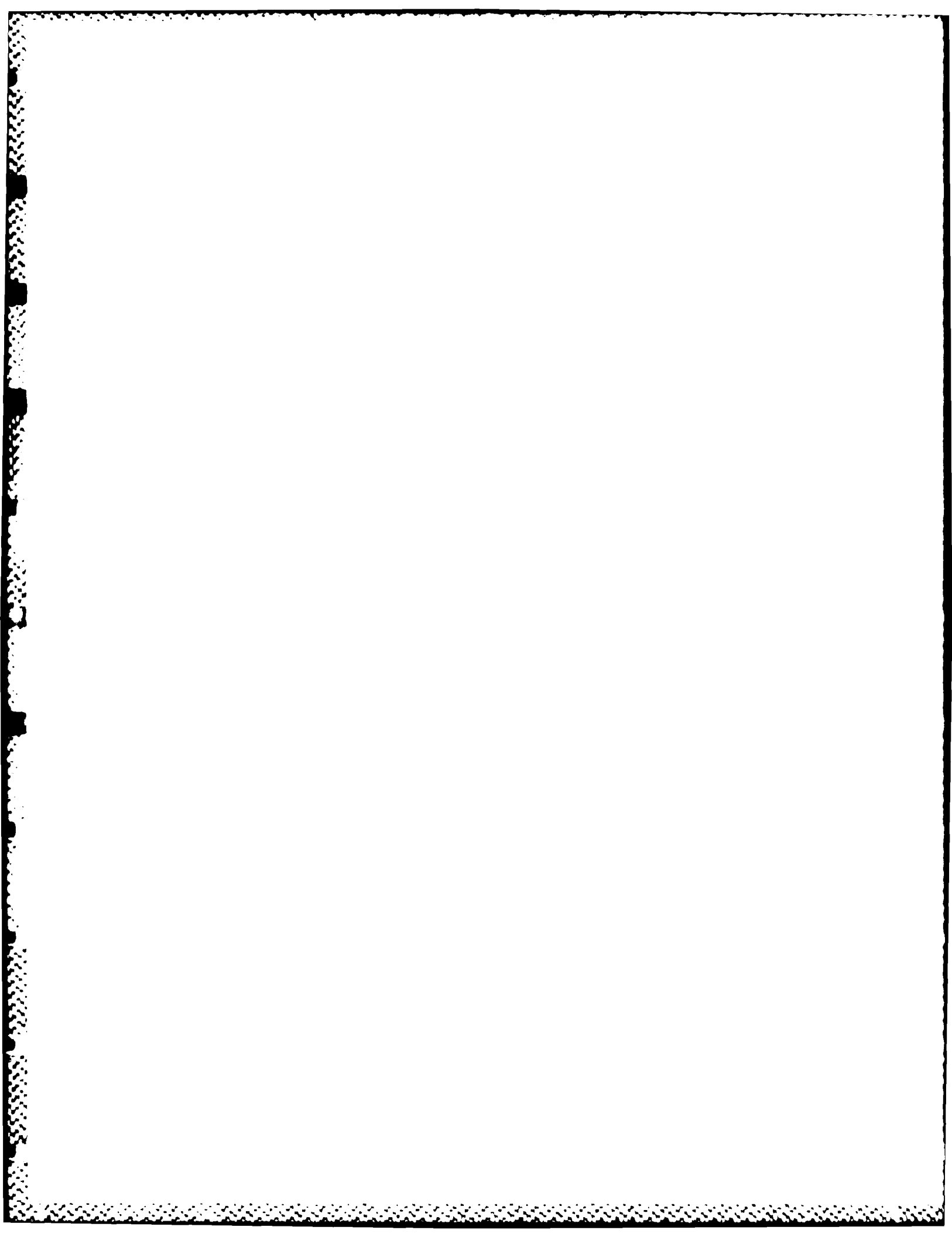


Fig. 5 Loss coefficient in the turn region



[illegible]

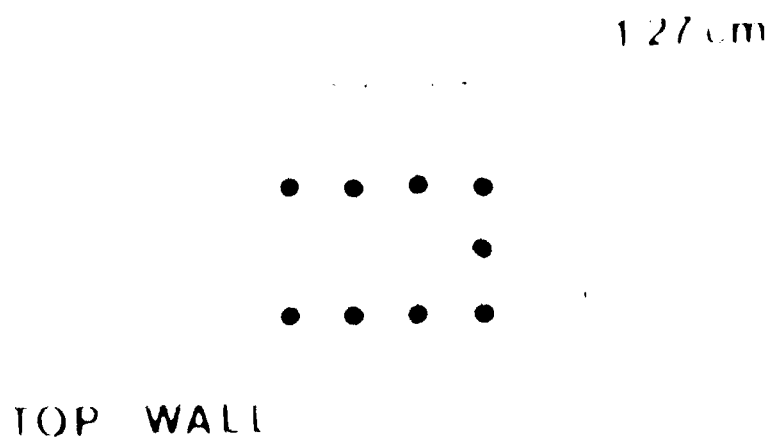
and  $\gamma = 1$  with respect to the base field  $\mathbb{F}_q$  in the graph theory.

where  $\beta_{\text{eff}} = \beta_{\text{eff}}(\mathbf{p}, \mathbf{p}_0)$  was kept open in the measurement table in

The tubalator, for  $\leq 4$  m, the depth was measured and recorded.

\_\_\_\_\_

the plates are separated by a distance of 1.27 cm. The plates are connected to a power source which can be set to any voltage from 0 to 1000 V. The plates are connected to a power source which can be set to any voltage from 0 to 1000 V. The plates are connected to a power source which can be set to any voltage from 0 to 1000 V.



The top wall is the upper plate of the capacitor. The bottom wall is the lower plate of the capacitor. The plates are connected to a power source which can be set to any voltage from 0 to 1000 V. The plates are connected to a power source which can be set to any voltage from 0 to 1000 V. The plates are connected to a power source which can be set to any voltage from 0 to 1000 V.

$$V_1 = V_2 = 1000 \text{ V} \quad \text{for } V_1 = 0$$

$$V_1 = 18 \text{ V} \quad \text{for } V_1 = 1000 \text{ V} \quad \text{for } V_1 = 10$$

Using these equations, depending on the time for which each plate is connected to the power source, the voltage across the capacitor can be calculated. The voltage across the capacitor can be calculated. The voltage across the capacitor can be calculated.

- before turn
- ▲ in turn
- after turn

Nature Curves of Loss

$$\Delta Z = 18 + 0.6 \Delta t \cdot 10000$$

$\Delta Z$  (mm)

$$\Delta Z = \Delta t - 10 \cdot 10000$$

$\Delta t$  min

$$T_{\text{eff}} = T_0 \left( 1 + \frac{\alpha}{2} \right) \quad \text{for } T_0 < T_c$$

## APPENDIX B

### HEAT-MASS TRANSFER DATA

|      |            |             |
|------|------------|-------------|
| T.W. | Top Wall   | after 1 day |
| O.W. | Outer Wall | after 1 day |
| I.W. | Inner Wall | after 1 day |

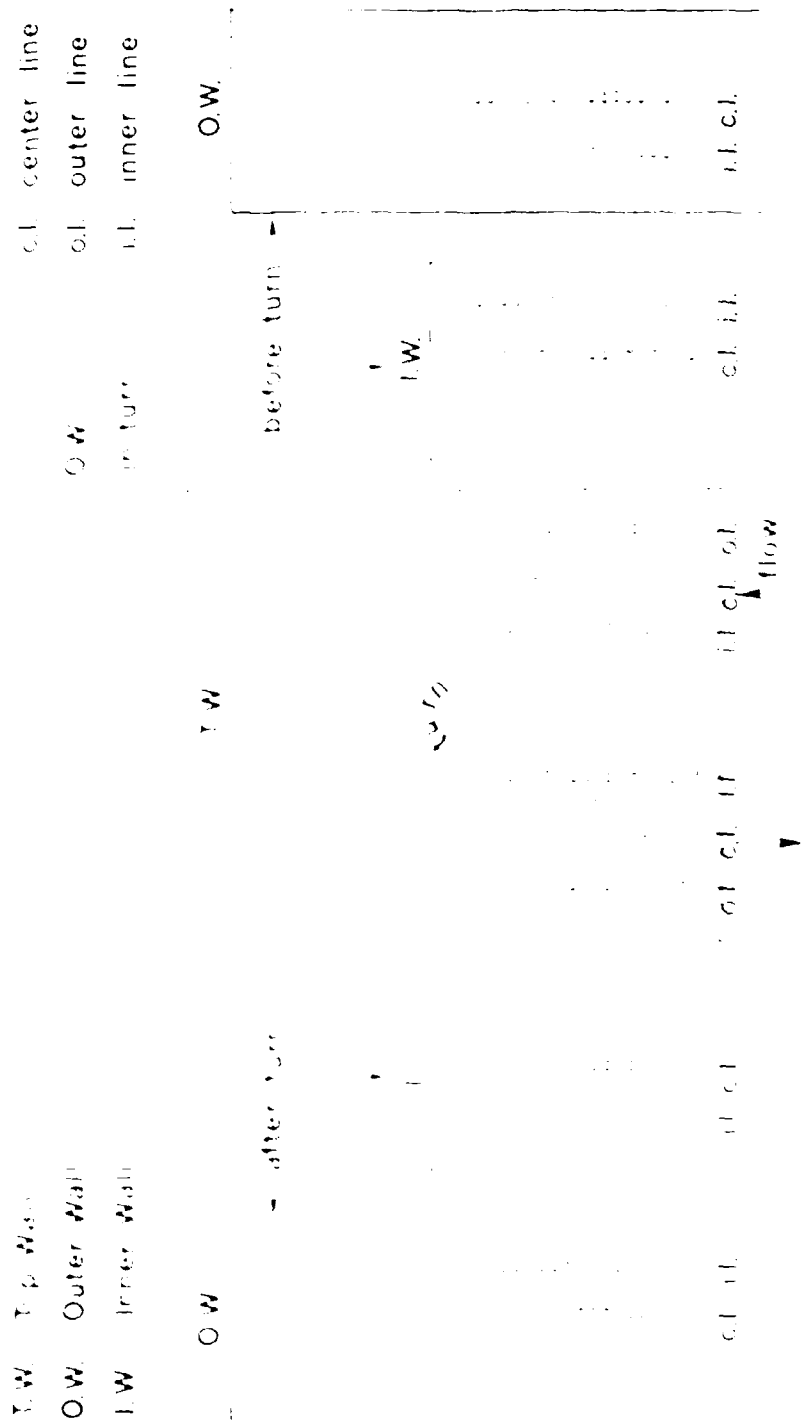
|      |      |
|------|------|
| O.W. | O.W. |
|------|------|

after 1 day

after 1 day

after 1 day

Sh Sh<sub>0</sub> for Re 30.000 Smooth Channel

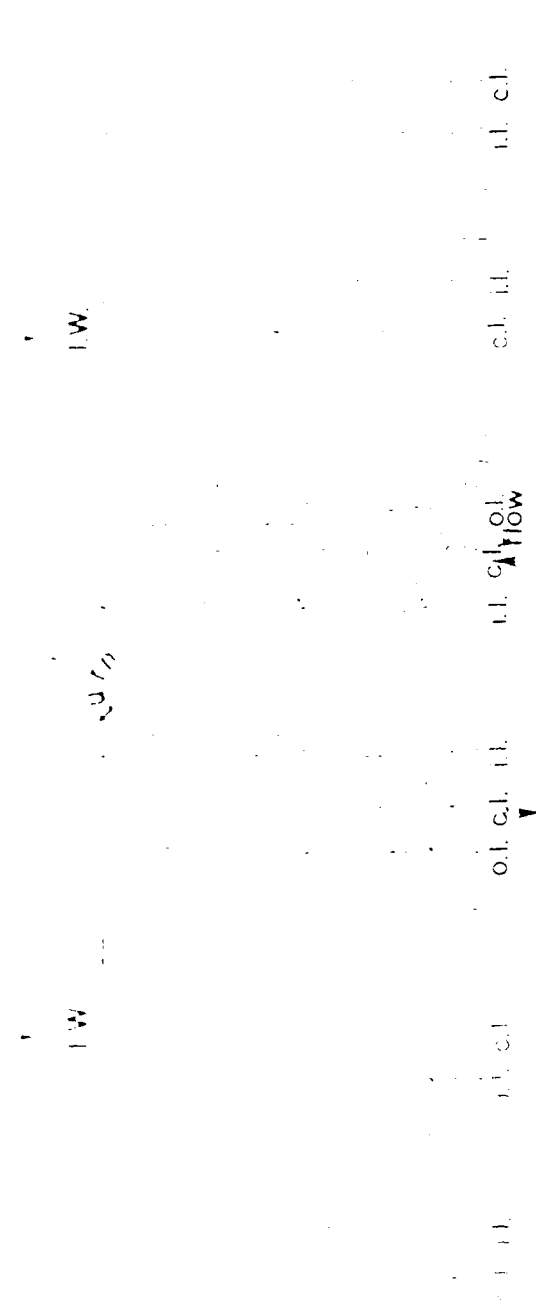


Sh/Sh<sub>0</sub> for Re = 60,000, P/e = 10, e/D = 0.063,  $\alpha = 90^\circ$

$\dot{Q}_w$  Top wall  
 $\dot{Q}_w$  Outer wall  
 $\dot{Q}_w$  Inner wall

$\dot{Q}_w$  ———— TW ———— OW

———— after turn ———— before turn



$Sh/Sh_0$  for  $Re=30,000$ ,  $P/e=10$ ,  $e/D=0.063$ ,  $\alpha=60^\circ$

NO-A191 003

LOCAL HEAT/MASS TRANSFER AND PRESSURE DROP IN A  
TWO-PASS RIB-ROUGHENED CH. (U) TEXAS A AND M UNIV  
COLLEGE STATION TURBOMACHINERY LABS J C HAN ET AL.

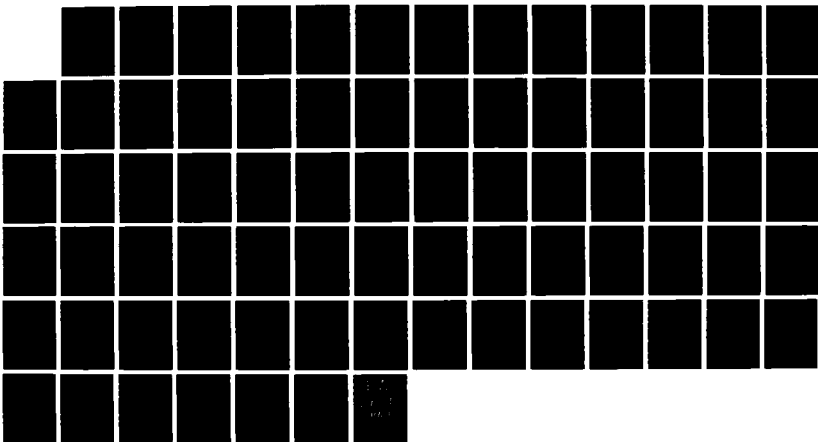
**2/2**

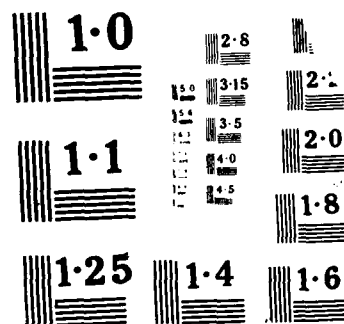
**UNCLASSIFIED**

SEP 87 NASA-CR-179635 NAS3-24227

F/G 13/1

NL





c.l.—center line  
o.l.—outer line  
i.l.—inner line

The drawing shows a cross-section of a ship's hull. At the top, there are three horizontal lines labeled 'Top Wall', 'Outer Wall', and 'Inner Wall'. Below these, there are several vertical dimensions. The main body of the hull is divided into sections labeled 'before turn' and 'after turn'. The 'before turn' section is on the left, and the 'after turn' section is on the right. The hull tapers towards the bottom. There are various structural lines and dimensions throughout the drawing, including a large 'X' shape in the center. The drawing is oriented vertically with the bow at the top.

**Sh/Sh<sub>0</sub> for Re=30000, P/e=10, e/D=0.063, α=45°**

Table 1 AVERAGE REGIONAL  $SH/SH_0$  RATIOS

| Re<br>$\times 10^{-3}$ | P/e | e/D   | $\alpha$ | TW1  | TW2  | TW3  | OW1  | OW2  | OW3  | OW4  | OW5  | IW1  | IW2  |
|------------------------|-----|-------|----------|------|------|------|------|------|------|------|------|------|------|
| 15                     | -   | -     | -        | 1.14 | 1.82 | 2.08 | 1.16 | 1.16 | 2.10 | 2.25 | 1.81 | 1.15 | 2.16 |
| 30                     | -   | -     | -        | 1.09 | 1.73 | 2.07 | 1.13 | 1.13 | 1.82 | 2.17 | 1.86 | 1.12 | 2.18 |
| 60                     | -   | -     | -        | 1.08 | 1.69 | 2.07 | 1.04 | 1.12 | 1.66 | 1.93 | 1.86 | 1.13 | 2.20 |
| 15                     | 10  | 0.063 | 90°      | 2.53 | 2.40 | 3.53 | 1.82 | 2.09 | 3.01 | 3.49 | 2.72 | 1.73 | 2.74 |
| 30                     | 10  | 0.063 | 90°      | 2.61 | 2.55 | 3.50 | 1.67 | 2.13 | 2.56 | 2.77 | 2.39 | 1.78 | 2.44 |
| 60                     | 10  | 0.063 | 90°      | 2.48 | 2.23 | 2.99 | 1.52 | 1.82 | 2.54 | 2.44 | 2.35 | 1.48 | 2.53 |
| 15                     | 10  | 0.063 | 60°      | 3.37 | 2.31 | 2.91 | 2.37 | 2.27 | 3.11 | 2.63 | 2.10 | 2.05 | 3.00 |
| 30                     | 10  | 0.063 | 60°      | 3.29 | 2.17 | 2.75 | 2.24 | 2.12 | 2.37 | 2.57 | 2.15 | 2.25 | 2.76 |
| 60                     | 10  | 0.063 | 60°      | 3.03 | 1.92 | 2.80 | 2.00 | 2.03 | 2.35 | 2.43 | 2.33 | 2.05 | 2.46 |
| 15                     | 10  | 0.063 | 45°      | 3.07 | 2.80 | 2.93 | 2.00 | 2.28 | 1.96 | 3.60 | 2.39 | 2.35 | 2.93 |
| 30                     | 10  | 0.063 | 45°      | 2.86 | 2.63 | 3.14 | 2.03 | 2.12 | 2.10 | 2.86 | 2.25 | 1.98 | 2.61 |
| 60                     | 10  | 0.063 | 45°      | 2.29 | 1.87 | 2.62 | 1.91 | 1.69 | 2.00 | 2.35 | 2.33 | 2.03 | 2.80 |
| 30                     | 20  | 0.063 | 90°      | 2.12 | 2.06 | 2.49 | 1.55 | 1.62 | 2.05 | 1.29 | 1.94 | 1.61 | 2.21 |
| 30                     | 10  | 0.094 | 90°      | 2.85 | 2.80 | 3.50 | 2.20 | 2.29 | 2.88 | 3.31 | 2.80 | 2.20 | 3.20 |

Re : REYNOLDS NUMBER

P/e : PITCH-TO-RIB HEIGHT RATIO

e/D : RIB HEIGHT-TO-HYDRAULIC DIAMETER RATIO

 $\alpha$  : RIB ANGLE-OF-ATTACK

## REGIONS

TW1 : TOP WALL BEFORE TURN (X/D=9.0 to 12.0)

TW2 : TOP WALL IN-TURN (X/D=12.0 to 14.0)

TW3 : TOP WALL AFTER TURN (X/D=14.0 to 17.0)

OW1 : OUTER WALL BEFORE TURN (X/D=9.0 to 12.0)

OW2 : OUTER WALL IN-TURN (X/D=12.0 to 12.5)

OW3 : OUTER WALL IN-TURN (X/D=12.5 to 13.5)

OW4 : OUTER WALL IN-TURN (X/D=13.5 to 14.0)

OW5 : OUTER WALL AFTER TURN (X/D=14.0 to 17.0)

IW1 : INNER WALL BEFORE TURN (X/D=9.0 to 12.0)

IW2 : INNER WALL AFTER TURN (X/D=14.0 to 17.0)

Smooth Channel:  $Re = 15,000$

$Sh/Sh_0$

TOP WALL

| X/D    | O.L.   | C.L.   | I.L.  |
|--------|--------|--------|-------|
|        | BEFORE | TURN   |       |
| 8.313  | 1.014  | 1.014  | 1.023 |
| 8.938  | 1.033  | 0.9846 | 1.030 |
| 9.563  | 1.054  | 1.006  | 1.073 |
| 10.125 | 1.178  | 1.030  | 1.057 |
| 10.375 | 1.140  | 1.159  | 1.239 |
| 10.625 | 1.042  | 1.069  | 1.133 |
| 10.875 | 1.186  | 1.212  | 1.187 |
| 11.125 | 1.306  | 1.213  | 1.202 |
| 11.375 | 1.366  | 1.295  | 1.098 |
| 11.625 | 1.523  | 1.318  | 1.106 |
|        | IN     | TURN   |       |
| 11.875 | 1.900  | 1.562  | 1.477 |
| 12.375 | 1.407  | 1.787  | 1.853 |
| 12.875 | 1.738  | 1.836  | 1.834 |
| 13.125 | 1.985  | 1.612  | 1.500 |
| 13.625 | 2.014  | 2.130  | 1.565 |
| 14.125 | 2.132  | 2.031  | 1.796 |
|        | AFTER  | TURN   |       |
| 14.375 | 2.260  | 2.025  | 2.080 |
| 14.625 | 2.301  | 1.982  | 2.442 |
| 14.875 | 2.244  | 1.789  | 2.483 |
| 15.125 | 2.300  | 1.716  | 2.465 |
| 15.375 | 2.356  | 1.763  | 2.408 |
| 15.625 | 2.201  | 1.772  | 2.398 |
| 15.875 | 2.106  | 1.805  | 2.349 |
| 16.438 | 2.166  | 2.114  | 2.193 |
| 17.063 | 1.976  | 1.947  | 1.840 |
| 17.688 | 1.672  | 1.673  | 1.644 |

| -----       |            |       |            |       |
|-------------|------------|-------|------------|-------|
|             | OUTER WALL | AND   | INNER WALL |       |
| -----       |            |       |            |       |
| X/D         | I.L.       | O.L.  | I.L.       | O.L.  |
| -----       |            |       |            |       |
| BEFORE TURN |            |       |            |       |
| -----       |            |       |            |       |
|             | OUTER      | WALL  | INNER      | WALL  |
| -----       |            |       |            |       |
| 8.313       | 1.186      | 1.105 | 0.983      | 0.946 |
| 8.938       | 1.256      | 1.204 | 1.087      | 1.021 |
| 9.563       | 1.233      | 1.104 | 1.218      | 1.182 |
| 10.125      | 1.213      | 1.057 | 1.061      | 0.989 |
| 10.375      | 1.327      | 1.089 | 1.147      | 1.045 |
| 10.625      | 1.310      | 1.073 | 1.195      | 1.109 |
| 10.875      | 1.197      | 1.050 | 1.251      | 1.172 |
| 11.125      | 1.100      | 1.021 | 1.278      | 1.235 |
| 11.375      | 1.165      | 1.060 | 1.455      | 1.326 |
| 11.625      | 1.311      | 1.044 |            |       |
| -----       |            |       |            |       |
| IN TURN     |            |       |            |       |
| -----       |            |       |            |       |
| 11.875      | 1.365      | 1.047 |            |       |
| 12.375      | 1.548      | 1.450 |            |       |
| 12.875      | 2.116      | 1.983 |            |       |
| 13.125      | 1.960      | 2.113 |            |       |
| 13.625      | 2.041      | 2.240 |            |       |
| 14.125      | 2.123      | 2.598 |            |       |
| -----       |            |       |            |       |
| AFTER TURN  |            |       |            |       |
| -----       |            |       |            |       |
| 14.375      | 2.058      | 2.505 |            |       |
| 14.625      | 1.752      | 2.380 | 1.457      | 1.586 |
| 14.875      | 1.474      | 2.194 | 1.725      | 1.837 |
| 15.125      | 1.285      | 2.083 | 2.281      | 2.100 |
| 15.375      | 1.268      | 1.956 | 2.584      | 2.397 |
| 15.625      | 1.502      | 1.911 | 2.867      | 2.618 |
| 15.875      | 1.860      | 1.852 | 2.847      | 2.697 |
| 16.438      | 1.810      | 1.861 | 2.326      | 2.138 |
| 17.063      | 1.607      | 1.650 | 2.110      | 1.843 |
| 17.688      | 1.540      | 1.631 | 1.787      | 1.651 |

Smooth Channel:  $Re = 30,000$

$Sh/Sh_0$

TOP WALL

| $X/T$  | O.L.   | C.L.  | I.L.  |
|--------|--------|-------|-------|
|        | BEFORE | TURN  |       |
| 1.125  | 2.559  | 2.731 | 2.819 |
| 2.125  | 1.523  | 1.499 | 1.647 |
| 3.125  | 1.357  | 1.328 | 1.429 |
| 4.125  | 1.234  | 1.251 | 1.259 |
| 5.125  | 1.203  | 1.193 | 1.156 |
| 6.125  | 1.222  | 1.158 | 1.080 |
| 7.125  | 1.171  | 1.070 | 1.121 |
| 8.125  | 1.122  | 1.012 | 1.063 |
| 9.125  | 1.081  | 1.008 | 1.044 |
| 10.125 | 1.116  | 1.049 | 1.099 |
| 10.375 | 1.058  | 1.095 | 1.183 |
| 10.625 | 1.007  | 1.009 | 1.132 |
| 10.875 | 1.025  | 1.014 | 1.093 |
| 11.125 | 1.068  | 1.015 | 1.068 |
| 11.375 | 1.107  | 1.122 | 1.103 |
| 11.625 | 1.319  | 1.186 | 1.124 |
|        | IN     | TURN  |       |
| 11.875 | 1.521  | 1.368 | 1.333 |
| 12.375 | 1.104  | 1.548 | 1.549 |
| 12.875 | 1.891  | 1.911 | 1.681 |
| 13.125 | 1.911  | 1.797 | 1.609 |
| 13.625 | 2.043  | 2.110 | 1.471 |
| 14.125 | 2.196  | 1.800 | 1.810 |

|        | ----- |       |       |
|--------|-------|-------|-------|
|        | AFTER | TURN  |       |
|        | ----- |       |       |
| 14.375 | 2.287 | 1.840 | 2.108 |
| 14.625 | 2.267 | 1.951 | 2.403 |
| 14.875 | 2.120 | 1.803 | 2.479 |
| 15.125 | 2.150 | 1.670 | 2.550 |
| 15.375 | 2.108 | 1.954 | 2.539 |
| 15.625 | 2.117 | 2.008 | 2.495 |
| 15.875 | 2.015 | 2.074 | 2.387 |
| 16.875 | 1.765 | 1.864 | 1.775 |
| 17.875 | 1.675 | 1.642 | 1.463 |
| 18.875 | 1.523 | 1.387 | 1.282 |
| 19.875 | 1.337 | 1.220 | 1.158 |
| 20.875 | 1.187 | 1.174 | 1.075 |
| 21.875 | 1.070 | 1.062 | 1.018 |
| 22.875 | 1.045 | 1.055 | 1.010 |
| 23.875 | 1.019 | 1.052 | 1.012 |
| 24.875 | 1.431 | 1.380 | 1.634 |

| -----      |       |        |            |       |
|------------|-------|--------|------------|-------|
| OUTER WALL |       | AND    | INNER WALL |       |
| -----      |       |        |            |       |
| X/D        | I.L.  | C.L.   | I.L.       | C.L.  |
| -----      |       |        |            |       |
|            |       | BEFORE | TURN       |       |
| -----      |       |        |            |       |
|            | OUTER | WALL   | INNER      | WALL  |
| -----      |       |        |            |       |
| 1.125      | 2.333 | 2.289  | 2.490      | 2.056 |
| 2.125      | 1.900 | 1.700  | 1.840      | 1.655 |
| 3.125      | 1.600 | 1.500  | 1.548      | 1.442 |
| 4.125      | 1.410 | 1.300  | 1.387      | 1.264 |
| 5.125      | 1.326 | 1.260  | 1.201      | 1.256 |
| 6.125      | 1.150 | 1.206  | 1.202      | 1.103 |
| 7.125      | 1.136 | 1.145  | 1.217      | 1.077 |
| 8.125      | 1.150 | 1.097  | 1.060      | 1.064 |
| 9.125      | 1.173 | 1.125  | 1.055      | 1.072 |
| 10.125     | 1.213 | 1.113  | 1.130      | 1.106 |
| 10.375     | 1.238 | 1.064  | 1.107      | 1.084 |
| 10.625     | 1.252 | 1.045  | 1.117      | 1.064 |
| 10.875     | 1.136 | 1.045  | 1.183      | 1.061 |
| 11.125     | 1.158 | 1.008  | 1.176      | 1.089 |
| 11.375     | 1.128 | 1.049  | 1.207      | 1.154 |
| 11.625     | 1.261 | 1.071  | 1.281      | 1.228 |
| -----      |       |        |            |       |
|            |       | IN     | TURN       |       |
| -----      |       |        |            |       |
| 11.875     | 1.297 | 1.108  |            |       |
| 12.375     | 1.375 | 1.308  |            |       |
| 12.875     | 1.970 | 1.855  |            |       |
| 13.125     | 1.700 | 1.883  |            |       |
| 13.625     | 1.810 | 1.878  |            |       |
| 14.125     | 1.984 | 2.472  |            |       |

# APPROXIMATE

|        |        |        |       |       |
|--------|--------|--------|-------|-------|
| 14.875 | 1.700  | 1.700  | 1.700 | 1.700 |
| 14.625 | 1.731  | 1.700  | 1.770 | 1.718 |
| 14.875 | 1.700  | 1.700  | 1.700 | 2.107 |
| 15.125 | 1.487  | 1.911  | 2.548 | 2.403 |
| 15.875 | 1.630  | 1.811  | 2.747 | 2.874 |
| 15.625 | 1.863  | 1.800  | 2.684 | 2.596 |
| 15.875 | 2.123  | 1.151  | 2.620 | 2.592 |
| 16.875 | 1.784  | 1.923  | 2.028 | 1.983 |
| 17.875 | 1.578  | 1.630  | 1.823 | 1.778 |
| 18.875 | 1.496  | 1.597  | 1.455 | 1.517 |
| 19.875 | 1.408  | 1.436  | 1.281 | 1.208 |
| 20.875 | 1.345  | 1.424  | 1.080 | 1.135 |
| 21.875 | 1.176  | 1.232  | 1.170 | 1.174 |
| 22.875 | 0.9526 | 0.9493 | 1.167 | 1.245 |
| 23.875 | 1.066  | 1.188  | 1.499 | 1.643 |
| 24.875 |        |        | 1.465 | 1.259 |

Smooth Channel:  $Re = 60,000$

$Sh/Sh_0$

TOP WALL

| E/D    | O.L.   | C.L.   | I.L.   |
|--------|--------|--------|--------|
|        | BEFORE | TURN   |        |
| 8.125  | 1.174  | 1.191  | 1.179  |
| 9.125  | 1.061  | 1.061  | 1.075  |
| 10.125 | 1.105  | 1.035  | 1.051  |
| 10.375 | 1.100  | 1.027  | 1.081  |
| 10.625 | 1.074  | 1.014  | 1.063  |
| 10.875 | 1.027  | 1.013  | 1.037  |
| 11.125 | 1.001  | 1.050  | 1.012  |
|        | IN     | TURN   |        |
| 11.375 | 0.9806 | 0.9919 | 0.9865 |
| 11.625 | 1.147  | 1.117  | 1.115  |
| 11.875 | 1.315  | 1.350  | 1.377  |
| 12.375 | 1.106  | 1.482  | 1.492  |
| 12.875 | 1.882  | 1.688  | 1.562  |
| 13.125 | 1.933  | 1.735  | 1.535  |
| 13.625 | 2.122  | 1.958  | 1.518  |
| 14.125 | 2.076  | 1.825  | 1.549  |
|        | AFTER  | TURN   |        |
| 14.375 | 1.540  | 1.462  | 1.779  |
| 14.625 | 1.426  | 1.602  | 1.947  |
| 14.875 | 1.471  | 1.706  | 2.239  |
| 15.125 | 1.688  | 1.916  | 2.558  |
| 15.375 | 1.994  | 2.207  | 2.755  |
| 15.625 | 2.259  | 2.425  | 2.754  |
| 15.875 | 2.472  | 2.583  | 2.649  |
| 16.875 | 2.261  | 2.265  | 2.076  |
| 17.875 | 1.845  | 1.924  | 1.887  |

|        | OUTER WALL  | AND   | INNER WALL |       |
|--------|-------------|-------|------------|-------|
| X/D    | I.L.        | C.L.  | I.L.       | C.L.  |
|        | BEFORE TURN |       |            |       |
|        | OUTER WALL  |       | INNER WALL |       |
| 8.125  | 1.150       | 1.200 | 1.102      | 1.130 |
| 9.125  | 1.095       | 1.100 | 1.065      | 1.061 |
| 10.125 | 1.130       | 1.127 | 1.127      | 1.101 |
| 10.375 | 1.169       | 1.139 | 1.071      | 1.065 |
| 10.625 | 1.094       | 1.004 | 1.058      | 1.035 |
| 10.875 | 1.068       | 0.964 | 1.076      | 1.046 |
| 11.125 | 1.032       | 0.900 | 1.084      | 1.041 |
| 11.375 | 0.930       | 0.851 | 1.285      | 1.276 |
| 11.625 | 0.983       | 0.830 | 1.367      | 1.338 |
|        | IN TURN     |       |            |       |
| 11.875 | 1.082       | 0.970 |            |       |
| 12.375 | 1.447       | 1.274 |            |       |
| 12.875 | 1.690       | 1.745 |            |       |
| 13.125 | 1.683       | 1.659 |            |       |
| 13.625 | 1.765       | 1.784 |            |       |
| 14.125 | 1.645       | 2.223 |            |       |
|        | AFTER TURN  |       |            |       |
| 14.375 | 1.390       | 1.828 | 1.708      | 1.842 |
| 14.625 | 1.384       | 1.831 | 2.027      | 1.964 |
| 14.875 | 1.275       | 1.737 | 2.319      | 2.275 |
| 15.125 | 1.551       | 1.921 | 2.527      | 2.417 |
| 15.375 | 1.960       | 2.212 | 2.703      | 2.471 |
| 15.625 | 2.052       | 2.407 | 2.560      | 2.475 |
| 15.875 | 2.180       | 2.498 | 2.471      | 2.524 |
| 16.875 | 1.788       | 2.007 | 1.969      | 1.966 |
| 17.875 | 1.652       | 1.824 | 1.670      | 1.656 |

Rough Channel:  $Re=15,000$ ,  $P/e=10$ ,  $e/D=0.063$ ,  $\alpha=90^\circ$

# $Sh/Sh_0$

|        | TOP    |       | WALL  |  |
|--------|--------|-------|-------|--|
|        | C.L.   |       | C.L.  |  |
|        | BEFORE |       | TURN  |  |
| 8.313  | 3.322  | 2.635 | 2.625 |  |
| 8.935  | 3.131  | 3.045 | 2.856 |  |
| 9.563  | 2.686  | 2.520 | 2.361 |  |
| 9.938  | 2.165  | 1.656 | 2.300 |  |
| 10.000 | 3.355  | 2.802 | 2.820 |  |
| 10.063 | 3.620  | 3.200 | 3.143 |  |
| 10.125 | 3.261  | 2.674 | 2.794 |  |
| 10.188 | 3.067  | 2.593 | 2.414 |  |
| 10.250 | 2.611  | 2.170 | 2.166 |  |
| 10.313 | 2.483  | 1.956 | 1.942 |  |
| 10.375 | 2.498  | 1.906 | 1.849 |  |
| 10.438 | RIB    | RIB   | RIB   |  |
| 10.500 | RIB    | RIB   | RIB   |  |
| 10.563 | 2.470  | 2.325 | 2.571 |  |
| 10.625 | 3.374  | 2.926 | 2.878 |  |
| 10.688 | 3.691  | 3.156 | 3.521 |  |
| 10.750 | 3.206  | 2.601 | 2.354 |  |
| 10.813 | 3.013  | 2.588 | 2.357 |  |
| 10.875 | 2.703  | 2.146 | 2.134 |  |
| 10.938 | 2.522  | 1.969 | 1.922 |  |
| 11.000 | 2.300  | 1.747 | 1.732 |  |
| 11.063 | RIB    | RIB   | RIB   |  |
| 11.125 | RIB    | RIB   | RIB   |  |
| 11.188 | 2.497  | 1.967 | 1.609 |  |
| 11.250 | 3.660  | 2.797 | 2.461 |  |
| 11.313 | 3.694  | 3.037 | 2.829 |  |
| 11.375 | 3.097  | 2.547 | 2.394 |  |
| 11.438 | 2.832  | 2.411 | 2.220 |  |
| 11.500 | 2.237  | 1.881 | 1.856 |  |
| 11.563 | 1.612  | 1.693 | 1.647 |  |
| 11.625 | 2.649  | 1.528 | 1.471 |  |

| IN TURN    |       |       |       |
|------------|-------|-------|-------|
| 11.875     | 3.721 | 3.125 | 2.250 |
| 12.375     | 1.874 | 2.303 | 2.175 |
| 12.875     | 1.692 | 2.373 | 1.488 |
| 13.125     | 2.181 | 2.015 | 1.500 |
| 13.625     | 1.135 | 2.157 | 1.500 |
| 14.125     | 2.134 | 1.537 | 1.175 |
| AFTER TURN |       |       |       |
| 14.375     | 2.282 | 1.523 | 1.347 |
| 14.438     | 6.306 | 2.345 | 1.710 |
| 14.500     | 6.383 | 2.619 | 2.271 |
| 14.563     | 6.161 | 3.301 | 2.449 |
| 14.625     | 4.536 | 3.427 | 2.585 |
| 14.688     | 4.353 | 3.628 | 2.936 |
| 14.750     | 2.592 | 3.401 | 2.439 |
| 14.813     | 3.426 | 3.591 | 2.446 |
| 14.875     | RIB   | RIB   | RIB   |
| 14.938     | RIB   | RIB   | RIB   |
| 15.000     | 1.853 | 3.051 | 2.646 |
| 15.063     | 5.480 | 4.741 | 3.376 |
| 15.125     | 5.989 | 4.763 | 3.375 |
| 15.188     | 6.186 | 4.460 | 3.091 |
| 15.250     | 5.799 | 4.363 | 2.970 |
| 15.313     | 5.203 | 3.907 | 2.339 |
| 15.375     | 3.325 | 3.503 | 2.138 |
| 15.438     | 4.181 | 3.066 | 1.961 |
| 15.500     | RIB   | RIB   | RIB   |
| 15.563     | RIB   | RIB   | RIB   |
| 15.625     | 2.079 | 2.029 | 2.250 |
| 15.688     | 3.525 | 3.474 | 2.933 |
| 15.750     | 4.472 | 3.952 | 3.454 |
| 15.813     | 5.958 | 4.213 | 3.135 |
| 15.875     | 5.543 | 3.916 | 2.957 |
| 15.938     | 5.226 | 3.893 | 2.707 |
| 16.000     | 3.415 | 3.166 | 2.517 |
| 16.063     | 4.335 | 2.856 | 1.970 |
| 16.438     | 3.855 | 3.216 | 2.810 |
| 17.063     | 5.107 | 3.755 | 3.061 |
| 17.688     | 3.915 | 3.376 | 2.837 |

| -----       |       |       |            |       |
|-------------|-------|-------|------------|-------|
| OUTER WALL  |       | AND   | INNER WALL |       |
| -----       |       |       |            |       |
| E/D         | I.L.  | C.L.  | I.L.       | C.L.  |
| -----       |       |       |            |       |
| BEFORE TURN |       |       |            |       |
| -----       |       |       |            |       |
|             | OUTER | WALL  | INNER      | WALL  |
| -----       |       |       |            |       |
| 8.313       | 2.019 | 1.826 | 2.320      | 2.313 |
| 8.938       | 1.761 | 1.884 | 1.981      | 1.828 |
| 9.563       | 1.640 | 1.717 | 1.580      | 1.607 |
| 9.938       | 1.840 | 1.604 | 1.401      | 1.486 |
| 10.000      | 1.780 | 1.599 | 1.231      | 1.425 |
| 10.125      | 1.791 | 1.654 | 1.340      | 1.720 |
| 10.250      | 1.692 | 1.709 | 1.590      | 1.574 |
| 10.375      | 2.118 | 1.666 | 1.708      | 1.662 |
| 10.500      | 1.869 | 1.907 | 2.002      | 1.749 |
| 10.625      | 1.827 | 1.843 | 1.838      | 1.770 |
| 10.750      | 1.794 | 1.756 | 1.966      | 1.703 |
| 10.875      | 1.718 | 1.572 | 1.941      | 1.722 |
| 11.000      | 1.890 | 1.701 | 2.003      | 1.752 |
| 11.125      | 2.010 | 1.800 | 2.046      | 1.655 |
| 11.250      | 1.892 | 1.833 | 1.926      | 1.633 |
| 11.375      | 1.956 | 1.780 | 1.838      | 1.482 |
| 11.500      | 1.955 | 1.758 | 1.505      | 1.555 |
| 11.625      | 2.168 | 1.993 |            |       |

|        | IN TURN |       |
|--------|---------|-------|
| 11.875 | 2.255   | 2.243 |
| 12.375 | 2.544   | 2.439 |
| 12.875 | 3.275   | 3.400 |
| 13.125 | 3.047   | 3.073 |
| 13.625 | 3.209   | 3.586 |
| 14.125 | 2.805   | 3.484 |

|        | AFTER TURN |       |       |       |
|--------|------------|-------|-------|-------|
| 14.375 | 2.357      | 3.586 |       |       |
| 14.500 | 2.416      | 3.520 | 3.707 | 4.447 |
| 14.625 | 2.188      | 3.509 | 3.783 | 3.711 |
| 14.750 | 1.925      | 3.250 | 2.613 | 3.463 |
| 14.875 | 2.166      | 3.224 | 2.641 | 3.299 |
| 15.000 | 2.352      | 3.272 | 2.936 | 3.154 |
| 15.125 | 2.445      | 3.271 | 2.934 | 3.207 |
| 15.250 | 2.345      | 3.378 | 2.814 | 3.120 |
| 15.375 | 2.329      | 3.083 | 2.822 | 2.846 |
| 15.500 | 2.780      | 2.981 | 2.872 | 2.918 |
| 15.625 | 2.926      | 2.887 | 2.768 | 2.814 |
| 15.750 | 2.661      | 2.938 | 2.644 | 2.494 |
| 15.875 | 2.581      | 2.991 | 3.123 | 2.229 |
| 16.000 | 2.588      | 2.527 | 2.638 | 2.071 |
| 16.063 | 2.607      | 2.876 | 2.581 | 1.991 |
| 16.438 | 2.512      | 2.615 | 1.963 | 1.987 |
| 17.063 | 2.365      | 2.200 | 1.811 | 1.477 |
| 17.688 | 2.134      | 2.194 | 1.463 | 1.476 |

Rough Channel:  $Re=30,000$ ,  $P/e=10$ ,  $e/D=0.063$ ,  $\alpha = 90^\circ$

# $Sh/Sh_0$

TOP WALL

| $z/D$ | O.L.   | C.L.   | I.L.   |
|-------|--------|--------|--------|
|       | BEFORE | TURN   |        |
| 0.563 | 1.369  | 0.9620 | 0.9345 |
| 0.625 | 1.609  | 1.431  | 1.782  |
| 0.688 | 2.014  | 1.930  | 2.302  |
| 0.750 | 2.399  | 2.154  | 2.676  |
| 0.813 | 2.265  | 1.812  | 2.277  |
| 0.875 | 1.965  | 1.828  | 2.345  |
| 0.938 | 1.649  | 1.358  | 2.164  |
| 1.000 | 2.194  | 2.710  | 3.014  |
| 1.063 | RIB    | RIB    | RIB    |
| 1.125 | RIB    | RIB    | RIB    |
| 1.188 | 2.026  | 1.441  | 1.181  |
| 1.250 | 3.179  | 2.708  | 3.677  |
| 1.313 | 3.788  | 3.079  | 4.013  |
| 1.375 | 4.170  | 3.662  | 4.198  |
| 1.438 | 3.972  | 3.517  | 3.876  |
| 1.500 | 3.827  | 3.449  | 3.736  |
| 1.563 | 3.517  | 3.253  | 3.344  |
| 1.625 | 3.331  | 3.067  | 3.117  |
| 2.063 |        | 3.415  |        |
| 2.688 |        | 3.347  |        |
| 3.313 |        | 3.230  |        |
| 3.938 |        | 3.071  |        |
| 4.563 |        | 3.078  |        |
| 5.188 |        | 3.093  |        |
| 5.813 |        | 3.059  |        |
| 6.438 |        | 2.996  |        |
| 6.813 | 1.539  | 1.288  | 1.219  |
| 6.875 | 3.055  | 2.703  | 2.774  |
| 6.938 | 3.212  | 3.038  | 3.076  |
| 7.000 | 3.369  | 3.181  | 3.271  |
| 7.063 | 3.156  | 2.882  | 3.231  |
| 7.125 | 3.001  | 2.804  | 3.153  |
| 7.188 | 2.511  | 2.587  | 2.883  |
| 7.250 | 2.764  | 2.481  | 2.638  |
| 7.313 | RIB    | RIB    | RIB    |
| 7.375 | RIB    | RIB    | RIB    |
| 7.438 | 1.598  | 1.545  | 1.787  |

|        |       |       |       |
|--------|-------|-------|-------|
| 7.500  | 2.982 | 2.814 | 2.851 |
| 7.563  | 3.491 | 3.252 | 3.284 |
| 7.625  | 3.317 | 3.159 | 3.177 |
| 7.688  | 3.269 | 3.100 | 2.947 |
| 7.750  | 3.109 | 2.780 | 2.860 |
| 7.813  | 2.927 | 2.584 | 2.559 |
| 7.875  | 2.755 | 2.412 | 2.487 |
| 8.313  |       | 3.087 |       |
| 8.938  |       | 3.087 |       |
| 9.313  | 1.549 | 1.324 | 1.337 |
| 9.375  | 2.704 | 2.735 | 2.622 |
| 9.438  | 3.133 | 3.095 | 3.103 |
| 9.500  | 3.144 | 2.985 | 3.132 |
| 9.563  | 3.025 | 2.913 | 2.944 |
| 9.625  | 2.735 | 2.655 | 2.755 |
| 9.688  | 2.529 | 2.417 | 2.466 |
| 9.750  | 2.369 | 2.262 | 2.316 |
| 9.813  | RIB   | RIB   | RIB   |
| 9.875  | RIB   | RIB   | RIB   |
| 9.938  | 1.426 | 1.420 | 1.543 |
| 10.000 | 2.611 | 2.675 | 2.549 |
| 10.063 | 3.147 | 3.118 | 3.043 |
| 10.125 | 3.134 | 3.009 | 2.902 |
| 10.188 | 2.970 | 2.895 | 2.729 |
| 10.250 | 2.870 | 2.681 | 2.638 |
| 10.313 | 2.597 | 2.408 | 2.402 |
| 10.375 | 2.480 | 2.273 | 2.290 |
| 10.438 | RIB   | RIB   | RIB   |
| 10.500 | RIB   | RIB   | RIB   |
| 10.563 | 1.504 | 1.580 | 1.538 |
| 10.625 | 2.764 | 2.744 | 2.761 |
| 10.688 | 3.148 | 3.142 | 2.886 |
| 10.750 | 3.149 | 3.057 | 3.073 |
| 10.813 | 2.927 | 2.908 | 2.820 |
| 10.875 | 2.756 | 2.628 | 2.595 |
| 10.938 | 2.540 | 2.380 | 2.361 |
| 11.000 | 2.442 | 2.174 | 2.240 |
| 11.063 | RIB   | RIB   | RIB   |
| 11.125 | RIB   | RIB   | RIB   |
| 11.188 | 1.846 | 1.642 | 1.320 |
| 11.250 | 3.052 | 2.884 | 2.450 |
| 11.313 | 3.359 | 3.219 | 2.826 |
| 11.375 | 3.257 | 3.120 | 2.890 |
| 11.438 | 3.028 | 2.856 | 2.738 |
| 11.500 | 2.796 | 2.674 | 2.614 |
| 11.563 | 2.439 | 2.442 | 2.365 |
| 11.625 | 2.495 | 2.135 | 2.018 |

|        | -----<br>IN TURN<br>----- |       |       |
|--------|---------------------------|-------|-------|
| 11.875 | 3.710                     | 3.485 | 3.322 |
| 12.375 | 2.094                     | 2.185 | 2.373 |
| 12.875 | 2.781                     | 2.403 | 2.384 |
| 13.125 | 2.730                     | 2.493 | 2.522 |
| 13.625 | 3.014                     | 2.486 | 2.176 |
| 14.125 | 1.841                     | 1.919 | 2.270 |

|        | -----<br>AFTER TURN<br>----- |       |       |
|--------|------------------------------|-------|-------|
| 14.375 | 3.201                        | 2.366 | 2.094 |
| 14.438 | 4.692                        | 3.000 | 2.531 |
| 14.500 | 5.132                        | 3.483 | 2.843 |
| 14.563 | 4.919                        | 3.600 | 3.031 |
| 14.625 | 4.479                        | 3.734 | 3.156 |
| 14.688 | 3.940                        | 3.716 | 3.285 |
| 14.750 | 3.205                        | 3.481 | 3.199 |
| 14.813 | 4.467                        | 3.539 | 3.261 |
| 14.875 | RIB                          | RIB   | RIB   |
| 14.938 | RIB                          | RIB   | RIB   |
| 15.000 | 3.034                        | 3.980 | 3.647 |
| 15.063 | 4.178                        | 4.474 | 3.855 |
| 15.125 | 4.601                        | 4.276 | 3.588 |
| 15.188 | 4.697                        | 4.004 | 3.311 |
| 15.250 | 4.507                        | 3.836 | 3.038 |
| 15.313 | 4.167                        | 3.531 | 2.891 |
| 15.375 | 3.638                        | 3.184 | 2.643 |
| 15.438 | 3.888                        | 3.406 | 3.599 |
| 15.500 | RIB                          | RIB   | RIB   |
| 15.563 | RIB                          | RIB   | RIB   |
| 15.625 | 2.630                        | 2.947 | 3.103 |
| 15.688 | 4.156                        | 4.080 | 3.619 |
| 15.750 | 4.610                        | 4.099 | 3.514 |
| 15.813 | 4.464                        | 3.865 | 3.229 |
| 15.875 | 4.107                        | 3.590 | 3.026 |
| 15.938 | 3.799                        | 3.267 | 2.795 |
| 16.000 | 3.297                        | 2.902 | 2.480 |
| 16.063 | 3.788                        | 3.237 | 2.888 |
| 16.125 | RIB                          | RIB   | RIB   |
| 16.188 | RIB                          | RIB   | RIB   |
| 16.250 | 2.877                        | 2.777 | 2.884 |
| 16.313 | 3.919                        | 3.648 | 3.423 |
| 16.375 | 4.206                        | 3.610 | 3.343 |
| 16.438 | 4.076                        | 3.471 | 3.120 |
| 16.500 | 3.723                        | 3.280 | 2.831 |
| 16.563 | 3.237                        | 3.019 | 2.644 |

|        |       |       |       |
|--------|-------|-------|-------|
| 16.625 | 2.959 | 1.860 | 1.767 |
| 16.688 | 3.799 | 1.019 | 1.718 |
| 17.063 |       | 1.447 |       |
| 17.688 |       | 1.347 |       |
| 18.125 | 2.041 | 1.000 | 1.751 |
| 18.188 | 3.329 | 1.100 | 1.699 |
| 18.250 | 3.611 | 1.101 | 1.711 |
| 18.313 | 3.639 | 1.200 | 1.711 |
| 18.375 | 3.300 | 1.000 | 1.711 |
| 18.438 | 3.200 | 1.700 | 1.711 |
| 18.500 | 2.847 | 2.451 | 2.252 |
| 18.563 | 2.905 | 2.519 | 2.286 |
| 18.625 | RIB   | RIB   | RIB   |
| 18.688 | RIB   | RIB   | RIB   |
| 18.750 | 2.006 | 1.768 | 1.797 |
| 18.813 | 3.199 | 3.128 | 2.784 |
| 18.875 | 3.599 | 3.288 | 3.155 |
| 18.938 | 2.238 | 3.141 | 3.012 |
| 19.000 | 3.367 | 3.008 | 2.846 |
| 19.063 | 2.927 | 2.817 | 2.376 |
| 19.125 | 2.837 | 2.467 | 2.223 |
| 19.188 | 2.703 | 2.140 | 1.968 |
| 19.563 |       | 3.058 |       |
| 20.188 |       | 3.034 |       |
| 20.813 |       | 3.019 |       |
| 21.438 |       | 2.977 |       |
| 22.063 |       | 2.864 |       |
| 22.688 |       | 2.860 |       |
| 23.313 |       | 2.908 |       |
| 23.938 |       | 2.992 |       |
| 24.375 | 2.312 | 2.087 | 2.616 |
| 24.438 | 3.274 | 3.209 | 3.133 |
| 24.500 | 3.435 | 3.385 | 3.278 |
| 24.563 | 3.255 | 3.123 | 2.815 |
| 24.625 | 3.189 | 2.917 | 2.697 |
| 24.688 | 2.957 | 2.638 | 2.500 |
| 24.750 | 2.854 | 2.519 | 2.412 |
| 24.813 | 2.579 | 2.245 | 2.350 |
| 24.875 | RIB   | RIB   | RIB   |
| 24.938 | RIB   | RIB   | RIB   |
| 25.000 | 2.540 | 2.464 | 2.528 |
| 25.063 | 2.188 | 2.138 | 1.731 |
| 25.125 | 2.410 | 2.329 | 1.761 |
| 25.188 | 2.389 | 2.300 | 1.706 |
| 25.250 | 2.311 | 2.290 | 1.800 |
| 25.313 | 2.419 | 2.380 | 1.801 |
| 25.375 | 2.381 | 2.300 | 1.700 |
| 25.438 | 1.094 | 1.700 | 1.700 |

| -----      |       |            |            |       |
|------------|-------|------------|------------|-------|
| OUTER WALL |       | AND        | INNER WALL |       |
| -----      |       |            |            |       |
| X/D        | I.L.  | C.L.       | I.L.       | C.L.  |
| -----      |       |            |            |       |
| BEFORE     |       | TURN       |            |       |
| -----      |       |            |            |       |
| OUTER WALL |       | INNER WALL |            |       |
| -----      |       |            |            |       |
| 8.313      | 1.822 | 1.552      | 1.894      | 1.740 |
| 8.938      | 1.760 | 1.558      | 2.072      | 1.872 |
| 9.563      | 1.729 | 1.513      | 1.719      | 1.654 |
| 10.188     | 1.862 | 1.639      | 1.883      | 1.800 |
| 10.813     | 1.819 | 1.603      | 1.780      | 1.666 |
| 11.438     | 1.798 | 1.445      | 1.777      | 1.507 |
| -----      |       |            |            |       |
| IN         |       | TURN       |            |       |
| -----      |       |            |            |       |
| 11.875     | 2.511 | 2.128      |            |       |
| 12.375     | 2.374 | 2.172      |            |       |
| 12.875     | 2.775 | 2.962      |            |       |
| 13.125     | 2.288 | 2.561      |            |       |
| 13.625     | 2.759 | 2.819      |            |       |
| 14.125     | 2.297 | 2.289      |            |       |
| -----      |       |            |            |       |
| AFTER      |       | TURN       |            |       |
| -----      |       |            |            |       |
| 14.563     | 2.335 | 2.323      | 3.062      | 2.925 |
| 15.188     | 2.380 | 2.277      | 2.818      | 2.480 |
| 15.813     | 2.754 | 2.678      | 2.747      | 2.295 |
| 16.438     | 2.481 | 2.450      | 2.214      | 2.123 |
| 17.063     | 2.370 | 2.326      | 2.293      | 1.762 |
| 17.688     | 2.201 | 2.185      | 2.347      | 2.110 |

Rough Channel:  $Re = 60,000$ ,  $P/e = 10$ ,  $e/D = 0.063$ ,  $\alpha = 90^\circ$

# $Sh/Sh_0$

TOP WALL

| $x/D$ | $Sh_0$ | $Sh_1$ | $Sh_2$ |
|-------|--------|--------|--------|
|       | BEFORE | TURN   |        |
| 0.188 | 3.414  | 3.904  | 3.839  |
| 0.250 | 4.438  | 4.495  | 4.602  |
| 0.313 | 4.700  | 4.604  | 4.658  |
| 0.375 | 4.301  | 4.281  | 4.403  |
| 0.438 | RIB    | RIB    | RIB    |
| 0.500 | RIB    | RIB    | RIB    |
| 0.563 | 2.124  | 1.677  | 1.729  |
| 0.625 | 3.613  | 3.597  | 3.888  |
| 0.688 | 4.088  | 4.466  | 4.251  |
| 0.750 | 3.905  | 4.337  | 4.255  |
| 0.813 | 3.686  | 4.194  | 4.217  |
| 0.875 | 2.340  | 3.935  | 3.839  |
| 0.938 | 2.930  | 3.261  | 3.472  |
| 1.000 | 3.373  | 3.526  | 3.521  |
| 1.063 | RIB    | RIB    | RIB    |
| 1.125 | RIB    | RIB    | RIB    |
| 1.188 | 2.023  | 1.722  | 2.124  |
| 1.250 | 2.966  | 2.611  | 3.193  |
| 1.313 | 3.422  | 3.082  | 3.307  |
| 1.375 | 3.376  | 3.255  | 3.250  |
| 1.438 | 3.265  | 3.318  | 3.039  |
| 1.500 | 3.216  | 3.167  | 2.817  |
| 1.563 | 3.062  | 3.078  | 3.142  |
| 1.625 | 3.092  | 3.094  | 2.965  |
| 2.063 | 3.093  | 2.915  | 3.050  |
| 2.688 | 2.934  | 2.925  | 2.890  |
| 3.313 | 2.843  | 2.747  | 2.836  |
| 3.938 | 2.785  | 2.783  | 2.865  |
| 4.563 | 2.797  | 2.722  | 2.800  |
| 5.188 | 2.757  | 2.712  | 2.801  |
| 5.813 | 2.671  | 2.665  | 2.733  |
| 6.438 | 2.714  | 2.603  | 2.734  |
| 6.813 | 1.931  | 2.003  | 1.947  |
| 6.875 | 2.816  | 3.117  | 1.976  |
| 6.938 | 2.915  | 2.993  | 2.981  |
| 7.000 | 2.965  | 2.759  | 2.979  |
| 7.063 | 2.965  | 2.759  | 2.979  |
| 7.125 | 2.965  | 2.759  | 2.979  |
| 7.188 | 2.965  | 2.759  | 2.979  |

|        |       |       |       |
|--------|-------|-------|-------|
| 7.250  | 2.521 | 2.217 | 2.517 |
| 7.317  | RIB   | RIB   | RIB   |
| 7.378  | RIB   | RIB   | RIB   |
| 7.438  | 1.872 | 1.889 | 1.824 |
| 7.500  | 2.829 | 2.847 | 2.551 |
| 7.563  | 2.993 | 2.925 | 2.772 |
| 7.625  | 2.915 | 2.698 | 2.752 |
| 7.688  | 2.642 | 2.419 | 2.567 |
| 7.750  | 2.470 | 2.244 | 2.375 |
| 7.813  | 2.289 | 2.096 | 2.157 |
| 7.875  | 2.402 | 2.212 | 2.512 |
| 8.313  | 2.776 | 2.444 | 2.563 |
| 8.938  | 2.638 | 2.452 | 2.594 |
| 9.313  | 1.824 | 1.918 | 2.066 |
| 9.375  | 2.750 | 2.844 | 2.669 |
| 9.438  | 2.915 | 2.820 | 2.772 |
| 9.500  | 2.858 | 2.650 | 2.681 |
| 9.563  | 2.701 | 2.431 | 2.542 |
| 9.625  | 2.466 | 2.216 | 2.363 |
| 9.688  | 2.228 | 2.041 | 2.167 |
| 9.750  | 2.386 | 2.242 | 2.441 |
| 9.813  | RIB   | RIB   | RIB   |
| 9.875  | RIB   | RIB   | RIB   |
| 9.938  | 1.643 | 1.976 | 1.941 |
| 10.000 | 2.702 | 2.737 | 2.567 |
| 10.063 | 2.919 | 2.795 | 2.793 |
| 10.125 | 2.855 | 2.551 | 2.684 |
| 10.188 | 2.634 | 2.376 | 2.519 |
| 10.250 | 2.331 | 2.195 | 2.344 |
| 10.313 | 2.226 | 2.025 | 2.078 |
| 10.375 | 2.498 | 2.188 | 2.543 |
| 10.438 | RIB   | RIB   | RIB   |
| 10.500 | RIB   | RIB   | RIB   |
| 10.563 | 1.793 | 2.010 | 1.969 |
| 10.625 | 2.700 | 2.702 | 2.605 |
| 10.688 | 2.863 | 2.766 | 2.748 |
| 10.750 | 2.787 | 2.609 | 2.633 |
| 10.813 | 2.616 | 2.416 | 2.453 |
| 10.875 | 2.437 | 2.204 | 2.329 |
| 10.938 | 2.325 | 2.028 | 2.075 |
| 11.000 | 2.328 | 2.167 | 2.292 |
| 11.063 | RIB   | RIB   | RIB   |
| 11.125 | RIB   | RIB   | RIB   |
| 11.188 | 2.060 | 2.019 | 2.020 |
| 11.250 | 3.118 | 2.834 | 2.800 |
| 11.313 | 3.462 | 2.921 | 2.931 |
| 11.375 | 3.257 | 2.859 | 2.801 |
| 11.438 | 2.984 | 2.609 | 2.668 |
| 11.500 | 2.773 | 2.334 | 2.403 |
| 11.563 | 2.571 | 2.087 | 2.084 |
| 11.625 | 2.371 | 2.014 | 2.009 |

|        | IN TURN |       |       |
|--------|---------|-------|-------|
| 11.875 | 3.977   | 3.452 | 3.377 |
| 12.375 | 1.833   | 1.877 | 2.214 |
| 12.675 | 2.262   | 2.027 | 2.089 |
| 13.125 | 2.108   | 2.029 | 2.074 |
| 13.625 | 2.525   | 1.978 | 1.948 |
| 14.125 | 1.683   | 1.761 | 2.332 |

|        | AFTER TURN |       |       |
|--------|------------|-------|-------|
| 14.375 | 2.878      | 2.076 | 2.010 |
| 14.438 | 3.745      | 2.549 | 2.306 |
| 14.500 | 4.217      | 2.855 | 2.445 |
| 14.563 | 4.116      | 3.041 | 2.678 |
| 14.625 | 3.756      | 3.168 | 2.711 |
| 14.688 | 3.361      | 3.208 | 2.777 |
| 14.750 | 3.013      | 3.122 | 2.845 |
| 14.813 | 3.406      | 3.217 | 2.876 |
| 14.875 | RIB        | RIB   | RIB   |
| 14.938 | RIB        | RIB   | RIB   |
| 15.000 | 2.810      | 3.127 | 2.879 |
| 15.063 | 3.665      | 3.852 | 3.351 |
| 15.125 | 4.165      | 3.731 | 3.135 |
| 15.188 | 4.135      | 3.431 | 2.870 |
| 15.250 | 3.746      | 3.201 | 2.614 |
| 15.313 | 3.393      | 2.948 | 2.461 |
| 15.375 | 3.084      | 2.783 | 2.331 |
| 15.438 | 3.007      | 2.633 | 2.276 |
| 15.500 | RIB        | RIB   | RIB   |
| 15.563 | RIB        | RIB   | RIB   |
| 15.625 | 2.343      | 2.482 | 2.497 |
| 15.688 | 3.152      | 3.409 | 3.133 |
| 15.750 | 3.635      | 3.575 | 3.141 |
| 15.813 | 3.765      | 3.436 | 2.975 |
| 15.875 | 3.668      | 3.224 | 2.759 |
| 15.938 | 3.417      | 2.988 | 2.565 |
| 16.000 | 3.195      | 2.854 | 2.330 |
| 16.063 | 3.071      | 2.730 | 2.222 |
| 16.125 | RIB        | RIB   | RIB   |
| 16.188 | RIB        | RIB   | RIB   |
| 16.250 | 2.219      | 2.146 | 2.111 |
| 16.313 | 3.131      | 3.037 | 2.826 |
| 16.375 | 3.671      | 3.299 | 2.849 |
| 16.438 | 3.630      | 3.026 | 2.750 |
| 16.500 | 3.399      | 2.832 | 2.529 |
| 16.563 | 3.162      | 2.690 | 2.388 |
| 16.625 | 2.779      | 2.515 | 2.109 |
| 16.688 | 2.664      | 2.422 | 2.036 |
| 16.750 | 2.411      | 2.231 | 1.766 |

|        |       |       |       |
|--------|-------|-------|-------|
| 17.688 | 3.336 | 2.981 | 2.942 |
| 18.125 | 1.851 | 1.564 | 1.827 |
| 18.189 | 2.544 | 2.449 | 1.764 |
| 18.250 | 3.104 | 2.844 | 2.080 |
| 18.313 | 3.113 | 2.725 | 2.908 |
| 18.375 | 2.978 | 2.592 | 2.564 |
| 18.436 | 2.703 | 2.449 | 2.239 |
| 18.500 | 2.499 | 2.272 | 2.031 |
| 18.563 | 2.358 | 2.143 | 1.826 |
| 18.625 | RIB   | RIB   | RIB   |
| 18.688 | RIB   | RIB   | RIB   |
| 18.750 | 1.728 | 1.895 | 1.709 |
| 18.813 | 2.872 | 2.753 | 2.522 |
| 18.875 | 3.048 | 3.106 | 3.126 |
| 18.938 | 3.119 | 2.833 | 3.177 |
| 19.000 | 2.951 | 2.611 | 2.979 |
| 19.063 | 2.763 | 2.457 | 2.491 |
| 19.125 | 2.602 | 2.367 | 2.190 |
| 19.188 | 2.468 | 2.192 | 1.879 |
| 19.563 | 2.917 | 2.915 | 3.006 |
| 20.188 | 2.872 | 2.857 | 2.776 |
| 20.813 | 2.913 | 2.821 | 2.767 |
| 21.438 | 2.762 | 2.813 | 2.734 |
| 22.063 | 2.622 | 2.804 | 2.655 |
| 22.688 | 2.690 | 2.710 | 2.602 |
| 23.313 | 2.716 | 2.714 | 2.702 |
| 23.938 | 2.680 | 2.740 | 2.663 |
| 24.375 | 1.776 | 2.073 | 2.071 |
| 24.438 | 2.979 | 2.919 | 2.910 |
| 24.500 | 3.320 | 3.458 | 3.233 |
| 24.563 | 3.268 | 3.288 | 2.760 |
| 24.625 | 3.073 | 2.938 | 2.309 |
| 24.688 | 2.830 | 2.518 | 2.094 |
| 24.750 | 2.601 | 2.217 | 1.930 |
| 24.813 | 2.495 | 2.042 | 1.885 |
| 24.875 | RIB   | RIB   | RIB   |
| 24.938 | RIB   | RIB   | RIB   |
| 25.000 | 2.022 | 1.847 | 2.130 |
| 25.063 | 1.756 | 1.653 | 1.864 |
| 25.125 | 1.960 | 1.922 | 1.931 |
| 25.188 | 2.070 | 2.021 | 2.062 |
| 25.250 | 2.053 | 1.936 | 1.963 |
| 25.313 | 2.297 | 2.049 | 2.087 |
| 25.375 | 2.299 | 2.018 | 1.915 |
| 25.438 | 2.268 | 2.099 | 1.913 |
| 25.500 | RIB   | RIB   | RIB   |
| 25.563 | RIB   | RIB   | RIB   |
| 25.625 | 3.186 | 3.049 | 2.924 |
| 25.688 | 3.796 | 4.248 | 3.046 |
| 25.750 | 2.344 | 2.278 | 1.914 |
| 25.813 | 2.251 | 2.049 | 1.815 |

|       | OUTER WALL |       | AND INNER WALL |       |
|-------|------------|-------|----------------|-------|
| X/D   | I.L.       | C.L.  | I.L.           | C.L.  |
|       | BEFORE     |       | TURN           |       |
|       | OUTER      | WALL  | INNER          | WALL  |
| 0.188 | 2.215      | 2.634 | 2.283          | 3.182 |
| 0.250 | 2.243      | 2.858 | 2.676          | 3.868 |
| 0.313 | 2.329      | 3.186 | 2.937          | 3.766 |
| 0.375 | 2.262      | 2.938 | 2.893          | 3.685 |
| 0.438 | 2.511      | 3.161 | 2.781          | 3.529 |
| 0.500 | 2.580      | 3.338 | 2.656          | 3.425 |
| 0.563 | 2.640      | 3.467 | 2.783          | 3.332 |
| 0.625 | 2.574      | 3.075 | 2.661          | 3.224 |
| 0.688 | 2.880      | 3.269 | 3.153          | 3.137 |
| 0.750 | 2.825      | 3.022 | 3.233          | 3.040 |
| 0.813 | 2.929      | 2.977 | 3.222          | 2.820 |
| 0.875 | 2.978      | 2.853 | 3.187          | 2.661 |
| 0.938 | 2.999      | 2.798 | 3.267          | 2.528 |
| 1.000 | 2.932      | 2.706 | 3.032          | 2.417 |
| 1.063 | 2.906      | 2.522 | 3.058          | 2.339 |
| 1.125 | 2.898      | 2.546 | 3.002          | 2.416 |
| 1.188 | 2.790      | 2.556 | 2.898          | 2.337 |
| 1.250 | 2.734      | 2.465 | 2.830          | 2.327 |
| 1.313 | 2.614      | 2.475 | 2.812          | 2.281 |
| 1.375 | 2.577      | 2.304 | 2.646          | 2.292 |
| 1.438 | 2.514      | 2.278 | 2.629          | 2.130 |
| 1.500 | 2.465      | 2.258 | 2.610          | 2.062 |
| 1.563 | 2.414      | 2.196 | 2.546          | 2.034 |
| 1.625 | 2.340      | 2.176 | 2.553          | 2.059 |
| 2.063 | 2.107      | 2.098 | 1.973          | 1.869 |
| 2.688 | 1.813      | 1.944 | 1.727          | 1.656 |
| 3.313 | 1.768      | 1.846 | 1.640          | 1.698 |
| 3.938 | 1.664      | 1.734 | 1.605          | 1.677 |
| 4.563 | 1.663      | 1.712 | 1.732          | 1.689 |
| 5.188 | 1.644      | 1.671 | 1.661          | 1.592 |
| 5.813 | 1.661      | 1.663 | 1.659          | 1.621 |
| 6.438 | 1.723      | 1.675 | 1.656          | 1.627 |
| 6.813 | 1.731      | 1.558 | 1.789          | 1.701 |
| 6.875 | 1.654      | 1.564 | 1.781          | 1.664 |
| 6.938 | 1.655      | 1.594 | 1.739          | 1.705 |
| 7.000 | 1.613      | 1.567 | 1.716          | 1.670 |
| 7.063 | 1.595      | 1.575 | 1.744          | 1.671 |
| 7.125 | 1.601      | 1.544 | 1.844          | 1.687 |
| 7.188 | 1.596      | 1.551 | 1.751          | 1.687 |

|        |       |       |       |       |
|--------|-------|-------|-------|-------|
| 7.437  | 1.437 | 1.434 | 1.437 | 1.428 |
| 7.513  | 1.437 | 1.437 | 1.437 | 1.437 |
| 7.599  | 1.438 | 1.437 | 1.437 | 1.433 |
| 7.638  | 1.437 | 1.437 | 1.437 | 1.427 |
| 7.691  | 1.437 | 1.437 | 1.437 | 1.431 |
| 7.694  | 1.437 | 1.437 | 1.437 | 1.433 |
| 7.697  | 1.437 | 1.437 | 1.437 | 1.434 |
| 7.688  | 1.437 | 1.437 | 1.437 | 1.434 |
| 7.757  | 1.437 | 1.437 | 1.437 | 1.438 |
| 7.817  | 1.437 | 1.437 | 1.437 | 1.436 |
| 7.875  | 1.616 | 1.540 | 1.684 | 1.525 |
| 8.313  | 1.446 | 1.522 | 1.616 | 1.474 |
| 8.938  | 1.423 | 1.539 | 1.574 | 1.502 |
| 9.313  | 1.591 | 1.439 | 1.616 | 1.401 |
| 9.375  | 1.517 | 1.561 | 1.519 | 1.350 |
| 9.438  | 1.528 | 1.510 | 1.631 | 1.442 |
| 9.500  | 1.550 | 1.412 | 1.596 | 1.415 |
| 9.563  | 1.519 | 1.470 | 1.568 | 1.339 |
| 9.625  | 1.613 | 1.492 | 1.568 | 1.286 |
| 9.688  | 1.555 | 1.553 | 1.671 | 1.464 |
| 9.750  | 1.557 | 1.505 | 1.615 | 1.402 |
| 9.813  | 1.582 | 1.456 | 1.627 | 1.386 |
| 9.875  | 1.605 | 1.461 | 1.692 | 1.386 |
| 9.938  | 1.580 | 1.440 | 1.675 | 1.461 |
| 10.000 | 1.556 | 1.425 | 1.607 | 1.417 |
| 10.063 | 1.531 | 1.470 | 1.669 | 1.475 |
| 10.125 | 1.523 | 1.485 | 1.634 | 1.409 |
| 10.188 | 1.535 | 1.510 | 1.573 | 1.365 |
| 10.250 | 1.536 | 1.534 | 1.572 | 1.367 |
| 10.313 | 1.495 | 1.483 | 1.721 | 1.352 |
| 10.375 | 1.514 | 1.485 | 1.605 | 1.363 |
| 10.438 | 1.581 | 1.468 | 1.602 | 1.387 |
| 10.500 | 1.528 | 1.549 | 1.592 | 1.412 |
| 10.563 | 1.556 | 1.456 | 1.583 | 1.421 |
| 10.625 | 1.542 | 1.406 | 1.520 | 1.401 |
| 10.688 | 1.416 | 1.466 | 1.603 | 1.365 |
| 10.750 | 1.451 | 1.510 | 1.530 | 1.336 |
| 10.813 | 1.469 | 1.450 | 1.501 | 1.266 |
| 10.875 | 1.519 | 1.413 | 1.546 | 1.277 |
| 10.938 | 1.521 | 1.492 | 1.600 | 1.316 |
| 11.000 | 1.516 | 1.475 | 1.623 | 1.463 |
| 11.063 | 1.540 | 1.451 | 1.713 | 1.468 |
| 11.125 | 1.614 | 1.567 | 1.721 | 1.356 |
| 11.188 | 1.574 | 1.504 | 1.757 | 1.548 |
| 11.250 | 1.569 | 1.460 | 1.897 | 1.323 |
| 11.313 | 1.581 | 1.530 | 1.711 | 1.335 |
| 11.375 | 1.593 | 1.632 | 1.834 | 1.220 |
| 11.438 | 1.519 | 1.520 | 1.834 | 1.300 |
| 11.500 | 1.573 | 1.519 | 1.921 | 1.307 |
| 11.563 | 1.687 | 1.470 | 1.921 | 1.307 |
| 11.625 | 1.601 | 1.449 | 1.921 | 1.307 |

IN TURN

|        |       |       |
|--------|-------|-------|
| 11.800 | 1.114 | 1.114 |
| 11.875 | 1.076 | 1.109 |
| 11.875 | 1.071 | 1.108 |
| 11.125 | 1.404 | 1.418 |
| 11.625 | 1.393 | 1.471 |
| 14.125 | 2.308 | 1.417 |

AFTER TURN

|        |       |       |       |       |
|--------|-------|-------|-------|-------|
| 14.375 | 2.385 | 2.292 | 2.360 | 1.980 |
| 14.438 | 2.475 | 2.288 | 2.147 | 2.114 |
| 14.500 | 2.433 | 2.158 | 2.181 | 2.093 |
| 14.563 | 2.474 | 2.250 | 2.213 | 2.287 |
| 14.625 | 2.479 | 2.382 | 2.378 | 2.310 |
| 14.688 | 2.466 | 2.329 | 2.485 | 2.378 |
| 14.750 | 2.433 | 2.354 | 2.561 | 2.407 |
| 14.813 | 2.477 | 2.392 | 2.712 | 2.404 |
| 14.875 | 2.359 | 2.339 | 2.824 | 2.427 |
| 14.938 | 2.399 | 2.382 | 2.849 | 2.447 |
| 15.000 | 2.349 | 2.339 | 2.682 | 2.444 |
| 15.063 | 2.446 | 2.370 | 2.570 | 2.490 |
| 15.125 | 2.478 | 2.487 | 2.607 | 2.439 |
| 15.188 | 2.533 | 2.473 | 2.605 | 2.481 |
| 15.250 | 2.627 | 2.554 | 2.582 | 2.544 |
| 15.313 | 2.541 | 2.482 | 2.558 | 2.505 |
| 15.375 | 2.518 | 2.481 | 2.527 | 2.455 |
| 15.438 | 2.576 | 2.447 | 2.619 | 2.473 |
| 15.500 | 2.555 | 2.452 | 2.630 | 2.531 |
| 15.563 | 2.543 | 2.424 | 2.657 | 2.522 |
| 15.625 | 2.427 | 2.380 | 2.669 | 2.497 |
| 15.688 | 2.459 | 2.468 | 2.585 | 2.455 |
| 15.750 | 2.471 | 2.434 | 2.593 | 2.484 |
| 15.813 | 2.467 | 2.420 | 2.654 | 2.527 |
| 15.875 | 2.417 | 2.363 | 2.694 | 2.503 |
| 15.938 | 2.410 | 2.353 | 2.660 | 2.533 |
| 16.000 | 2.297 | 2.303 | 2.674 | 2.488 |
| 16.063 | 2.250 | 2.335 | 2.731 | 2.507 |
| 16.125 | 2.248 | 2.284 | 2.710 | 2.548 |
| 16.188 | 2.315 | 2.285 | 2.707 | 2.579 |
| 16.250 | 2.157 | 2.243 | 2.698 | 2.530 |
| 16.313 | 2.170 | 2.233 | 2.700 | 2.544 |
| 16.375 | 2.159 | 2.235 | 2.780 | 2.573 |
| 16.438 | 2.113 | 2.200 | 2.710 | 2.533 |
| 16.500 | 2.114 | 2.200 | 2.700 | 2.564 |
| 16.563 | 2.100 | 2.200 | 2.700 | 2.500 |
| 16.625 | 2.100 | 2.200 | 2.700 | 2.500 |
| 16.688 | 2.100 | 2.200 | 2.700 | 2.500 |
| 16.750 | 2.100 | 2.200 | 2.700 | 2.500 |

|        |       |       |       |       |
|--------|-------|-------|-------|-------|
| 17.688 | 1.864 | 1.986 | 2.274 | 1.171 |
| 18.125 | 1.849 | 1.964 | 2.086 | 1.174 |
| 18.188 | 1.774 | 1.840 | 2.001 | 1.942 |
| 18.250 | 1.800 | 1.840 | 2.065 | 1.971 |
| 18.313 | 1.817 | 1.817 | 1.970 | 1.917 |
| 18.375 | 1.840 | 1.873 | 1.966 | 1.914 |
| 18.438 | 1.795 | 1.808 | 2.057 | 1.843 |
| 18.500 | 1.835 | 1.828 | 1.984 | 1.836 |
| 18.563 | 1.818 | 1.854 | 2.011 | 1.891 |
| 18.625 | 1.844 | 1.816 | 1.976 | 1.846 |
| 18.688 | 1.761 | 1.801 | 1.863 | 1.827 |
| 18.750 | 1.774 | 1.800 | 1.851 | 1.846 |
| 18.813 | 1.726 | 1.776 | 1.837 | 1.838 |
| 18.875 | 1.762 | 1.680 | 1.850 | 1.909 |
| 18.938 | 1.680 | 1.703 | 1.846 | 1.905 |
| 19.000 | 1.625 | 1.652 | 1.855 | 1.894 |
| 19.063 | 1.805 | 1.692 | 1.865 | 1.887 |
| 19.125 | 1.791 | 1.681 | 1.939 | 1.889 |
| 19.188 | 1.770 | 1.762 | 1.856 | 1.909 |
| 19.563 | 1.680 | 1.651 | 1.953 | 1.943 |
| 20.188 | 1.571 | 1.535 | 1.893 | 1.849 |
| 20.813 | 1.763 | 1.717 | 1.809 | 1.750 |
| 21.438 | 1.779 | 1.789 | 1.783 | 1.713 |
| 22.063 | 1.831 | 1.731 | 1.830 | 1.686 |
| 22.688 | 1.837 | 1.814 | 1.796 | 1.658 |
| 23.313 | 1.535 | 1.434 | 1.729 | 1.630 |
| 23.938 | 1.611 | 1.469 | 1.647 | 1.601 |
| 24.375 | 1.855 | 1.641 | 1.769 | 1.743 |
| 24.438 | 1.791 | 1.602 | 1.883 | 1.725 |
| 24.500 | 1.742 | 1.582 | 1.948 | 1.685 |
| 24.563 | 1.779 | 1.629 | 1.936 | 1.713 |
| 24.625 |       |       | 1.925 | 1.662 |
| 24.688 |       |       | 2.022 | 1.729 |
| 24.750 |       |       | 1.963 | 1.761 |
| 24.813 |       |       | 1.984 | 1.760 |
| 24.875 |       |       | 2.041 | 1.752 |
| 24.938 |       |       | 1.946 | 1.743 |
| 25.000 |       |       | 1.930 | 1.695 |
| 25.063 |       |       | 1.864 | 1.795 |
| 25.125 |       |       | 1.784 | 1.751 |
| 25.188 |       |       | 1.790 | 1.822 |
| 25.250 |       |       | 1.768 | 1.803 |
| 25.313 |       |       | 1.698 | 1.875 |
| 25.375 |       |       | 1.722 | 2.051 |
| 25.438 |       |       | 1.801 | 2.232 |
| 25.500 |       |       | 1.923 | 2.115 |
| 25.563 |       |       | 2.277 | 2.450 |
| 25.625 |       |       | 2.754 | 3.076 |
| 25.688 |       |       | 3.077 | 3.117 |
| 25.750 |       |       | 1.325 | 1.887 |
| 25.813 |       |       | 1.654 | 1.628 |

Rough Channel:  $Re=15,000$ ,  $P/e=10$ ,  $e/D=0.063$ ,  $\alpha=60^\circ$

# $Sh/Sh_0$

WALL

| X/T    | 0.1    | 0.2   | 1.0   |
|--------|--------|-------|-------|
|        | BEFORE | TURN  |       |
| 8.063  | 4.004  | 4.034 | 3.288 |
| 8.688  | 2.671  | 3.288 | 2.648 |
| 9.313  | 4.736  | 4.129 | 3.364 |
| 9.375  | 4.005  | 3.991 | 3.575 |
| 9.438  | RIB    | 3.726 | 3.173 |
| 9.500  | RIB    | 3.240 | 2.994 |
| 9.563  | RIB    | RIB   | 2.837 |
| 9.625  | 2.802  | RIB   | 2.554 |
| 9.688  | 4.373  | RIB   | RIB   |
| 9.750  | 5.204  | 2.391 | RIB   |
| 9.813  | 5.118  | 3.885 | RIB   |
| 9.875  | 5.578  | 3.863 | 2.105 |
| 9.938  | 5.050  | 3.316 | 2.211 |
| 10.000 | 3.172  | 3.567 | 2.872 |
| 10.063 | RIB    | 3.629 | 2.924 |
| 10.125 | RIB    | 3.043 | 2.810 |
| 10.188 | RIB    | RIB   | 2.633 |
| 10.250 | 2.995  | RIB   | 2.551 |
| 10.313 | 3.434  | RIB   | RIB   |
| 10.375 | 5.655  | 2.159 | RIB   |
| 10.438 | 6.496  | 3.264 | RIB   |
| 10.500 | 5.108  | 3.701 | 1.993 |
| 10.563 | 4.202  | 3.720 | 2.564 |
| 10.625 | 2.923  | 3.294 | 2.890 |
| 10.688 | RIB    | 3.055 | 2.793 |
| 10.750 | RIB    | 2.693 | 2.617 |
| 10.813 | RIB    | RIB   | 2.349 |
| 10.875 | 1.715  | RIB   | 2.133 |
| 10.938 | 3.205  | RIB   | RIB   |
| 11.000 | 5.424  | 2.159 | RIB   |
| 11.063 | 5.462  | 2.871 | RIB   |
| 11.125 | 4.964  | 3.262 | 1.673 |
| 11.188 | 4.436  | 3.744 | 1.203 |
| 11.250 | 1.527  | 3.619 | 1.566 |
| 11.313 | RIB    | 4.213 | 1.877 |
| 11.375 | RIB    | 2.587 | 1.183 |
| 11.438 | RIB    | RIB   | 1.183 |
| 11.500 | 1.113  | RIB   | 1.183 |
| 11.563 | 4.481  | RIB   | RIB   |
| 11.625 | 1.113  | 1.145 | 1.183 |

|        | IN TURN |       |       |
|--------|---------|-------|-------|
| 11.875 | 2.769   | 4.290 | 3.446 |
| 12.375 | 2.140   | 1.863 | 2.125 |
| 12.875 | 2.485   | 1.539 | 2.658 |
| 13.125 | 2.124   | 2.195 | 2.141 |
| 13.625 | 2.170   | 2.108 | 1.956 |
| 14.125 | 2.474   | 2.228 | 2.165 |

|        | AFTER TURN |       |       |
|--------|------------|-------|-------|
| 14.375 | 1.895      | 2.511 | RIB   |
| 14.438 | 1.463      | RIB   | RIB   |
| 14.500 | 3.171      | RIB   | 1.969 |
| 14.563 | RIB        | RIB   | 1.988 |
| 14.625 | RIB        | 2.414 | 2.058 |
| 14.688 | RIB        | 2.762 | 2.929 |
| 14.750 | 2.984      | 3.942 | 3.103 |
| 14.813 | 3.016      | 4.140 | 3.413 |
| 14.875 | 3.923      | 4.307 | 3.393 |
| 14.938 | 4.193      | 4.000 | RIB   |
| 15.000 | 4.266      | 4.063 | RIB   |
| 15.063 | 4.123      | RIB   | RIB   |
| 15.125 | 4.113      | RIB   | 1.938 |
| 15.188 | RIB        | RIB   | 2.764 |
| 15.250 | RIB        | 1.631 | 2.898 |
| 15.313 | RIB        | 2.625 | 3.063 |
| 15.375 | 1.884      | 3.257 | 3.053 |
| 15.438 | 3.369      | 3.476 | 2.794 |
| 15.500 | 3.516      | 3.290 | 2.586 |
| 15.563 | 3.516      | 3.124 | RIB   |
| 15.625 | 3.308      | 2.999 | RIB   |
| 15.688 | 3.235      | RIB   | RIB   |
| 15.750 | 3.005      | RIB   | 1.727 |
| 15.813 | RIB        | RIB   | 2.874 |
| 15.875 | RIB        | 1.207 | 2.842 |
| 15.938 | RIB        | 2.828 | 3.135 |
| 16.000 | 1.703      | 3.017 | 3.271 |
| 16.063 | 2.646      | 3.153 | 3.125 |
| 16.125 | 3.276      | 2.986 | 2.674 |
| 16.188 | 3.350      | 2.838 | RIB   |
| 16.250 | 3.414      | 2.985 | RIB   |
| 16.313 | 3.340      | RIB   | RIB   |
| 16.375 | 3.191      | RIB   | 1.353 |
| 16.438 | RIB        | RIB   | 2.416 |
| 16.500 | RIB        | 1.314 | 3.238 |
| 16.563 | RIB        | 2.432 | 3.037 |
| 16.625 | 1.719      | 2.822 | 2.951 |
| 16.688 | 2.554      | 2.811 | 2.444 |
| 16.750 | 2.018      | 2.796 | 2.161 |
| 16.813 | 2.794      | 2.116 | 2.197 |

| -----       |       |       |            |       |
|-------------|-------|-------|------------|-------|
| OUTER WALL  |       | AND   | INNER WALL |       |
| -----       |       |       |            |       |
| X/D         | I.L.  | C.L.  | I.L.       | C.L.  |
| -----       |       |       |            |       |
| BEFORE TURN |       |       |            |       |
| -----       |       |       |            |       |
|             | OUTER | WALL  | INNER      | WALL  |
| -----       |       |       |            |       |
| 8.063       | 2.590 | 2.243 | 2.744      | 1.965 |
| 8.688       | 3.074 | 2.677 | 2.371      | 1.963 |
| 9.375       | 2.700 | 2.925 | 2.096      | 1.801 |
| 9.500       | 2.830 | 2.991 | 2.716      | 1.956 |
| 9.625       | 2.770 | 2.014 | 2.280      | 1.901 |
| 9.750       | 2.594 | 1.966 | 2.213      | 1.687 |
| 9.875       | 2.502 | 2.316 | 1.862      | 1.484 |
| 10.000      | 2.609 | 2.067 | 2.004      | 1.523 |
| 10.125      | 2.444 | 2.060 | 2.534      | 1.855 |
| 10.250      | 2.406 | 2.054 | 2.373      | 1.894 |
| 10.375      | 2.378 | 2.214 | 2.307      | 1.599 |
| 10.500      | 2.755 | 2.155 | 2.084      | 1.346 |
| 10.625      | 2.362 | 2.074 | 1.985      | 1.623 |
| 10.750      | 2.313 | 2.233 | 1.774      | 1.869 |
| 10.875      | 2.348 | 2.226 | 2.237      | 1.845 |
| 11.000      | 2.217 | 2.281 | 1.995      | 2.099 |
| 11.125      | 2.188 | 2.252 | 1.960      | 1.765 |
| 11.250      | 2.313 | 2.162 | 2.335      | 1.812 |
| 11.375      | 2.459 | 2.114 | 2.771      | 2.075 |
| 11.500      | 1.880 | 2.179 | 3.238      | 2.133 |
| 11.625      | 2.621 | 2.122 |            |       |

| -----  |       |       |       |       |  |
|--------|-------|-------|-------|-------|--|
|        |       | IN    | TURN  |       |  |
| -----  |       |       |       |       |  |
| 11.875 | 2.606 | 2.095 |       |       |  |
| 12.375 | 2.705 | 3.306 |       |       |  |
| 12.875 | 3.490 | 2.983 |       |       |  |
| 13.125 | 3.419 | 2.859 |       |       |  |
| 13.625 | 2.667 | 2.493 |       |       |  |
| 14.125 | 2.522 | 2.466 |       |       |  |
| -----  |       |       |       |       |  |
|        |       | AFTER | TURN  |       |  |
| -----  |       |       |       |       |  |
| 14.375 | 2.209 | 2.182 |       |       |  |
| 14.500 | 2.128 | 2.224 | 2.904 | 2.804 |  |
| 14.625 | 2.324 | 2.051 | 2.595 | 2.812 |  |
| 14.750 | 2.419 | 2.105 | 2.655 | 2.945 |  |
| 14.875 | 2.413 | 1.964 | 3.016 | 3.049 |  |
| 15.000 | 2.407 | 1.957 | 3.131 | 3.505 |  |
| 15.125 | 2.431 | 2.186 | 3.245 | 3.557 |  |
| 15.250 | 1.977 | 1.908 | 2.954 | 3.723 |  |
| 15.375 | 2.114 | 1.838 | 3.037 | 3.879 |  |
| 15.500 | 1.992 | 1.819 | 2.819 | 3.737 |  |
| 15.625 | 1.953 | 2.009 | 2.819 | 3.686 |  |
| 15.750 | 2.205 | 1.990 | 3.131 | 3.707 |  |
| 15.875 | 2.374 | 1.887 | 3.234 | 3.613 |  |
| 16.000 | 2.251 | 1.888 | 3.151 | 3.163 |  |
| 16.125 | 2.380 | 1.870 | 2.910 | 2.965 |  |
| 16.250 | 2.341 | 1.861 | 2.762 | 2.922 |  |
| 16.375 | 2.301 | 1.789 | 2.644 | 3.269 |  |
| 16.500 | 2.197 | 1.895 | 2.442 | 3.162 |  |
| 16.625 | 2.210 | 1.907 | 2.545 | 2.759 |  |
| 17.313 | 2.376 | 2.134 | 2.004 | 2.157 |  |
| 17.938 | 1.867 | 2.055 | 2.211 | 2.312 |  |

Rough Channel:  $Re = 30,000$ ,  $P/e = 10$ ,  $e/D = 0.063$ ,  $\alpha = 60^\circ$

$Sh/Sh_0$

2.1 WALL

| $x/D$ | $z/D$ | $Sh$   | $Sh_0$ |
|-------|-------|--------|--------|
|       |       | BEFORE | TURN   |
| 0.375 |       |        | 2.767  |
| 0.438 |       |        | 2.779  |
| 0.500 |       |        | 4.100  |
| 0.563 |       |        | 2.547  |
| 0.625 |       |        | 2.247  |
| 0.688 |       |        | 2.701  |
| 0.750 |       |        | 2.114  |
| 1.000 |       |        | 3.406  |
| 1.063 |       |        | 3.828  |
| 1.125 |       |        | 4.181  |
| 1.188 |       |        | 4.855  |
| 1.250 |       |        | 4.310  |
| 1.313 |       |        | 4.071  |
| 1.375 |       |        | 2.853  |
| 1.438 |       |        | 4.268  |
| 1.500 |       |        | 4.145  |
| 1.563 |       |        | 4.044  |
| 1.625 |       |        | 3.669  |
| 1.688 |       |        | 3.577  |
| 1.750 |       |        | 3.391  |
| 1.813 |       |        | 3.390  |
| 1.875 |       |        | 3.460  |
| 1.938 |       |        | 3.029  |
| 2.000 |       |        | 3.013  |
| 2.063 |       |        | 3.507  |
| 2.125 |       |        | 3.477  |
| 2.188 |       |        | 3.564  |
| 2.250 |       |        | 3.293  |
| 2.313 |       |        | 2.791  |
| 2.375 |       |        | 3.509  |
| 2.438 |       |        | 3.751  |
| 2.500 |       |        | 3.718  |
| 2.563 |       |        | 3.820  |
| 2.625 |       |        | 3.413  |
| 2.688 |       |        | 3.200  |
| 2.750 |       |        | 3.131  |
| 2.813 |       |        | 3.047  |
| 2.875 |       |        | 3.077  |
| 2.938 |       |        | 3.117  |
| 3.000 | 3.000 | 3.117  | 3.117  |

|        |       |       |       |
|--------|-------|-------|-------|
| 9.471  | 3.028 | 4.771 | 3.361 |
| 9.498  | RIB   | 4.38  | 3.177 |
| 9.500  | RIB   | 4.967 | 3.213 |
| 9.563  | RIB   | RIB   | 2.691 |
| 9.625  | 3.610 | RIB   | 2.394 |
| 9.688  | 4.818 | RIB   | RIB   |
| 9.750  | 5.087 | 1.681 | RIB   |
| 9.813  | 5.174 | 4.748 | RIB   |
| 9.875  | 4.161 | 4.104 | 2.187 |
| 9.938  | 3.411 | 4.142 | 2.663 |
| 10.000 | 2.531 | 3.775 | 3.022 |
| 10.063 | RIB   | 3.286 | 2.863 |
| 10.125 | RIB   | 2.824 | 2.793 |
| 10.188 | RIB   | RIB   | 2.801 |
| 10.250 | 2.910 | RIB   | 2.469 |
| 10.313 | 4.997 | RIB   | RIB   |
| 10.375 | 5.048 | 2.709 | RIB   |
| 10.438 | 4.484 | 3.755 | RIB   |
| 10.500 | 3.971 | 3.966 | 2.117 |
| 10.563 | 3.005 | 3.978 | 2.508 |
| 10.625 | 1.926 | 3.780 | 2.931 |
| 10.688 | RIB   | 3.257 | 3.009 |
| 10.750 | RIB   | 2.709 | 2.863 |
| 10.813 | RIB   | RIB   | 2.750 |
| 10.875 | 2.489 | RIB   | 2.401 |
| 10.938 | 4.247 | RIB   | RIB   |
| 11.000 | 5.207 | 2.652 | RIB   |
| 11.063 | 4.964 | 3.377 | RIB   |
| 11.125 | 3.985 | 3.840 | 1.950 |
| 11.188 | 2.970 | 3.890 | 2.457 |
| 11.250 | 1.824 | 3.611 | 2.757 |
| 11.313 | RIB   | 2.736 | 2.621 |
| 11.375 | RIB   | 2.094 | 2.759 |
| 11.438 | RIB   | RIB   | 2.657 |
| 11.500 | 3.107 | RIB   | 2.330 |
| 11.563 | 4.743 | RIB   | RIB   |
| 11.625 | 4.391 | 2.271 | RIB   |

-----  
IN TURN  
-----

|        |       |       |       |
|--------|-------|-------|-------|
| 11.875 | 1.878 | 2.965 | 3.460 |
| 12.375 | 2.352 | 2.287 | 1.819 |
| 12.875 | 2.590 | 1.877 | 1.050 |
| 13.125 | 2.381 | 1.021 | 1.984 |
| 13.625 | 2.014 | 1.807 | 1.807 |
| 14.125 | 1.880 | 1.607 | 1.807 |

|        | AFTER | TURN  |       |
|--------|-------|-------|-------|
| 14.375 | 1.736 | 1.74  | RIB   |
| 14.400 | 1.541 | RIB   | RIB   |
| 14.500 | 1.786 | RIB   | 1.500 |
| 14.500 | RIB   | RIB   | 1.000 |
| 14.625 | RIB   | 1.000 | 1.000 |
| 14.688 | RIB   | 1.125 | 1.125 |
| 14.750 | 1.125 | 1.000 | 1.000 |
| 14.813 | 3.369 | 3.761 | 1.000 |
| 14.875 | 3.522 | 3.724 | 1.000 |
| 14.938 | 3.725 | 1.800 | RIB   |
| 15.000 | 3.711 | 3.591 | RIB   |
| 15.063 | 3.610 | RIB   | RIB   |
| 15.125 | 3.456 | RIB   | 2.115 |
| 15.188 | RIB   | RIB   | 1.695 |
| 15.250 | RIB   | 2.178 | 2.751 |
| 15.313 | RIB   | 3.535 | 2.600 |
| 15.375 | 2.188 | 3.637 | 2.595 |
| 15.438 | 3.357 | 3.669 | 2.460 |
| 15.500 | 3.619 | 3.471 | 2.405 |
| 15.563 | 3.433 | 3.029 | RIB   |
| 15.625 | 3.458 | 2.797 | RIB   |
| 15.688 | 2.950 | RIB   | RIB   |
| 15.750 | 2.887 | RIB   | 1.915 |
| 15.813 | RIB   | RIB   | 2.681 |
| 15.875 | RIB   | 1.440 | 2.989 |
| 15.938 | RIB   | 2.532 | 1.045 |
| 16.000 | 1.649 | 3.116 | 2.856 |
| 16.063 | 2.652 | 3.212 | 2.600 |
| 16.125 | 2.851 | 2.953 | 2.320 |
| 16.188 | 2.947 | 2.972 | RIB   |
| 16.250 | 2.803 | 2.699 | RIB   |
| 16.313 | 2.034 | RIB   | RIB   |
| 16.375 | 2.541 | RIB   | 1.900 |
| 16.438 | RIB   | RIB   | 2.900 |
| 16.500 | RIB   | 1.500 | 2.900 |
| 16.563 | RIB   | 2.619 | 2.715 |
| 16.625 | 1.750 | 3.053 | 2.523 |
| 16.688 | 2.149 | 2.857 | 2.235 |
| 17.313 |       | 3.199 |       |
| 17.438 |       | 2.703 |       |
| 18.175 |       | 2.014 |       |
| 18.400 |       | 1.000 |       |
| 18.500 |       | 4.110 |       |
| 18.500 |       | 4.110 |       |
| 18.500 |       | 4.110 |       |
| 18.500 |       | 4.110 |       |
| 18.500 |       | 4.110 |       |
| 18.500 |       | 4.110 |       |
| 18.500 |       | 4.110 |       |
| 18.500 |       | 4.110 |       |

|        |       |
|--------|-------|
| 19.063 | 4.014 |
| 19.125 | 4.378 |
| 19.188 | 4.030 |
| 19.250 | 3.862 |
| 19.313 | 3.647 |
| 19.375 | 2.773 |
| 19.813 | 3.796 |
| 20.438 | 3.610 |
| 21.063 | 3.575 |
| 21.688 | 3.331 |
| 22.313 | 3.267 |
| 22.938 | 3.288 |
| 23.563 | 3.542 |
| 24.188 | 3.720 |
| 24.625 | 2.739 |
| 24.688 | 4.069 |
| 24.750 | 4.479 |
| 24.813 | 3.951 |
| 24.875 | 3.765 |
| 24.938 | 3.356 |
| 25.000 | 3.232 |
| 25.250 | 3.155 |
| 25.313 | 2.738 |
| 25.375 | 3.212 |
| 25.438 | 3.381 |
| 25.500 | 2.880 |
| 25.563 | 2.486 |
| 25.625 | 2.219 |

| OUTER WALL | AN. | INNER WALL |
|------------|-----|------------|
| X/P        | 11. | 11.        |

| HILL ON WEST |            |       |            |       |
|--------------|------------|-------|------------|-------|
|              | OUTER WALL |       | INNER WALL |       |
| 0.543        |            | 1.765 |            | 4.046 |
| 1.188        |            | 1.237 |            | 3.321 |
| 1.813        |            | 1.800 |            | 2.861 |
| 2.438        |            | 2.151 |            | 2.749 |
| 3.063        |            | 2.314 |            | 2.449 |
| 3.688        |            | 2.162 |            | 2.554 |
| 4.313        |            | 2.092 |            | 2.451 |
| 4.938        |            | 1.860 |            | 2.264 |
| 5.563        |            | 2.013 |            | 2.086 |
| 6.188        |            | 2.122 |            | 2.200 |
| 6.813        |            | 2.289 |            | 2.137 |
| 7.438        |            | 2.303 |            | 2.114 |
| 8.063        |            | 2.402 |            | 1.937 |
| 8.688        |            | 2.463 |            | 1.874 |
| 9.375        | 2.297      | 2.675 | 2.283      | 1.649 |
| 9.500        | 2.247      | 2.339 | 2.574      | 1.682 |
| 9.625        | 2.183      | 2.566 | 2.477      | 1.729 |
| 9.750        | 2.127      | 2.355 | 2.129      | 1.652 |
| 9.875        | 2.122      | 2.194 | 2.361      | 1.640 |
| 10.000       | 2.193      | 2.298 | 2.760      | 1.686 |
| 10.125       | 2.201      | 2.350 | 3.046      | 1.661 |
| 10.250       | 2.139      | 2.352 | 2.951      | 1.720 |
| 10.375       | 2.089      | 2.276 | 2.579      | 1.747 |
| 10.500       | 2.096      | 2.411 | 2.201      | 1.856 |
| 10.625       | 2.180      | 2.347 | 2.481      | 1.914 |
| 10.750       | 2.238      | 2.322 | 2.984      | 1.921 |
| 10.875       | 2.182      | 2.324 | 2.811      | 1.845 |
| 11.000       | 2.152      | 2.306 | 2.563      | 1.801 |
| 11.125       | 2.101      | 2.268 | 2.625      | 1.814 |
| 11.250       | 2.127      | 2.223 | 3.097      | 1.845 |
| 11.375       | 2.197      | 2.236 | 3.469      | 1.890 |
| 11.500       | 2.091      | 2.149 | 3.354      | 2.023 |
| 11.625       | 2.238      | 2.000 |            |       |

| IN TURN |       |       |
|---------|-------|-------|
| 14.875  | 1.444 | 1.103 |
| 14.938  | 1.400 | 1.044 |
| 15.000  | 1.355 | 1.000 |
| 15.125  | 1.340 | 1.040 |
| 15.250  | 1.300 | 1.000 |
| 15.375  | 1.255 | 1.040 |

| AFTER TURN |       |       |       |       |
|------------|-------|-------|-------|-------|
| 14.875     | 2.694 | 2.295 |       |       |
| 14.938     | 2.775 | 2.174 | 2.995 | 3.072 |
| 14.962     | 2.604 | 1.996 | 3.092 | 3.080 |
| 14.750     | 2.490 | 2.014 | 3.260 | 3.033 |
| 14.875     | 2.301 | 1.976 | 3.202 | 3.070 |
| 15.000     | 2.105 | 1.874 | 3.219 | 3.042 |
| 15.125     | 1.887 | 1.835 | 2.993 | 3.154 |
| 15.250     | 1.956 | 1.833 | 2.881 | 3.156 |
| 15.375     | 2.057 | 1.851 | 2.769 | 2.911 |
| 15.500     | 2.147 | 1.915 | 2.536 | 2.780 |
| 15.625     | 2.197 | 1.901 | 2.500 | 2.687 |
| 15.750     | 2.286 | 1.983 | 2.463 | 2.631 |
| 15.875     | 2.343 | 1.962 | 2.439 | 2.537 |
| 16.000     | 2.349 | 2.000 | 2.358 | 2.520 |
| 16.125     | 2.284 | 2.077 | 2.405 | 2.497 |
| 16.250     | 2.264 | 2.076 | 2.388 | 2.422 |
| 16.375     | 2.289 | 2.048 | 2.493 | 2.255 |
| 16.500     | 2.346 | 2.060 | 2.624 | 2.476 |
| 16.625     | 2.248 | 2.091 | 2.627 | 2.887 |
| 17.313     |       | 2.532 |       | 2.666 |
| 17.938     |       | 2.595 |       | 2.708 |
| 18.563     |       | 2.529 |       | 2.576 |
| 19.188     |       | 2.310 |       | 2.512 |
| 19.813     |       | 2.358 |       | 2.397 |
| 20.438     |       | 1.922 |       | 2.111 |
| 21.063     |       | 1.916 |       | 2.151 |
| 21.688     |       | 1.934 |       | 2.105 |
| 22.313     |       | 2.148 |       | 2.089 |
| 22.938     |       | 2.273 |       | 2.326 |
| 23.563     |       | 2.377 |       | 2.563 |
| 24.188     |       | 2.376 |       | 2.622 |
| 24.813     |       |       |       | 2.852 |
| 25.438     |       |       |       | 3.390 |

Rough Channel:  $Re = 60,000$ ,  $P/e = 10$ ,  $e/D = 0.063$ ,  $\alpha = 60^\circ$

TOE WALL

| X/H    | Y/H    | Y/H   | Y/H   |
|--------|--------|-------|-------|
|        | BEFORE | TURN  |       |
| 9.313  | 3.522  | 3.871 | 3.413 |
| 9.375  | 2.614  | 3.512 | 3.247 |
| 9.438  | RIB    | 3.347 | 3.083 |
| 9.500  | RIB    | 3.022 | 2.884 |
| 9.563  | RIB    | RIB   | 2.747 |
| 9.625  | 2.812  | RIB   | 2.567 |
| 9.688  | 3.952  | RIB   | RIB   |
| 9.750  | 4.465  | 2.190 | RIB   |
| 9.813  | 4.276  | 3.421 | RIB   |
| 9.875  | 3.719  | 3.717 | 1.946 |
| 9.938  | 3.142  | 3.574 | 2.387 |
| 10.000 | 2.095  | 3.290 | 2.609 |
| 10.063 | RIB    | 3.021 | 2.609 |
| 10.125 | RIB    | 2.692 | 2.495 |
| 10.188 | RIB    | RIB   | 2.442 |
| 10.250 | 3.052  | RIB   | 2.382 |
| 10.313 | 4.394  | RIB   | RIB   |
| 10.375 | 4.447  | 2.524 | RIB   |
| 10.438 | 4.019  | 2.978 | RIB   |
| 10.500 | 3.310  | 3.672 | 1.972 |
| 10.563 | 2.595  | 3.881 | 2.671 |
| 10.625 | 1.826  | 3.697 | 2.880 |
| 10.688 | RIB    | 3.270 | 2.941 |
| 10.750 | RIB    | 2.712 | 2.910 |
| 10.813 | RIB    | RIB   | 2.771 |
| 10.875 | 3.028  | RIB   | 2.719 |
| 10.938 | 4.089  | RIB   | RIB   |
| 11.000 | 4.233  | 3.555 | RIB   |
| 11.063 | 3.671  | 2.915 | RIB   |
| 11.125 | 2.834  | 3.664 | 1.811 |
| 11.188 | 2.081  | 3.644 | 2.477 |
| 11.250 | 1.802  | 3.710 | 2.180 |
| 11.313 | RIB    | 2.694 | 2.180 |
| 11.375 | RIB    | 2.047 | 1.844 |
| 11.438 | RIB    | RIB   | 1.844 |
| 11.500 | 2.814  | RIB   | 1.844 |
| 11.563 | 4.111  | RIB   | 1.844 |
| 11.625 | 3.719  | 2.694 | 1.844 |

|        | IN TURN |       |       |
|--------|---------|-------|-------|
| 11.875 | 1.732   | 2.642 | 1.840 |
| 12.375 | 1.631   | 1.680 | 1.720 |
| 12.875 | 1.927   | 1.728 | 1.987 |
| 13.125 | 1.794   | 1.785 | 1.902 |
| 13.625 | 1.664   | 1.910 | 2.071 |
| 14.125 | 1.907   | 2.221 | 2.265 |

|        | AFTER TURN |       |       |
|--------|------------|-------|-------|
| 14.375 | 1.702      | 2.209 | RIB   |
| 14.438 | 1.531      | RIB   | RIB   |
| 14.500 | 2.438      | RIB   | 2.355 |
| 14.563 | RIB        | RIB   | 2.554 |
| 14.625 | RIB        | 2.287 | 2.599 |
| 14.688 | RIB        | 2.928 | 2.673 |
| 14.750 | 2.352      | 3.151 | 2.690 |
| 14.813 | 2.873      | 3.299 | 2.646 |
| 14.875 | 3.362      | 3.299 | 2.684 |
| 14.938 | 3.506      | 3.182 | RIB   |
| 15.000 | 3.529      | 3.065 | RIB   |
| 15.063 | 3.389      | RIB   | RIB   |
| 15.125 | 3.199      | RIB   | 2.531 |
| 15.188 | RIB        | RIB   | 3.009 |
| 15.250 | RIB        | 2.675 | 3.008 |
| 15.313 | RIB        | 3.440 | 2.878 |
| 15.375 | 2.566      | 3.600 | 2.753 |
| 15.438 | 3.397      | 3.498 | 2.639 |
| 15.500 | 3.394      | 3.220 | 2.547 |
| 15.563 | 3.280      | 3.083 | RIB   |
| 15.625 | 3.169      | 2.789 | RIB   |
| 15.688 | 2.985      | RIB   | RIB   |
| 15.750 | 2.805      | RIB   | 1.967 |
| 15.813 | RIB        | RIB   | 2.674 |
| 15.875 | RIB        | 1.817 | 2.815 |
| 15.938 | RIB        | 2.874 | 2.761 |
| 16.000 | 2.012      | 2.969 | 2.618 |
| 16.063 | 2.637      | 2.908 | 2.419 |
| 16.125 | 2.917      | 2.827 | 2.245 |
| 16.188 | 2.898      | 2.631 | RIB   |
| 16.250 | 2.844      | 2.526 | RIB   |
| 16.313 | 2.670      | RIB   | RIB   |
| 16.375 | 2.592      | RIB   | 2.719 |
| 16.438 | RIB        | RIB   | 2.269 |
| 16.500 | RIB        | 2.226 | 1.215 |
| 16.563 | RIB        | 2.968 | 2.961 |
| 16.625 | 2.170      | 3.013 | 2.500 |
| 16.688 | 2.781      | 3.000 | 2.150 |

| -----  |            |       |            |       |
|--------|------------|-------|------------|-------|
|        | OUTER WALL | AND   | INNER WALL |       |
| -----  |            |       |            |       |
| N/L    | I.L.       | O.L.  | I.L.       | O.L.  |
| -----  |            |       |            |       |
|        | BEFORE     |       | TURN       |       |
| -----  |            |       |            |       |
|        | OUTER      | WALL  | INNER      | WALL  |
| -----  |            |       |            |       |
| 9.375  | 2.070      | 2.083 | 2.191      | 1.680 |
| 9.500  | 2.004      | 2.596 | 2.574      | 1.670 |
| 9.625  | 1.926      | 2.075 | 2.504      | 1.634 |
| 9.750  | 1.880      | 2.159 | 2.237      | 1.621 |
| 9.875  | 1.918      | 2.177 | 2.208      | 1.590 |
| 10.000 | 1.932      | 2.142 | 2.413      | 1.643 |
| 10.125 | 1.939      | 2.137 | 2.525      | 1.636 |
| 10.250 | 1.916      | 2.148 | 2.566      | 1.618 |
| 10.375 | 1.881      | 2.109 | 2.308      | 1.721 |
| 10.500 | 1.918      | 2.108 | 2.085      | 1.742 |
| 10.625 | 1.936      | 2.083 | 2.126      | 1.740 |
| 10.750 | 1.905      | 2.063 | 2.434      | 1.716 |
| 10.875 | 1.863      | 2.013 | 2.512      | 1.696 |
| 11.000 | 1.843      | 2.009 | 2.328      | 1.657 |
| 11.125 | 1.835      | 1.924 | 2.144      | 1.671 |
| 11.250 | 1.788      | 1.885 | 2.482      | 1.707 |
| 11.375 | 1.786      | 1.813 | 2.849      | 1.710 |
| 11.500 | 1.761      | 1.805 | 2.881      | 1.743 |
| 11.625 | 1.803      | 1.779 |            |       |

|        |       | IN    | TURN |
|--------|-------|-------|------|
| 11.875 | 1.987 | 1.775 |      |
| 12.375 | 2.232 | 2.776 |      |
| 12.875 | 2.566 | 2.228 |      |
| 13.125 | 2.426 | 1.996 |      |
| 13.625 | 2.171 | 2.100 |      |
| 14.125 | 2.696 | 2.158 |      |

|        |       | AFTER | TURN  |       |
|--------|-------|-------|-------|-------|
| 14.375 | 2.528 | 1.975 |       |       |
| 14.500 | 2.653 | 1.968 | 2.486 | 1.890 |
| 14.625 | 2.624 | 2.040 | 2.587 | 2.077 |
| 14.750 | 2.543 | 2.041 | 2.685 | 2.171 |
| 14.875 | 2.485 | 2.047 | 2.686 | 2.356 |
| 15.000 | 2.404 | 2.094 | 2.724 | 2.489 |
| 15.125 | 2.352 | 2.113 | 2.751 | 2.557 |
| 15.250 | 2.365 | 2.221 | 2.754 | 2.518 |
| 15.375 | 2.549 | 2.234 | 2.751 | 2.621 |
| 15.500 | 2.625 | 2.362 | 2.718 | 2.577 |
| 15.625 | 2.650 | 2.368 | 2.673 | 2.523 |
| 15.750 | 2.636 | 2.400 | 2.569 | 2.511 |
| 15.875 | 2.603 | 2.378 | 2.518 | 2.503 |
| 16.000 | 2.490 | 2.337 | 2.434 | 2.457 |
| 16.125 | 2.350 | 2.301 | 2.357 | 2.369 |
| 16.250 | 2.301 | 2.267 | 2.376 | 2.314 |
| 16.375 | 2.302 | 2.241 | 2.275 | 2.305 |
| 16.500 | 2.218 | 2.196 | 2.266 | 2.274 |
| 16.625 | 2.030 | 2.170 | 2.176 | 2.157 |

Rough Channel:  $Re = 15,000$ ,  $P/e = 10$ ,  $e/D = 0.063$ ,  $\alpha = 45^\circ$

| X/D    | TOP WALL |       | Y/D   |
|--------|----------|-------|-------|
|        | 0.12     | 0.12  |       |
|        | BEFORE   | TURN  |       |
| 8.875  | 3.180    | 3.255 | 1.948 |
| 8.938  | 3.974    | 4.461 | RIF   |
| 9.000  | 1.544    | 4.184 | RIF   |
| 9.063  | RIF      | 3.619 | 2.725 |
| 9.125  | RIF      | 2.443 | 2.843 |
| 9.188  | 4.958    | 2.708 | 2.448 |
| 9.250  | 6.088    | 2.223 | 2.305 |
| 9.313  | 6.454    | RIF   | 2.517 |
| 9.375  | 4.465    | RIF   | 2.241 |
| 9.438  | 3.303    | 2.124 | 2.117 |
| 9.500  | 2.703    | 2.671 | 1.968 |
| 9.563  | 2.261    | 4.512 | RIF   |
| 9.625  | 1.810    | 3.983 | RIF   |
| 9.688  | RIF      | 3.013 | 2.734 |
| 9.750  | RIF      | 2.565 | 2.541 |
| 9.813  | 5.757    | 2.443 | 2.363 |
| 9.875  | 6.855    | RIF   | 2.225 |
| 9.938  | 6.231    | RIF   | 2.219 |
| 10.000 | 5.114    | RIF   | 2.174 |
| 10.063 | 3.547    | 2.245 | 2.117 |
| 10.125 | 2.298    | 3.376 | 1.643 |
| 10.188 | 1.635    | 4.460 | RIF   |
| 10.250 | 1.751    | 4.117 | RIF   |
| 10.313 | RIF      | 3.143 | 2.843 |
| 10.375 | RIF      | 1.953 | 2.216 |
| 10.438 | 4.893    | 2.073 | 2.104 |
| 10.500 | 6.045    | 1.217 | 2.287 |
| 10.563 | 5.434    | RIF   | 2.245 |
| 10.625 | 4.345    | RIF   | 1.904 |
| 10.688 | 3.514    | 1.178 | 2.117 |
| 10.750 | 2.363    | 2.933 | 1.948 |
| 10.813 | 1.887    | 4.355 | RIF   |
| 10.875 | 1.253    | 4.185 | RIF   |
| 10.938 | RIF      | 3.485 | 2.458 |
| 11.000 | RIF      | 2.379 | 2.565 |
| 11.063 | 4.688    | 2.223 | 2.241 |
| 11.125 | 3.545    | 2.124 | 2.117 |
| 11.188 | 2.715    | 2.671 | 1.968 |
| 11.250 | 4.153    | RIF   | 2.241 |

|        |       |       |       |
|--------|-------|-------|-------|
| 11.313 | 3.646 | 2.548 | 3.061 |
| 11.375 | 2.868 | 2.879 | 2.647 |
| 11.438 | 2.472 | 4.337 | RIB   |
| 11.500 | 2.190 | 4.126 | RIB   |
| 11.563 | 1.959 | 3.316 | 1.860 |
| 11.625 | 1.954 | 2.688 | 2.173 |

-----  
IN TURN

|        |       |       |       |
|--------|-------|-------|-------|
| 11.875 | 2.120 | 2.195 | 1.935 |
| 12.375 | 2.179 | 2.411 | 2.139 |
| 12.875 | 2.639 | 2.434 | 2.180 |
| 13.125 | 2.543 | 2.415 | 2.292 |
| 13.625 | 2.651 | 2.141 | 2.151 |
| 14.125 | 2.319 | 2.321 | 2.117 |

-----  
AFTER TURN

|        |       |       |       |
|--------|-------|-------|-------|
| 14.375 | 2.518 | 2.310 | 2.230 |
| 14.438 | 2.525 | 2.307 | 2.202 |
| 14.500 | 2.453 | 2.089 | RIB   |
| 14.563 | 2.451 | 2.656 | RIB   |
| 14.625 | 2.310 | 3.598 | 2.220 |
| 14.688 | 2.022 | 2.254 | 3.283 |
| 14.750 | 1.751 | RIB   | 2.770 |
| 14.813 | 1.201 | RIB   | 3.080 |
| 14.875 | 2.544 | 2.273 | 3.609 |
| 14.938 | 1.437 | 1.862 | 3.956 |
| 15.000 | RIB   | 2.225 | 4.182 |
| 15.063 | RIB   | 2.763 | 4.007 |
| 15.125 | 2.326 | 3.214 | RIB   |
| 15.188 | 2.114 | 3.736 | RIB   |
| 15.250 | 2.697 | 4.549 | 2.719 |
| 15.313 | 3.588 | 4.943 | 2.184 |
| 15.375 | 4.026 | RIB   | 2.480 |
| 15.438 | 4.455 | RIB   | 2.907 |
| 15.500 | 4.622 | 3.215 | 3.432 |
| 15.563 | 4.790 | 3.012 | 3.713 |
| 15.625 | RIB   | 3.503 | 3.669 |
| 15.688 | RIB   | 3.978 | 2.857 |
| 15.750 | 2.832 | 3.968 | RIB   |
| 15.813 | 2.839 | 3.790 | RIB   |
| 15.875 | 3.597 | 3.710 | 1.463 |
| 15.938 | 4.348 | 3.267 | 2.097 |
| 16.000 | 4.446 | RIB   | 2.785 |
| 16.063 | 4.428 | RIB   | 3.209 |
| 16.125 | 3.966 | 2.535 | 3.261 |
| 16.188 | 3.593 | 2.720 | 2.975 |
| 16.250 | RIB   | 3.011 | 2.938 |
| 16.313 | RIB   | 3.276 | 1.393 |
| 16.375 | 1.566 | 3.108 | RIB   |

|        |       |       |       |
|--------|-------|-------|-------|
| 16.438 | 1.722 | 1.498 | RIB   |
| 16.500 | 2.600 | 1.351 | 2.441 |
| 16.563 | 3.486 | 1.155 | 2.755 |
| 16.625 | 3.616 | RIB   | 2.135 |
| 16.688 | 3.896 | RIB   | 3.141 |
| 16.750 | 3.590 | 1.121 | 2.859 |
| 16.813 | 2.053 | 1.746 | 2.723 |
| 16.875 | RIB   | 2.731 | 2.532 |
| 16.938 | RIB   | 3.044 | 2.450 |
| 17.000 | RIB   | 3.222 | RIB   |
| 17.063 | 1.879 | 3.175 | RIB   |
| 17.125 | 2.534 | 3.055 | 2.476 |

| -----       |       |       |            |       |
|-------------|-------|-------|------------|-------|
| OUTER WALL  |       | AND   | INNER WALL |       |
| -----       |       |       |            |       |
| X/D         | I.L.  | C.L.  | I.L.       | C.L.  |
| -----       |       |       |            |       |
| BEFORE TURN |       |       |            |       |
| -----       |       |       |            |       |
|             | OUTER | WALL  | INNER      | WALL  |
| -----       |       |       |            |       |
| 8.875       | 1.903 | 2.069 | 2.270      | 1.950 |
| 9.000       | 1.918 | 2.129 | 2.555      | 2.020 |
| 9.125       | 1.943 | 2.109 | 2.497      | 1.918 |
| 9.250       | 1.922 | 2.132 | 2.421      | 1.879 |
| 9.375       | 2.017 | 2.165 | 2.506      | 1.822 |
| 9.500       | 1.987 | 2.143 | 2.627      | 1.757 |
| 9.625       | 1.949 | 2.149 | 2.266      | 1.826 |
| 9.750       | 1.991 | 2.155 | 2.307      | 1.796 |
| 9.875       | 1.987 | 2.249 | 2.658      | 1.820 |
| 10.000      | 1.922 | 2.343 | 2.494      | 1.844 |
| 10.125      | 1.884 | 2.391 | 2.542      | 1.893 |
| 10.250      | 1.898 | 2.405 | 2.838      | 1.917 |
| 10.375      | 1.975 | 2.340 | 3.035      | 1.940 |
| 10.500      | 2.024 | 2.204 | 2.897      | 2.007 |
| 10.625      | 1.907 | 2.121 | 2.769      | 2.012 |
| 10.750      | 1.947 | 2.091 | 3.026      | 2.017 |
| 10.875      | 1.892 | 2.123 | 3.108      | 2.066 |
| 11.000      | 1.880 | 2.093 | 3.068      | 2.089 |
| 11.125      | 1.825 | 2.107 | 3.375      | 1.990 |
| 11.250      | 1.710 | 2.035 | 3.447      | 1.926 |
| 11.375      | 1.664 | 1.980 | 3.155      | 1.940 |
| 11.500      | 1.627 | 1.666 | 3.141      | 1.859 |
| 11.625      | 1.659 | 1.543 |            |       |

| -----  |       |       |
|--------|-------|-------|
|        | IN    | TURN  |
| -----  |       |       |
| 11.875 | 1.935 | 1.645 |
| 12.375 | 2.435 | 1.707 |
| 12.875 | 2.854 | 1.768 |
| 13.125 | 2.894 | 1.709 |
| 13.625 | 2.495 | 2.361 |
| 14.125 | 2.769 | 3.040 |

| -----  |       |       |       |       |
|--------|-------|-------|-------|-------|
|        | AFTER | TURN  |       |       |
| -----  |       |       |       |       |
| 14.375 | 2.650 | 3.114 |       |       |
| 14.500 | 2.743 | 2.957 | 1.967 | 2.449 |
| 14.625 | 2.724 | 2.947 | 1.075 | 2.881 |
| 14.750 | 2.670 | 2.859 | 3.172 | 3.087 |
| 14.875 | 2.581 | 2.736 | 3.042 | 3.314 |
| 15.000 | 2.344 | 2.517 | 3.305 | 3.237 |
| 15.125 | 2.167 | 2.270 | 3.271 | 3.160 |
| 15.250 | 1.884 | 1.987 | 3.221 | 3.188 |
| 15.375 | 1.767 | 1.914 | 3.109 | 3.277 |
| 15.500 | 1.675 | 1.805 | 2.917 | 3.086 |
| 15.625 | 1.786 | 1.846 | 2.813 | 3.009 |
| 15.750 | 2.232 | 1.824 | 2.681 | 2.771 |
| 15.875 | 2.600 | 1.935 | 2.673 | 2.736 |
| 16.000 | 2.722 | 1.994 | 2.514 | 2.507 |
| 16.125 | 2.774 | 2.097 | 2.541 | 2.480 |
| 16.250 | 2.808 | 2.165 | 2.470 | 2.605 |
| 16.375 | 2.716 | 2.242 | 2.674 | 2.676 |
| 16.500 | 2.687 | 2.337 | 2.656 | 2.774 |
| 16.625 | 2.560 | 2.406 | 3.256 | 2.846 |
| 16.750 | 2.459 | 2.546 | 3.042 | 2.901 |
| 16.875 | 2.402 | 2.553 | 2.917 | 2.766 |
| 17.000 | 2.488 | 2.577 | 2.998 | 2.856 |
| 17.125 | 2.269 | 2.547 | 3.197 | 2.991 |

Rough Channel:  $Re=30,000$ ,  $P/e=10$ ,  $e/D=0.063$ ,  $\alpha = 45^\circ$

| ----- |      |        |       |
|-------|------|--------|-------|
|       |      | TOP    | WALL  |
| ----- |      |        |       |
| X/D   | O.L. | C.L.   | I.L.  |
| ----- |      |        |       |
|       |      | BEFORE | TURN  |
| ----- |      |        |       |
| 0.625 |      |        | 1.609 |
| 0.688 |      |        | 3.180 |
| 0.750 |      |        | 4.713 |
| 0.813 |      |        | 4.237 |
| 0.875 |      |        | 3.835 |
| 0.938 |      |        | 3.459 |
| 1.000 |      |        | 2.919 |
| 1.063 |      |        | 3.247 |
| 1.250 |      |        | 1.849 |
| 1.313 |      |        | 2.604 |
| 1.375 |      |        | 3.197 |
| 1.438 |      |        | 3.676 |
| 1.500 |      |        | 3.370 |
| 1.563 |      |        | 3.002 |
| 1.625 |      |        | 2.799 |
| 1.688 |      |        | 2.733 |
| 2.125 |      |        | 2.706 |
| 2.750 |      |        | 2.550 |
| 3.375 |      |        | 2.535 |
| 4.000 |      |        | 2.475 |
| 4.625 |      |        | 2.416 |
| 5.250 |      |        | 2.320 |
| 5.875 |      |        | 2.147 |
| 6.250 |      |        | 1.886 |
| 6.313 |      |        | 3.014 |
| 6.375 |      |        | 2.750 |
| 6.438 |      |        | 2.579 |
| 6.500 |      |        | 2.358 |
| 6.563 |      |        | 2.153 |
| 6.625 |      |        | 1.896 |
| 6.688 |      |        | 1.910 |
| 6.875 |      |        | 1.758 |
| 6.938 |      |        | 3.074 |
| 7.000 |      |        | 2.705 |
| 7.063 |      |        | 2.520 |
| 7.125 |      |        | 2.267 |
| 7.188 |      |        | 2.109 |
| 7.250 |      |        | 1.963 |
| 7.313 |      |        | 1.912 |

|        |       |       |       |
|--------|-------|-------|-------|
| 7.750  |       | 1.170 |       |
| 8.275  |       | 1.400 |       |
| 8.875  | 1.000 | 1.800 | 1.200 |
| 8.975  | 1.400 | 1.800 | RIB   |
| 9.000  | 1.800 | 1.634 | RIB   |
| 9.000  | RIB   | 1.100 | 1.470 |
| 9.125  | RIB   | 1.310 | 2.500 |
| 9.188  | 4.480 | 1.600 | 1.300 |
| 9.250  | 4.320 | 1.500 | 1.300 |
| 9.313  | 5.100 | RIB   | 1.300 |
| 9.375  | 4.280 | RIB   | 2.400 |
| 9.438  | 3.442 | 1.600 | 2.180 |
| 9.500  | 2.664 | 2.200 | 1.686 |
| 9.563  | 1.758 | 3.782 | RIB   |
| 9.625  | 1.781 | 3.775 | RIB   |
| 9.688  | RIB   | 3.387 | 1.905 |
| 9.750  | RIB   | 2.755 | 2.521 |
| 9.813  | 3.892 | 2.021 | 2.282 |
| 9.875  | 3.862 | 2.112 | 2.600 |
| 9.938  | 4.751 | RIB   | 2.963 |
| 10.000 | 3.865 | RIB   | 2.860 |
| 10.063 | 3.043 | 1.859 | 2.639 |
| 10.125 | 2.306 | 1.846 | 2.355 |
| 10.188 | 1.719 | 3.430 | RIB   |
| 10.250 | 1.771 | 3.520 | RIB   |
| 10.313 | RIB   | 3.164 | 2.367 |
| 10.375 | RIB   | 2.566 | 2.368 |
| 10.438 | 4.784 | 1.924 | 2.187 |
| 10.500 | 4.832 | 1.930 | 2.491 |
| 10.563 | 4.784 | RIB   | 2.826 |
| 10.625 | 3.761 | RIB   | 2.710 |
| 10.688 | 3.064 | 2.329 | 2.630 |
| 10.750 | 2.391 | 2.339 | 2.143 |
| 10.813 | 2.089 | 4.096 | RIB   |
| 10.875 | 1.703 | 4.016 | RIB   |
| 10.938 | RIB   | 3.473 | 2.607 |
| 11.000 | RIB   | 2.820 | 2.869 |
| 11.063 | 4.035 | 2.524 | 2.666 |
| 11.125 | 4.328 | 2.145 | 3.330 |
| 11.188 | 4.538 | RIB   | 3.602 |
| 11.250 | 3.659 | RIB   | 3.468 |
| 11.313 | 3.119 | 2.313 | 3.367 |
| 11.375 | 2.618 | 2.873 | 2.800 |
| 11.438 | 2.474 | 3.997 | RIB   |
| 11.500 | 2.300 | 4.686 | RIB   |
| 11.563 | 2.507 | 3.204 | 2.120 |
| 11.625 | 2.490 | 2.950 | 2.610 |

|        | IN TURN |       |       |
|--------|---------|-------|-------|
| 11.875 | 2.565   | 2.653 | 2.375 |
| 12.375 | 2.354   | 2.477 | 2.465 |
| 12.875 | 2.718   | 2.567 | 2.596 |
| 13.125 | 2.731   | 2.652 | 2.757 |
| 13.625 | 2.476   | 2.454 | 2.601 |
| 14.125 | 2.860   | 2.835 | 2.835 |

|        | AFTER TURN |       |       |
|--------|------------|-------|-------|
| 14.375 | 2.965      | 2.889 | 2.939 |
| 14.438 | 3.187      | 2.939 | 3.831 |
| 14.500 | 3.182      | 2.868 | RIB   |
| 14.563 | 3.166      | 3.627 | RIB   |
| 14.625 | 2.601      | 5.242 | 2.719 |
| 14.688 | 2.180      | 5.279 | 3.392 |
| 14.750 | 2.057      | RIB   | 3.143 |
| 14.813 | 1.967      | RIB   | 3.410 |
| 14.875 | 2.535      | 1.740 | 3.884 |
| 14.938 | 4.609      | 2.062 | 4.309 |
| 15.000 | RIB        | 2.246 | 4.535 |
| 15.063 | RIB        | 2.983 | 4.229 |
| 15.125 | 3.228      | 3.553 | RIB   |
| 15.188 | 3.324      | 3.840 | RIB   |
| 15.250 | 3.622      | 4.479 | 3.388 |
| 15.313 | 4.448      | 4.841 | 3.368 |
| 15.375 | 4.523      | RIB   | 3.206 |
| 15.438 | 4.609      | RIB   | 3.263 |
| 15.500 | 4.764      | 3.123 | 3.607 |
| 15.563 | 4.930      | 3.338 | 3.660 |
| 15.625 | RIB        | 3.570 | 3.650 |
| 15.688 | RIB        | 3.830 | 2.844 |
| 15.750 | 2.786      | 3.820 | RIB   |
| 15.813 | 2.730      | 3.781 | RIB   |
| 15.875 | 3.929      | 3.743 | 2.624 |
| 15.938 | 4.514      | 3.507 | 2.959 |
| 16.000 | 4.499      | RIB   | 3.447 |
| 16.063 | 4.251      | RIB   | 3.448 |
| 16.125 | 3.924      | 2.835 | 3.471 |
| 16.188 | 3.562      | 2.977 | 3.137 |
| 16.250 | RIB        | 3.296 | 3.132 |
| 16.313 | RIB        | 3.718 | 2.825 |
| 16.375 | 2.635      | 3.724 | RIB   |
| 16.438 | 2.732      | 3.811 | RIB   |
| 16.500 | 3.548      | 3.623 | 2.580 |
| 16.563 | 4.150      | 3.509 | 2.814 |
| 16.625 | 4.117      | RIB   | 3.021 |
| 16.688 | 3.608      | RIB   | 2.918 |
| 16.750 | 3.819      | 3.971 | 2.706 |

|        |       |       |       |
|--------|-------|-------|-------|
| 16.813 | 3.633 | 2.134 | 2.447 |
| 16.875 | R1B   | 2.791 | 2.527 |
| 16.938 | R1B   | 2.974 | 2.275 |
| 17.000 | 1.674 | 2.947 | R1B   |
| 17.063 | 1.326 | 2.813 | R1B   |
| 17.125 | 2.547 | 2.796 | 2.002 |
| 17.625 |       | 3.092 |       |
| 18.250 |       | 3.295 |       |
| 18.688 |       | 1.894 |       |
| 18.750 |       | 2.368 |       |
| 18.813 |       | 3.378 |       |
| 18.875 |       | 2.663 |       |
| 19.938 |       | 2.376 |       |
| 19.000 |       | 2.247 |       |
| 19.063 |       | 2.085 |       |
| 19.125 |       | 2.026 |       |
| 19.313 |       | 1.744 |       |
| 19.375 |       | 2.572 |       |
| 19.438 |       | 3.430 |       |
| 19.500 |       | 3.020 |       |
| 19.563 |       | 2.649 |       |
| 19.625 |       | 2.443 |       |
| 19.688 |       | 2.212 |       |
| 19.750 |       | 2.031 |       |
| 20.125 |       | 2.835 |       |
| 20.750 |       | 2.725 |       |
| 21.375 |       | 2.568 |       |
| 22.000 |       | 2.552 |       |
| 22.625 |       | 2.491 |       |
| 23.250 |       | 2.400 |       |
| 23.875 |       | 2.511 |       |
| 24.313 |       | 1.908 |       |
| 24.375 |       | 2.667 |       |
| 24.438 |       | 3.480 |       |
| 24.500 |       | 2.979 |       |
| 24.563 |       | 2.704 |       |
| 24.625 |       | 2.318 |       |
| 24.688 |       | 2.058 |       |
| 24.750 |       | 2.017 |       |
| 24.938 |       | 1.816 |       |
| 25.000 |       | 2.041 |       |
| 25.063 |       | 3.219 |       |
| 25.125 |       | 2.577 |       |
| 25.188 |       | 2.076 |       |
| 25.250 |       | 1.925 |       |
| 25.313 |       | 1.910 |       |
| 25.375 |       | 2.279 |       |

| -----       |       |       |            |       |
|-------------|-------|-------|------------|-------|
| OUTER WALL  |       | AND   | INNER WALL |       |
| -----       |       |       |            |       |
| X/D         | I.L.  | C.L.  | I.L.       | C.L.  |
| -----       |       |       |            |       |
| BEFORE TURN |       |       |            |       |
| -----       |       |       |            |       |
|             | OUTER | WALL  | INNER      | WALL  |
| -----       |       |       |            |       |
| 0.875       |       | 2.904 |            | 2.717 |
| 1.500       |       | 2.255 |            | 2.195 |
| 2.125       |       | 2.020 |            | 1.959 |
| 2.750       |       | 1.898 |            | 2.011 |
| 3.375       |       | 1.793 |            | 1.964 |
| 4.000       |       | 1.661 |            | 1.967 |
| 4.625       |       | 1.605 |            | 1.889 |
| 5.250       |       | 1.528 |            | 2.004 |
| 5.875       |       | 1.539 |            | 1.982 |
| 6.500       |       | 1.538 |            | 2.002 |
| 7.125       |       | 1.489 |            | 1.811 |
| 7.750       |       | 1.464 |            | 1.829 |
| 8.375       |       | 1.829 |            | 1.700 |
| 8.875       | 1.891 | 2.135 | 2.011      | 1.470 |
| 9.000       | 1.890 | 2.214 | 1.980      | 1.583 |
| 9.125       | 1.951 | 2.160 | 1.971      | 1.501 |
| 9.250       | 1.955 | 2.169 | 1.934      | 1.676 |
| 9.375       | 2.016 | 2.144 | 2.125      | 1.639 |
| 9.500       | 2.060 | 2.164 | 2.150      | 1.573 |
| 9.625       | 1.915 | 2.139 | 1.895      | 1.656 |
| 9.750       | 1.982 | 2.177 | 2.092      | 1.580 |
| 9.875       | 1.991 | 2.169 | 2.167      | 1.582 |
| 10.000      | 1.886 | 2.155 | 2.004      | 1.579 |
| 10.125      | 1.946 | 2.186 | 2.029      | 1.571 |
| 10.250      | 1.921 | 2.223 | 2.070      | 1.590 |
| 10.375      | 1.970 | 2.029 | 2.202      | 1.689 |
| 10.500      | 1.984 | 2.195 | 2.096      | 1.759 |
| 10.625      | 1.954 | 2.169 | 2.047      | 1.756 |
| 10.750      | 2.029 | 2.116 | 2.379      | 1.724 |
| 10.875      | 1.932 | 2.029 | 2.548      | 1.782 |
| 11.000      | 1.952 | 2.049 | 2.627      | 1.779 |
| 11.125      | 1.928 | 2.063 | 2.873      | 1.837 |
| 11.250      | 1.870 | 2.017 | 2.951      | 1.934 |
| 11.375      | 1.990 | 2.020 | 2.851      | 1.953 |
| 11.500      | 2.049 | 1.929 | 2.896      | 2.110 |
| 11.625      | 2.069 | 1.910 | 2.260      | 2.172 |

# 18 TUBE

|        |       |       |
|--------|-------|-------|
| 11.875 | 2.163 | 2.507 |
| 12.375 | 2.281 | 2.604 |
| 12.875 | 2.155 | 2.676 |
| 13.125 | 1.729 | 1.841 |
| 13.625 | 2.220 | 2.344 |
| 14.125 | 2.831 | 2.968 |

## AFTER TUBE

|        |       |       |       |       |
|--------|-------|-------|-------|-------|
| 14.375 | 2.507 | 2.699 | 2.734 | 2.779 |
| 14.500 | 2.229 | 2.682 | 2.837 | 2.816 |
| 14.625 | 2.145 | 2.454 | 2.706 | 2.731 |
| 14.750 | 2.178 | 2.455 | 2.687 | 2.764 |
| 14.875 | 2.054 | 2.542 | 2.273 | 2.418 |
| 15.000 | 1.924 | 2.374 | 2.039 | 2.850 |
| 15.125 | 1.761 | 2.234 | 2.104 | 2.982 |
| 15.250 | 1.680 | 2.189 | 2.067 | 2.481 |
| 15.375 | 1.757 | 2.236 | 2.034 | 2.381 |
| 15.500 | 1.756 | 2.260 | 2.907 | 2.984 |
| 15.625 | 2.013 | 2.175 | 2.771 | 2.878 |
| 15.750 | 2.181 | 2.213 | 2.784 | 2.804 |
| 15.875 | 2.276 | 2.307 | 2.640 | 2.711 |
| 16.000 | 2.304 | 2.268 | 2.564 | 2.607 |
| 16.125 | 2.388 | 2.233 | 2.487 | 2.564 |
| 16.250 | 2.365 | 2.215 | 2.427 | 2.514 |
| 16.375 | 2.301 | 2.293 | 2.389 | 2.394 |
| 16.500 | 2.294 | 2.377 | 2.283 | 2.380 |
| 16.625 | 2.327 | 2.291 | 2.291 | 2.288 |
| 16.750 | 2.274 | 2.375 | 2.216 | 2.147 |
| 16.875 | 2.261 | 2.391 | 2.197 | 2.142 |
| 17.000 | 2.259 | 2.447 | 2.197 | 2.161 |
| 17.125 | 2.240 | 2.382 | 2.158 | 2.110 |
| 17.625 |       | 2.048 |       | 2.343 |
| 18.250 |       | 1.868 |       | 2.004 |
| 18.875 |       | 1.705 |       | 1.831 |
| 19.500 |       | 1.555 |       | 1.801 |
| 20.125 |       | 1.354 |       | 1.68  |
| 20.750 |       | 1.512 |       | 1.644 |
| 21.375 |       | 1.663 |       | 1.571 |
| 22.000 |       | 1.575 |       | 1.547 |
| 22.625 |       | 1.575 |       | 1.547 |
| 23.250 |       | 1.469 |       | 1.504 |
| 23.875 |       | 1.462 |       | 1.471 |
| 24.500 |       | 1.336 |       | 1.374 |
| 25.125 |       |       |       | 1.244 |

Rough Channel:  $Re=60,000$ ,  $P/e=10$ ,  $e/D=0.063$ ,  $\alpha = 45^\circ$

|        | T.M. WALL |       |       |
|--------|-----------|-------|-------|
| X/D    | 111       | 111   | 111   |
|        | BEFORE    | TURN  |       |
| 8.875  | 2.850     | 2.902 | 1.771 |
| 8.938  | 2.854     | 3.341 | RIB   |
| 9.000  | 2.590     | 2.842 | RIB   |
| 9.063  | RIB       | 2.297 | 2.200 |
| 9.125  | RIB       | 1.664 | 2.211 |
| 9.188  | 4.133     | 2.459 | 2.273 |
| 9.250  | 4.253     | 2.232 | 2.412 |
| 9.313  | 4.341     | RIB   | 2.341 |
| 9.375  | 2.846     | RIB   | 2.175 |
| 9.438  | 2.105     | 2.482 | 1.899 |
| 9.500  | 1.464     | 3.053 | 1.620 |
| 9.563  | 1.104     | 3.216 | RIB   |
| 9.625  | 0.9461    | 2.898 | RIB   |
| 9.688  | RIB       | 2.251 | 2.253 |
| 9.750  | RIB       | 1.888 | 2.194 |
| 9.813  | 3.947     | 1.596 | 2.276 |
| 9.875  | 3.455     | 1.445 | 2.464 |
| 9.938  | 3.317     | RIB   | 2.454 |
| 10.000 | 2.609     | RIB   | 2.334 |
| 10.063 | 2.039     | 1.903 | 2.134 |
| 10.125 | 1.536     | 3.142 | 1.867 |
| 10.188 | 2.040     | 3.008 | RIB   |
| 10.250 | 1.862     | 2.524 | RIB   |
| 10.313 | RIB       | 2.054 | 2.221 |
| 10.375 | RIB       | 1.540 | 1.928 |
| 10.438 | 4.182     | 1.769 | 2.167 |
| 10.500 | 4.250     | 1.630 | 2.297 |
| 10.563 | 3.644     | RIB   | 2.175 |
| 10.625 | 2.780     | RIB   | 1.896 |
| 10.688 | 2.110     | 2.546 | 1.869 |
| 10.750 | 1.681     | 2.571 | 1.556 |
| 10.813 | 2.009     | 2.11  | RIB   |
| 10.875 | 1.689     | 2.72  | RIB   |
| 10.938 | RIB       | 2.175 | 1.951 |
| 11.000 | RIB       | 1.896 | 1.771 |
| 11.063 | 2.11      | 1.556 | 1.847 |
| 11.125 | 2.175     | 1.867 | 1.771 |
| 11.188 | 1.867     | RIB   | 1.556 |
| 11.250 | 1.556     | RIB   | 1.771 |

|        |       |       |       |
|--------|-------|-------|-------|
| 11.314 | 1.894 | 1.514 | 1.894 |
| 11.375 | 1.899 | 1.504 | 1.794 |
| 11.438 | 1.514 | 1.477 | RIB   |
| 11.500 | 1.484 | 1.401 | RIB   |
| 11.563 | 1.474 | 1.604 | 1.734 |
| 11.625 | 1.544 | 1.394 | 1.534 |

IN TURN

|        |       |       |       |
|--------|-------|-------|-------|
| 11.875 | 1.734 | 1.514 | 1.454 |
| 12.375 | 1.614 | 1.824 | 1.680 |
| 12.875 | 1.860 | 1.787 | 1.708 |
| 13.125 | 1.816 | 1.723 | 1.814 |
| 13.625 | 1.736 | 1.663 | 1.775 |
| 14.125 | 2.067 | 1.721 | 1.884 |

AFTER TURN

|        |       |       |       |
|--------|-------|-------|-------|
| 14.375 | 1.891 | 1.675 | 2.302 |
| 14.438 | 1.959 | 1.587 | 1.903 |
| 14.500 | 1.895 | 1.516 | RIB   |
| 14.563 | 1.794 | 1.856 | RIB   |
| 14.625 | 1.713 | 3.398 | 1.816 |
| 14.688 | 1.514 | 3.045 | 2.200 |
| 14.750 | 3.384 | RIB   | 1.911 |
| 14.813 | 1.754 | RIB   | 2.025 |
| 14.875 | 2.319 | 1.529 | 2.406 |
| 14.938 | 3.456 | 1.980 | 3.018 |
| 15.000 | RIB   | 2.177 | 3.571 |
| 15.063 | RIB   | 2.500 | 2.996 |
| 15.125 | 2.066 | 2.914 | RIB   |
| 15.188 | 2.337 | 3.427 | RIB   |
| 15.250 | 1.891 | 3.783 | 1.750 |
| 15.313 | 3.733 | 2.876 | 2.308 |
| 15.375 | 4.083 | RIB   | 2.566 |
| 15.438 | 4.179 | RIB   | 2.618 |
| 15.500 | 4.243 | 1.667 | 2.681 |
| 15.563 | 3.873 | 1.388 | 2.706 |
| 15.625 | RIB   | 2.601 | 2.673 |
| 15.688 | RIB   | 2.727 | 2.311 |
| 15.750 | 2.314 | 2.811 | RIB   |
| 15.813 | 2.728 | 2.930 | RIB   |
| 15.875 | 3.586 | 2.983 | 2.492 |
| 15.938 | 4.302 | 3.124 | 2.826 |
| 16.000 | 4.167 | RIB   | 2.885 |
| 16.063 | 3.972 | RIB   | 2.784 |
| 16.125 | 3.312 | 1.528 | 2.649 |
| 16.188 | 3.137 | 1.467 | 1.749 |
| 16.250 | RIB   | 1.447 | 1.741 |
| 16.313 | RIB   | 1.524 | 1.777 |
| 16.375 | 1.447 | 1.464 | RIB   |

|        |       |       |       |
|--------|-------|-------|-------|
| 16.438 | 1.981 | 2.893 | RIB   |
| 16.500 | 2.700 | 2.861 | 2.802 |
| 16.563 | 3.349 | 3.028 | 2.976 |
| 16.625 | 3.559 | RIB   | 2.870 |
| 16.688 | 3.498 | RIB   | 2.571 |
| 16.750 | 3.428 | 1.826 | 2.410 |
| 16.813 | 3.677 | 2.035 | 2.172 |
| 16.875 | RIB   | 2.479 | 2.010 |
| 16.938 | RIB   | 2.692 | 1.828 |
| 17.000 | 1.958 | 2.673 | RIB   |
| 17.063 | 1.864 | 2.548 | RIB   |
| 17.125 | 2.545 | 2.461 | 2.634 |

|        | OUTER WALL | ANG.   | INNER WALL |       |
|--------|------------|--------|------------|-------|
| X/D    | I.L.       | ALL    | I.L.       | ALL   |
|        |            | BEFORE | TURN       |       |
|        | OUTER      | WALL   | INNER      | WALL  |
| 8.875  | 1.862      | 2.049  | 2.484      | 1.747 |
| 9.000  | 1.850      | 2.069  | 2.223      | 1.740 |
| 9.125  | 1.855      | 2.035  | 2.301      | 1.712 |
| 9.250  | 1.829      | 2.054  | 2.325      | 1.793 |
| 9.375  | 1.859      | 2.055  | 2.341      | 1.772 |
| 9.500  | 1.867      | 2.042  | 2.358      | 1.775 |
| 9.625  | 1.848      | 2.040  | 2.162      | 1.764 |
| 9.750  | 1.843      | 2.056  | 2.253      | 1.697 |
| 9.875  | 1.869      | 2.100  | 2.429      | 1.665 |
| 10.000 | 1.881      | 2.073  | 2.290      | 1.736 |
| 10.125 | 1.833      | 2.038  | 2.274      | 1.671 |
| 10.250 | 1.842      | 2.018  | 2.189      | 1.643 |
| 10.375 | 1.833      | 1.929  | 2.255      | 1.660 |
| 10.500 | 1.831      | 2.018  | 2.344      | 1.681 |
| 10.625 | 1.755      | 2.022  | 2.200      | 1.740 |
| 10.750 | 1.774      | 1.975  | 2.327      | 1.739 |
| 10.875 | 1.787      | 1.976  | 2.215      | 1.697 |
| 11.000 | 1.789      | 1.999  | 2.225      | 1.694 |
| 11.125 | 1.745      | 1.934  | 2.331      | 1.716 |
| 11.250 | 1.737      | 1.925  | 2.490      | 1.732 |
| 11.375 | 1.791      | 1.924  | 2.402      | 1.849 |
| 11.500 | 1.768      | 1.867  | 2.471      | 1.981 |
| 11.625 | 1.712      | 1.810  |            |       |

|        |       | ----- |       |       |
|--------|-------|-------|-------|-------|
|        |       | IN    | TURN  |       |
|        |       | ----- |       |       |
| 11.875 | 1.625 | 1.747 |       |       |
| 12.721 | 1.951 | 2.141 |       |       |
| 13.875 | 2.080 | 1.896 |       |       |
| 14.175 | 1.803 | 1.757 |       |       |
| 14.601 | 2.037 | 2.003 |       |       |
| 14.125 | 2.257 | 2.570 |       |       |
|        |       | ----- |       |       |
|        |       | AFTER | TURN  |       |
|        |       | ----- |       |       |
| 14.375 | 2.140 | 2.538 |       |       |
| 14.500 | 2.113 | 2.449 | 2.886 | 2.886 |
| 14.625 | 2.044 | 2.443 | 2.928 | 2.880 |
| 14.750 | 2.006 | 2.396 | 3.051 | 3.001 |
| 14.875 | 2.069 | 2.424 | 3.123 | 2.940 |
| 15.000 | 2.070 | 2.356 | 3.133 | 2.880 |
| 15.125 | 2.081 | 2.336 | 2.982 | 2.899 |
| 15.250 | 2.131 | 2.358 | 2.802 | 2.758 |
| 15.375 | 2.177 | 2.384 | 2.693 | 2.754 |
| 15.500 | 2.315 | 2.515 | 2.653 | 2.661 |
| 15.625 | 2.551 | 2.559 | 2.592 | 2.590 |
| 15.750 | 2.595 | 2.585 | 2.534 | 2.651 |
| 15.875 | 2.564 | 2.551 | 2.589 | 2.593 |
| 16.000 | 2.545 | 2.490 | 2.602 | 2.673 |
| 16.125 | 2.568 | 2.530 | 2.636 | 2.725 |
| 16.250 | 2.531 | 2.497 | 2.666 | 2.777 |
| 16.375 | 2.415 | 2.303 | 2.696 | 2.771 |
| 16.500 | 2.367 | 2.201 | 2.641 | 2.844 |
| 16.625 | 2.347 | 2.376 | 2.796 | 2.836 |
| 16.750 | 2.277 | 2.282 | 2.905 | 2.870 |
| 16.875 | 2.189 | 2.219 | 2.964 | 2.816 |
| 17.000 | 2.093 | 2.144 | 2.937 | 2.831 |
| 17.125 | 2.022 | 2.048 | 2.864 | 2.762 |

Rough Channel:  $Re=30,000$ ,  $P/e=20$ ,  $e/D=0.063$ ,  $\alpha=90^\circ$

| TO WALL |        |       |       |
|---------|--------|-------|-------|
| X/D     | 6.00   | 7.00  | 8.00  |
|         | BEFORE | TURN  |       |
| 6.875   | 2.713  | 2.773 | 2.834 |
| 7.000   | 2.617  | 2.613 | 2.715 |
| 7.125   | 2.432  | 2.468 | 2.538 |
| 7.250   | 2.187  | 2.144 | 2.268 |
| 7.375   | 2.016  | 2.133 | 2.110 |
| 7.500   | 1.854  | 1.923 | 2.051 |
| 7.625   | 1.715  | 1.700 | 1.922 |
| 7.750   | 1.423  | 1.491 | 1.597 |
| 7.875   | 1.986  | 1.737 | 2.222 |
| 8.000   | RIB    | RIB   | RIB   |
| 8.125   | 2.465  | 2.446 | 2.413 |
| 8.250   | 2.657  | 2.733 | 2.751 |
| 8.375   | 2.457  | 2.438 | 2.506 |
| 8.500   | 2.307  | 2.154 | 2.371 |
| 8.625   | 1.897  | 2.030 | 2.149 |
| 8.750   | 1.919  | 1.889 | 2.026 |
| 8.875   | 1.860  | 1.762 | 1.920 |
| 9.000   | 1.460  | 1.545 | 1.585 |
| 9.125   | 2.248  | 2.035 | 2.488 |
| 9.250   | RIB    | RIB   | RIB   |
| 9.375   | 2.267  | 2.385 | 2.460 |
| 9.500   | 2.618  | 2.664 | 2.782 |
| 9.625   | 2.456  | 2.416 | 2.523 |
| 9.750   | 2.317  | 2.186 | 2.322 |
| 9.875   | 2.004  | 1.997 | 2.099 |
| 10.000  | 1.847  | 1.807 | 1.892 |
| 10.125  | 1.733  | 1.686 | 1.788 |
| 10.250  | 1.409  | 1.451 | 1.575 |
| 10.375  | 1.749  | 1.695 | 2.204 |
| 10.500  | RIB    | RIB   | RIB   |
| 10.625  | 2.404  | 2.329 | 2.540 |
| 10.750  | 2.646  | 2.610 | 2.740 |
| 10.875  | 2.408  | 2.454 | 2.474 |
| 11.000  | 2.207  | 2.206 | 2.255 |
| 11.125  | 2.088  | 1.989 | 2.008 |
| 11.250  | 2.008  | 1.917 | 1.911 |
| 11.375  | 1.848  | 1.751 | 1.778 |
| 11.500  | 1.536  | 1.531 | 1.538 |
| 11.625  | 2.255  | 1.971 | 2.255 |

|        | IN TURN |       |       |
|--------|---------|-------|-------|
| 11.875 | 2.168   | 2.894 | 1.775 |
| 12.375 | 1.673   | 1.689 | 2.077 |
| 12.875 | 2.097   | 1.916 | 2.043 |
| 13.125 | 2.001   | 2.020 | 2.121 |
| 13.625 | 2.335   | 2.118 | 1.974 |
| 14.125 | 1.476   | 1.534 | 1.989 |

|        | AFTER TURN |       |       |
|--------|------------|-------|-------|
| 14.375 | 3.120      | 1.724 | 1.557 |
| 14.500 | 4.606      | 2.712 | 2.042 |
| 14.625 | 3.545      | 3.102 | 2.253 |
| 14.750 | 2.792      | 3.182 | 2.317 |
| 14.875 | 2.781      | 3.037 | 2.420 |
| 15.000 | 2.477      | 2.744 | 2.482 |
| 15.125 | 2.306      | 2.556 | 2.434 |
| 15.250 | 2.120      | 2.286 | 2.417 |
| 15.375 | 1.803      | 2.185 | 2.203 |
| 15.500 | RIB        | RIB   | RIB   |
| 15.625 | 2.548      | 2.436 | 3.120 |
| 15.750 | 4.012      | 3.286 | 3.357 |
| 15.875 | 3.744      | 3.147 | 2.974 |
| 16.000 | 3.161      | 2.922 | 2.499 |
| 16.125 | 2.689      | 2.675 | 2.294 |
| 16.250 | 2.354      | 2.448 | 2.141 |
| 16.375 | 2.216      | 2.213 | 2.052 |
| 16.500 | 2.033      | 1.916 | 1.784 |
| 16.625 | 1.879      | 1.743 | 1.510 |
| 16.750 | RIB        | RIB   | RIB   |
| 16.875 | 1.873      | 1.755 | 2.105 |
| 17.000 | 3.181      | 3.013 | 3.154 |
| 17.125 | 3.336      | 3.019 | 2.763 |
| 17.250 | 3.039      | 2.815 | 2.479 |
| 17.375 | 2.766      | 2.592 | 2.253 |
| 17.500 | 2.506      | 2.340 | 2.032 |
| 17.625 | 2.249      | 2.097 | 1.872 |
| 17.750 | 1.944      | 1.755 | 1.690 |
| 17.875 | 1.692      | 1.488 | 1.362 |
| 18.000 | RIB        | RIB   | RIB   |
| 18.125 | 1.503      | 1.475 | 1.621 |
| 18.250 | 2.804      | 2.855 | 2.955 |
| 18.375 | 3.029      | 2.879 | 2.840 |
| 18.500 | 2.811      | 2.573 | 2.577 |
| 18.625 | 2.647      | 2.310 | 2.152 |
| 18.750 | 2.435      | 2.167 | 2.020 |
| 18.875 | 2.199      | 2.005 | 1.810 |
| 19.000 | 1.953      | 1.739 | 1.597 |
| 19.125 | 1.664      | 1.480 | 1.347 |

|        | OUTER WALL | IN.    | INNER WALL |       |
|--------|------------|--------|------------|-------|
| X/1    | 1.111      | 1.111  | 1.111      | 1.111 |
|        |            | BEFORE | TURN       |       |
|        | OUTER WALL |        | INNER WALL |       |
| 6.875  | 1.591      | 1.416  | 1.758      | 1.758 |
| 7.125  | 1.443      | 1.397  | 1.602      | 1.546 |
| 7.375  | 1.329      | 1.342  | 1.754      | 1.754 |
| 7.625  | 1.508      | 1.312  | 1.722      | 1.731 |
| 7.875  | 1.730      | 1.560  | 1.694      | 1.704 |
| 8.125  | 1.672      | 1.626  | 1.639      | 1.521 |
| 8.375  | 1.613      | 1.578  | 1.557      | 1.447 |
| 8.625  | 1.666      | 1.660  | 1.570      | 1.413 |
| 8.875  | 1.635      | 1.619  | 1.552      | 1.559 |
| 9.125  | 1.676      | 1.545  | 1.636      | 1.535 |
| 9.375  | 1.601      | 1.394  | 1.593      | 1.596 |
| 9.625  | 1.421      | 1.262  | 1.465      | 1.472 |
| 9.875  | 1.456      | 1.365  | 1.553      | 1.545 |
| 10.125 | 1.525      | 1.413  | 1.638      | 1.584 |
| 10.375 | 1.625      | 1.471  | 1.712      | 1.648 |
| 10.625 | 1.596      | 1.464  | 1.637      | 1.650 |
| 10.875 | 1.503      | 1.449  | 1.609      | 1.651 |
| 11.125 | 1.610      | 1.465  | 1.824      | 1.771 |
| 11.375 | 1.713      | 1.652  | 1.855      | 1.708 |
| 11.625 | 1.686      | 1.440  | 1.858      | 1.676 |

|        |       | -----<br>IN      TURN<br>----- |
|--------|-------|--------------------------------|
| 11.875 | 1.852 | 1.213                          |
| 12.375 | 1.841 | 1.734                          |
| 12.875 | 2.130 | 2.278                          |
| 13.125 | 1.921 | 2.121                          |
| 13.625 | 1.525 | 1.606                          |
| 14.125 | 1.825 | 1.809                          |

|        |       | -----<br>AFTER      TURN<br>----- |       |       |
|--------|-------|-----------------------------------|-------|-------|
| 14.375 | 2.261 | 2.183                             | 2.784 | 2.652 |
| 14.625 | 1.974 | 1.912                             | 2.329 | 2.252 |
| 14.875 | 1.800 | 1.731                             | 2.428 | 2.396 |
| 15.125 | 1.832 | 1.760                             | 2.422 | 2.411 |
| 15.375 | 1.981 | 1.922                             | 2.655 | 2.379 |
| 15.625 | 1.959 | 1.900                             | 2.735 | 2.356 |
| 15.875 | 1.939 | 1.898                             | 2.710 | 2.251 |
| 16.125 | 1.834 | 1.796                             | 2.556 | 2.202 |
| 16.375 | 1.852 | 1.803                             | 2.424 | 2.176 |
| 16.625 | 1.977 | 1.961                             | 2.150 | 2.078 |
| 16.875 | 1.936 | 1.880                             | 1.920 | 1.776 |
| 17.125 | 1.962 | 1.909                             | 1.861 | 1.666 |
| 17.375 | 2.108 | 2.026                             | 1.903 | 1.656 |
| 17.625 | 2.119 | 2.026                             | 1.923 | 1.635 |
| 17.875 | 2.105 | 1.953                             | 1.909 | 1.672 |
| 18.125 | 1.935 | 1.856                             | 1.803 | 1.645 |
| 18.375 | 1.690 | 1.721                             | 1.789 | 1.807 |
| 18.625 | 1.645 | 1.570                             | 1.934 | 2.004 |
| 18.875 | 1.559 | 1.546                             | 2.094 | 1.998 |
| 19.125 | 1.484 | 1.481                             | 2.191 | 1.910 |

Rough Channel:  $Re = 30,000$ ,  $P/e = 10$ ,  $e/D = 0.094$ ,  $\alpha = 90^\circ$

| TOP WALL |        |      |      |
|----------|--------|------|------|
| X/D      | O.D.   |      | I.D. |
|          | BEFORE | TURN |      |
| 9.063    | 1.77   | 1.47 | 1.41 |
| 9.125    | 2.27   | 1.79 | 2.08 |
| 9.188    | 3.05   | 2.42 | 2.79 |
| 9.250    | 3.44   | 2.90 | 3.05 |
| 9.313    | 3.57   | 3.18 | 3.10 |
| 9.375    | 3.50   | 3.15 | 3.05 |
| 9.438    | 3.41   | 3.03 | 2.88 |
| 9.500    | 3.28   | 3.00 | 2.80 |
| 9.563    | 3.12   | 2.93 | 2.63 |
| 9.625    | 2.99   | 2.78 | 2.55 |
| 9.688    | 2.72   | 2.66 | 2.57 |
| 9.750    | 3.04   | 2.78 | 2.74 |
| 9.875    | RIB    | RIB  | RIB  |
| 10.000   | 1.61   | 1.45 | 1.40 |
| 10.063   | 3.01   | 2.88 | 2.97 |
| 10.125   | 3.33   | 3.26 | 3.16 |
| 10.188   | 3.46   | 3.35 | 3.12 |
| 10.250   | 3.44   | 3.38 | 2.96 |
| 10.313   | 3.29   | 3.28 | 2.88 |
| 10.375   | 3.20   | 3.19 | 2.82 |
| 10.438   | 3.09   | 3.06 | 2.67 |
| 10.500   | 2.90   | 2.86 | 2.56 |
| 10.563   | 2.64   | 2.64 | 2.55 |
| 10.625   | 2.69   | 2.68 | 2.74 |
| 10.688   | 3.15   | 2.83 | 2.84 |
| 10.813   | RIB    | RIB  | RIB  |
| 10.938   | 1.97   | 2.12 | 2.07 |
| 11.000   | 2.81   | 2.96 | 2.87 |
| 11.063   | 3.25   | 3.33 | 3.12 |
| 11.125   | 3.41   | 3.37 | 3.18 |
| 11.188   | 3.46   | 3.32 | 3.08 |
| 11.250   | 3.35   | 3.19 | 2.91 |
| 11.313   | 3.24   | 3.08 | 2.79 |
| 11.375   | 3.04   | 3.01 | 2.65 |
| 11.438   | 2.95   | 2.77 | 2.53 |
| 11.500   | 2.64   | 2.54 | 2.42 |
| 11.563   | 2.85   | 2.57 | 2.42 |
| 11.625   | 3.25   | 2.98 | 2.70 |

|        | IN TURN |      |      |
|--------|---------|------|------|
| 11.875 | 4.10    | 3.82 | 3.41 |
| 12.375 | 2.38    | 2.51 | 2.81 |
| 12.875 | 2.95    | 2.61 | 2.95 |
| 13.125 | 2.74    | 2.74 | 2.76 |
| 13.625 | 3.08    | 2.54 | 2.39 |
| 14.125 | 1.88    | 2.04 | 2.61 |

|        | AFTER TURN |      |      |
|--------|------------|------|------|
| 14.375 | 2.77       | 2.32 | 2.68 |
| 14.438 | 3.44       | 2.75 | 3.20 |
| 14.500 | 4.31       | 3.22 | 3.33 |
| 14.563 | 4.64       | 3.50 | 3.52 |
| 14.625 | 4.76       | 3.65 | 3.60 |
| 14.688 | 4.63       | 3.73 | 3.57 |
| 14.750 | 4.50       | 3.81 | 3.57 |
| 14.813 | 4.28       | 3.72 | 3.61 |
| 14.875 | 3.99       | 3.73 | 3.52 |
| 14.938 | 3.77       | 3.53 | 3.53 |
| 15.000 | 3.43       | 3.34 | 3.45 |
| 15.063 | 4.18       | 3.55 | 3.37 |
| 15.188 | RIB        | RIB  | RIB  |
| 15.313 | 2.42       | 2.41 | 2.85 |
| 15.375 | 3.41       | 3.27 | 3.82 |
| 15.438 | 4.07       | 3.84 | 4.12 |
| 15.500 | 4.49       | 4.11 | 4.19 |
| 15.563 | 4.55       | 4.00 | 4.01 |
| 15.625 | 4.43       | 3.91 | 3.53 |
| 15.688 | 4.21       | 3.71 | 3.36 |
| 15.750 | 3.92       | 3.51 | 3.13 |
| 15.813 | 3.65       | 3.31 | 2.89 |
| 15.875 | 3.41       | 3.12 | 2.64 |
| 15.938 | 3.07       | 2.83 | 2.51 |
| 16.000 | 4.04       | 3.47 | 3.17 |
| 16.125 | RIB        | RIB  | RIB  |
| 16.250 | 2.65       | 2.59 | 2.99 |
| 16.313 | 3.51       | 3.32 | 3.57 |
| 16.375 | 3.86       | 3.57 | 3.76 |
| 16.438 | 4.05       | 3.66 | 3.65 |
| 16.500 | 4.04       | 3.54 | 3.46 |
| 16.563 | 3.84       | 3.38 | 3.24 |
| 16.625 | 3.75       | 3.27 | 3.07 |
| 16.688 | 3.49       | 3.17 | 2.79 |
| 16.750 | 3.21       | 2.90 | 2.63 |
| 16.813 | 2.90       | 2.71 | 2.41 |
| 16.875 | 2.57       | 2.89 | 2.60 |
| 16.938 | 2.77       | 2.19 | 3.08 |

| -----       |            |      |            |      |
|-------------|------------|------|------------|------|
|             | OUTER WALL | AND  | INNER WALL |      |
| -----       |            |      |            |      |
| X/T         | I.D.       | C.D. | I.D.       | C.D. |
| -----       |            |      |            |      |
| BEFORE TURN |            |      |            |      |
| -----       |            |      |            |      |
|             | OUTER WALL |      | INNER WALL |      |
| -----       |            |      |            |      |
| 9.063       | 2.37       | 1.87 | 2.16       | 2.10 |
| 9.125       | 2.55       | 2.10 | 2.29       | 2.18 |
| 9.250       | 2.42       | 2.02 | 2.29       | 2.18 |
| 9.375       | 2.43       | 2.02 | 2.29       | 2.13 |
| 9.500       | 2.38       | 1.99 | 2.30       | 2.17 |
| 9.625       | 2.54       | 2.04 | 2.23       | 2.11 |
| 9.750       | 2.46       | 2.07 | 2.17       | 2.03 |
| 10.000      | 2.46       | 1.80 | 2.17       | 2.10 |
| 10.063      | 2.57       | 2.12 | 2.19       | 2.12 |
| 10.188      | 2.23       | 1.90 | 2.27       | 2.04 |
| 10.313      | 2.34       | 1.93 | 2.29       | 2.14 |
| 10.438      | 2.40       | 2.03 | 2.30       | 2.13 |
| 10.563      | 2.51       | 1.86 | 2.29       | 2.24 |
| 10.688      | 2.49       | 1.93 | 2.33       | 2.25 |
| 10.938      | 2.47       | 1.97 | 2.40       | 2.16 |
| 11.000      | 2.32       | 2.15 | 2.41       | 2.14 |
| 11.125      | 2.32       | 1.89 | 2.40       | 2.03 |
| 11.250      | 2.24       | 1.90 | 2.29       | 1.86 |
| 11.375      | 2.40       | 1.93 | 2.29       | 1.96 |
| 11.500      | 2.39       | 1.93 | 2.31       | 2.10 |
| 11.625      | 2.45       | 1.90 | 2.35       | 2.22 |

# IN TURN

|        |      |      |
|--------|------|------|
| 14.675 | 2.84 | 2.84 |
| 14.675 | 2.84 | 2.84 |
| 14.675 | 2.84 | 2.84 |
| 14.675 | 2.84 | 2.84 |
| 14.675 | 2.84 | 2.84 |
| 14.675 | 2.84 | 2.84 |

# AFTER TURN

|        |      |      |      |      |
|--------|------|------|------|------|
| 14.675 | 2.84 | 2.84 | 3.25 | 2.83 |
| 14.675 | 2.84 | 2.84 | 3.25 | 2.92 |
| 14.675 | 2.84 | 2.82 | 3.28 | 3.00 |
| 14.750 | 2.73 | 2.80 | 3.32 | 3.02 |
| 14.875 | 2.96 | 2.83 | 3.26 | 3.05 |
| 14.900 | 2.89 | 2.84 | 3.34 | 3.09 |
| 14.900 | 2.91 | 2.89 | 3.31 | 3.13 |
| 14.913 | 2.92 | 2.82 | 3.31 | 3.16 |
| 14.938 | 2.88 | 2.75 | 3.40 | 3.19 |
| 14.963 | 2.94 | 2.76 | 3.33 | 3.15 |
| 14.988 | 2.91 | 2.87 | 3.33 | 3.12 |
| 14.913 | 2.93 | 2.83 | 3.25 | 3.14 |
| 14.938 | 2.97 | 2.81 | 3.24 | 3.17 |
| 14.900 | 3.02 | 2.65 | 3.31 | 3.21 |
| 14.950 | 2.86 | 2.66 | 3.34 | 3.18 |
| 14.975 | 2.69 | 2.56 | 3.17 | 3.13 |
| 14.900 | 2.68 | 2.64 | 3.24 | 3.11 |
| 14.925 | 2.66 | 2.45 | 3.26 | 3.17 |
| 14.950 | 2.82 | 2.47 | 3.24 | 3.16 |
| 14.975 | 2.86 | 2.54 | 3.18 | 3.16 |
| 14.938 | 2.88 | 2.60 | 3.27 | 3.11 |

## APPENDIX C

### PRESSURE DROP DATA

# LIST OF PRESSURE DROP TEST RUNS

| CHANNEL | Re     | P/e | e/D   | $\alpha$ |
|---------|--------|-----|-------|----------|
| SMOOTH  | 10,000 | —   | —     | —        |
|         | 20,000 | —   | —     | —        |
|         | 30,000 | —   | —     | —        |
|         | 40,000 | —   | —     | —        |
|         | 50,000 | —   | —     | —        |
|         | 60,000 | —   | —     | —        |
| ROUGH   | 10,000 | 10  | 0.063 | 90°      |
|         | 20,000 | 10  | 0.063 | 90°      |
|         | 30,000 | 10  | 0.063 | 90°      |
|         | 40,000 | 10  | 0.063 | 90°      |
|         | 50,000 | 10  | 0.063 | 90°      |
|         | 60,000 | 10  | 0.063 | 90°      |
| ROUGH   | 10,000 | 10  | 0.063 | 60°      |
|         | 20,000 | 10  | 0.063 | 60°      |
|         | 30,000 | 10  | 0.063 | 60°      |
|         | 40,000 | 10  | 0.063 | 60°      |
|         | 50,000 | 10  | 0.063 | 60°      |
|         | 60,000 | 10  | 0.063 | 60°      |
| ROUGH   | 10,000 | 10  | 0.063 | 45°      |
|         | 20,000 | 10  | 0.063 | 45°      |
|         | 30,000 | 10  | 0.063 | 45°      |
|         | 40,000 | 10  | 0.063 | 45°      |
|         | 50,000 | 10  | 0.063 | 45°      |
|         | 60,000 | 10  | 0.063 | 45°      |
| ROUGH   | 10,000 | 20  | 0.063 | 90°      |
|         | 20,000 | 20  | 0.063 | 90°      |
|         | 30,000 | 20  | 0.063 | 90°      |
|         | 40,000 | 20  | 0.063 | 90°      |
|         | 50,000 | 20  | 0.063 | 90°      |
|         | 60,000 | 20  | 0.063 | 90°      |
| ROUGH   | 10,000 | 10  | 0.094 | 90°      |
|         | 20,000 | 10  | 0.094 | 90°      |
|         | 30,000 | 10  | 0.094 | 90°      |
|         | 40,000 | 10  | 0.094 | 90°      |
|         | 50,000 | 10  | 0.094 | 90°      |
|         | 60,000 | 10  | 0.094 | 90°      |

Re REYNOLDS NUMBER

P/e PITCH TO RIB HEIGHT RATIO

e/D RIB HEIGHT TO HYDRAULIC DIAMETER RATIO

$\alpha$  RIB ANGLE OF ATTACK

# Smooth Channel

$$2(P - P_{atm})/\rho V^2$$

| TAI | X/D     | RE 10000 | RE 12000 | RE 14000 | RE 16000 | RE 18000 | RE 20000 |
|-----|---------|----------|----------|----------|----------|----------|----------|
| 1   | 0.1125  | -1.9931  | -1.9470  | -1.9041  | -1.8644  | -1.8284  | -1.7957  |
| 1   | 3.1875  | -1.1831  | -1.1767  | -1.1714  | -1.1670  | -1.1636  | -1.1610  |
| 3   | 4.6875  | -1.3200  | -1.3061  | -1.2987  | -1.2934  | -1.2898  | -1.2874  |
| 4   | 7.1875  | -1.4009  | -1.2710  | -1.1980  | -1.1640  | -1.1436  | -1.1281  |
| 5   | 9.6875  | -1.4655  | -1.3250  | -1.2579  | -1.2111  | -1.1859  | -1.1681  |
| 6   | 10.3125 | -1.5086  | -1.3440  | -1.2639  | -1.2313  | -1.2069  | -1.1981  |
| 7   | 10.9375 | -1.5086  | -1.3656  | -1.2819  | -1.2280  | -1.2177  | -1.2201  |
| 8   | 11.5625 | -1.2392  | -1.1493  | -1.0603  | -1.0429  | -1.0345  | -1.0034  |
| 9   | 13.0000 | -2.1552  | -1.9470  | -1.9049  | -1.8840  | -1.8534  | -1.8271  |
| 10  | 14.4375 | -2.9095  | -2.7582  | -2.6956  | -2.6578  | -2.5862  | -2.5459  |
| 11  | 15.0625 | -4.2026  | -3.8061  | -3.6540  | -3.5830  | -3.5345  | -3.5096  |
| 12  | 15.6875 | -3.6638  | -3.3532  | -3.2587  | -3.2297  | -3.1034  | -2.9802  |
| 13  | 16.3125 | -3.2328  | -3.0557  | -2.9232  | -2.8596  | -2.8448  | -2.6957  |
| 14  | 18.8125 | -3.1789  | -3.0287  | -2.8813  | -2.8260  | -2.8017  | -2.6657  |
| 15  | 21.3125 | -3.1401  | -3.1101  | -2.9671  | -2.9312  | -2.9011  | -2.7710  |
| 16  | 23.8125 | -3.1102  | -3.0901  | -2.9471  | -2.9112  | -2.8811  | -2.7510  |

Rough Channel:  $P/e = 10$ ,  $e/D = 0.063$ ,  $\alpha = 90^\circ$

$$2(P - P_{atm})/\rho V^2$$

| TAP | X/D     | RE=10000 | RE=20000 | RE=30000 | RE=40000 | RE=50000 | RE=60000 |
|-----|---------|----------|----------|----------|----------|----------|----------|
| 1   | 0.3125  | -2.1013  | -2.0552  | -2.0247  | -2.0186  | -1.9828  | -1.8570  |
| 2   | 2.1875  | -1.6918  | -1.6766  | -1.6473  | -1.6149  | -1.5948  | -1.4976  |
| 3   | 4.6875  | -1.7996  | -1.7847  | -1.7042  | -1.6990  | -1.6810  | -1.5725  |
| 4   | 7.1875  | -2.1121  | -2.0957  | -2.0367  | -1.9849  | -1.9612  | -1.8870  |
| 5   | 9.6875  | -2.4246  | -2.4067  | -2.3002  | -2.2877  | -2.2629  | -2.1565  |
| 6   | 10.3125 | -2.5108  | -2.4986  | -2.3961  | -2.3550  | -2.3362  | -2.2614  |
| 7   | 10.9375 | -2.5970  | -2.5622  | -2.4560  | -2.4559  | -2.4310  | -2.3153  |
| 8   | 11.5625 | -2.3707  | -2.2985  | -2.1265  | -2.1868  | -2.0690  | -2.0367  |
| 9   | 13.0000 | -3.3190  | -3.2856  | -3.1748  | -3.1288  | -3.0603  | -2.9353  |
| 10  | 14.4375 | -4.0409  | -4.0427  | -3.8936  | -3.8689  | -3.7931  | -3.6541  |
| 11  | 15.0625 | -4.8006  | -4.7052  | -4.5525  | -4.4577  | -4.3319  | -4.1932  |
| 12  | 15.6875 | -4.7953  | -4.7323  | -4.5525  | -4.4745  | -4.3103  | -4.1633  |
| 13  | 16.3125 | -4.8491  | -4.7593  | -4.5525  | -4.5081  | -4.3534  | -4.2532  |
| 14  | 18.8125 | -5.1724  | -5.1109  | -4.9119  | -4.8782  | -4.7414  | -4.5826  |
| 15  | 21.4125 | -5.5496  | -5.4759  | -5.2234  | -5.1810  | -5.0431  | -4.9121  |
| 16  | 24.0125 | -5.9267  | -5.8140  | -5.5709  | -5.5174  | -5.3874  | -5.2715  |

Rough Channel:  $P/e = 10$ ,  $e/D = 0.063$ ,  $\alpha = 60^\circ$

$$2(P - P_{atm})/\rho V^2$$

| Y/D | X/D     | RE=10000 | RE=25000 | RE=50000 | RE=100000 | RE=200000 | RE=500000 |
|-----|---------|----------|----------|----------|-----------|-----------|-----------|
| 1   | 0.4125  | -2.2629  | -2.1489  | -2.0714  | -2.2137   | -2.1963   | -2.1865   |
| 2   | 1.1875  | -1.9497  | -1.8157  | -1.7611  | -1.6821   | -1.6374   | -1.6174   |
| 3   | 4.6875  | -2.1821  | -2.1498  | -2.0720  | -1.9513   | -1.9181   | -1.8540   |
| 4   | 7.1875  | -2.5860  | -2.5490  | -2.4560  | -2.3886   | -2.3491   | -2.2913   |
| 5   | 9.6875  | -3.0172  | -2.9746  | -2.9352  | -2.8596   | -2.8017   | -2.7556   |
| 6   | 10.3125 | -3.1358  | -3.1098  | -3.0550  | -3.0009   | -2.9095   | -2.8754   |
| 7   | 10.9375 | -3.2597  | -3.2518  | -3.1628  | -3.0649   | -3.0172   | -2.9547   |
| 8   | 11.5625 | -2.8556  | -2.8123  | -2.7555  | -2.6914   | -2.6293   | -2.5908   |
| 9   | 13.0000 | -3.3405  | -3.3396  | -3.2946  | -3.2297   | -3.0386   | -2.9053   |
| 10  | 14.4375 | -4.3103  | -4.2726  | -4.1931  | -4.1044   | -3.8793   | -3.7140   |
| 11  | 15.0625 | -5.2802  | -5.2190  | -5.1516  | -5.0801   | -4.9136   | -4.7024   |
| 12  | 15.6875 | -5.2802  | -5.1379  | -4.9718  | -4.8446   | -4.6983   | -4.4926   |
| 13  | 16.3125 | -5.0647  | -4.8675  | -4.7322  | -4.6494   | -4.4828   | -4.3730   |
| 14  | 16.9375 | -5.2267  | -5.1103  | -4.9718  | -4.8446   | -4.6983   | -4.4926   |
| 15  | 17.5625 | -5.1679  | -5.0435  | -4.9012  | -4.7694   | -4.6174   | -4.4011   |
| 16  | 18.1875 | -5.0664  | -4.9760  | -4.8104  | -4.6825   | -4.5147   | -4.3011   |

Rough Channel:  $P/e = 10$ ,  $e/D = 0.063$ ,  $\alpha = 45^\circ$

$$2(P - P_{atm})/\rho V^2$$

|    |         | RE=10000 | RE=15000 | RE=30000 | RE=40000 | RE=50000 | RE=60000 |
|----|---------|----------|----------|----------|----------|----------|----------|
| 1  | 1.1111  | -1.1111  | -1.11174 | -1.1565  | -1.1431  | -1.0690  | -2.0517  |
| 2  | 1.1111  | -1.1114  | -1.0495  | -1.5874  | -1.5812  | -1.5086  | -1.4676  |
| 3  | 4.1111  | -1.1114  | -1.9511  | -1.8719  | -1.8739  | -1.7672  | -1.6923  |
| 4  | 1.1111  | -2.1168  | -2.2715  | -2.1565  | -2.1195  | -2.0043  | -1.9169  |
| 5  | 10.1111 | -2.6401  | -2.5960  | -2.4560  | -2.4223  | -2.2845  | -2.2015  |
| 6  | 10.1111 | -2.6940  | -2.6501  | -2.5159  | -2.4896  | -2.3621  | -2.2763  |
| 7  | 10.1111 | -2.7478  | -2.7244  | -2.6177  | -2.5703  | -2.4375  | -2.3362  |
| 8  | 11.1111 | -2.3707  | -2.3526  | -2.2763  | -2.2204  | -2.0474  | -2.0068  |
| 9  | 13.0000 | -3.1250  | -3.0287  | -2.9951  | -2.8596  | -2.6724  | -2.5759  |
| 10 | 14.4375 | -3.9871  | -3.9481  | -3.7738  | -3.5998  | -3.2974  | -3.1899  |
| 11 | 15.0625 | -5.6573  | -5.5638  | -5.3612  | -5.1474  | -4.8168  | -4.7174  |
| 12 | 15.6875 | -5.1724  | -5.0568  | -4.8520  | -4.6764  | -4.3534  | -4.2831  |
| 13 | 16.1111 | -4.7414  | -4.6241  | -4.4926  | -4.3736  | -4.0948  | -4.0135  |
| 14 | 16.8111 | -4.8491  | -4.7323  | -4.6124  | -4.5081  | -4.2241  | -4.1333  |
| 15 | 17.1111 | -4.1198  | -4.0027  | -4.8520  | -4.7436  | -4.4181  | -4.3430  |
| 16 | 17.1111 | -4.1198  | -4.0027  | -4.8520  | -4.7436  | -4.4181  | -4.3430  |
| 17 | 17.1111 | -4.1198  | -4.0027  | -4.8520  | -4.7436  | -4.4181  | -4.3430  |

Rough Channel:  $P/e = 20$ ,  $e/D = 0.063$ ,  $\alpha = 90^\circ$

$$2(P - P_{atm})/\rho V^2$$

| TAB | X/1     | RF=10000 | RF=20000 | RF=30000 | RF=40000 | RF=50000 | RF=60000 |
|-----|---------|----------|----------|----------|----------|----------|----------|
| 1   | 0.0000  | -1.1734  | -1.0537  | -1.0347  | -1.0136  | -1.0080  | -1.0000  |
| 2   | 1.1875  | -1.8164  | -1.5593  | -1.5215  | -1.4855  | -1.4653  | -1.4500  |
| 3   | 2.3875  | -1.7541  | -1.7442  | -1.6314  | -1.5921  | -1.5537  | -1.5400  |
| 4   | 3.5875  | -1.9335  | -2.0011  | -1.8330  | -1.8167  | -1.8834  | -1.7500  |
| 5   | 4.7875  | -2.2629  | -2.2309  | -2.0966  | -2.0724  | -2.0680  | -1.9400  |
| 6   | 5.9875  | -2.3162  | -2.2985  | -2.1565  | -2.1195  | -2.1375  | -1.9700  |
| 7   | 7.1875  | -2.3707  | -2.3526  | -2.2164  | -2.2204  | -2.2198  | -2.0442  |
| 8   | 8.3875  | -2.1013  | -2.0922  | -1.9528  | -1.9176  | -1.8534  | -1.7372  |
| 9   | 9.5875  | -3.1250  | -3.1098  | -2.9352  | -2.8933  | -2.8448  | -2.7855  |
| 10  | 10.7875 | -3.9332  | -3.8940  | -3.8337  | -3.7344  | -3.5951  | -3.4445  |
| 11  | 11.9875 | -4.3103  | -4.2658  | -4.1332  | -4.0371  | -3.9005  | -3.7290  |
| 12  | 13.1875 | -4.5259  | -4.4889  | -4.3129  | -4.2390  | -4.1375  | -3.9536  |
| 13  | 14.3875 | -4.3642  | -4.2726  | -4.1452  | -4.0371  | -3.9655  | -3.7589  |
| 14  | 15.5875 | -4.6121  | -4.5700  | -4.3728  | -4.2726  | -4.1595  | -3.9836  |
| 15  | 16.7875 | -4.7000  | -4.6675  | -4.3174  | -4.2419  | -4.1497  | -3.9531  |
| 16  | 17.9875 | -5.1100  | -5.1100  | -4.6000  | -4.5000  | -4.3000  | -4.0000  |

$$2(P_1 - P_2) \cdot \nabla \psi$$



## Report Documentation Page

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                              |                                                                    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------|
| 1 Report No<br>NASA CR-179635<br>AVSCOM TR-87-C-14                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 2 Government Accession No<br><i>F</i>                                        | 3 Recipient's Catalog No                                           |
| 4 Title and Subtitle<br>Local Heat/Mass Transfer and Pressure Drop in a<br>Two-Pass Rib-Roughened Channel for Turbine<br>Airfoil Cooling                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 5 Report Date<br>September 1987                                              | 6 Performing Organization Code                                     |
| 7 Author(s)<br>J.C. Han and P.R. Chandra                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 8 Performing Organization Report No<br>None                                  | 10 Work Unit No<br>TL162209AH76<br>505-31-4K                       |
| 9 Performing Organization Name and Address<br>Texas A&M University<br>Turbomachinery Laboratories<br>College Station, Texas 77843-3123                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 11 Contract or Grant No<br>NAS3-24227                                        | 13 Type of Report and Period Covered<br>Contractor Report<br>Final |
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| 15 Supplementary Notes<br>Project Manager, Robert J. Boyle, Internal Fluid Mechanics Division,<br>NASA Lewis Research Center.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                              |                                                                    |
| 16 Abstract<br>The heat transfer characteristics of turbulent air flow in a multipass channel were studied via the naphthalene sublimation technique. The naphthalene-coated test section, which consisted of two straight, square channels joined by a sharp 180° turn, resembled the internal cooling passages of gas turbine airfoils. The top and bottom surfaces of the test channel were roughened by rib turbulators. The rib height-to-hydraulic diameter ratio ( $e/D$ ) were 0.063 and 0.094, and the rib pitch-to-height ratio ( $P/e$ ) were 10 and 20. The local heat/mass transfer coefficients on the roughened top wall and on the smooth divider and side walls of the test channel were determined for three Reynolds numbers of 15,000, 30,000, and 60,000, and for three angles-of-attack ( $\alpha$ ) of 90°, 60°, and 45°. The results showed that the local Sherwood numbers on the ribbed walls were 1.5 to 6.5 times those for a fully developed flow in a smooth square duct. The average ribbed-wall Sherwood numbers were 2.5 to 3.5 times higher than the fully developed values, depending on the rib angle-of-attack and the Reynolds number. The results also indicated that, before the turn, the heat/mass transfer coefficients in the cases of $\alpha = 60^\circ$ and $45^\circ$ were higher than those in the case of $\alpha = 90^\circ$ . However, after the turn, the heat/mass transfer coefficients in the oblique-rib cases were lower than those in the traverse-rib case. Correlations for the average Sherwood number ratios for individual channel surfaces and for the overall Sherwood number ratios are reported. Correlations for the fully developed friction factors and for the loss coefficients are also provided. |                                                                              |                                                                    |
| 17 Key Words (Suggested by Author(s))<br>Heat transfer<br>Augmentation<br>Ducts<br>Turbine cooling                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 18 Distribution Statement<br>Unclassified - Unlimited<br>Subject Category 34 |                                                                    |
| 19 Security Classif (of this report)<br>Unclassified                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 20 Security Classif (of this page)<br>Unclassified                           | 21 No of pages<br>170                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                              | 22 Price*<br>A                                                     |

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