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J. C. Han, J. S. Park,
and C. K. Lei
*Texas A&M University*
*College Station, Texas*

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## Nomenclature

| | |
|---|---|
| $D$ | side to side dimension of square duct; equivalent diameter of square duct |
| $e$ | rib height |
| $e^+$ | roughness Reynolds number, $(e/D)Re(f/2)^{\frac{1}{2}}$ |
| $\bar{e}^+$ | average roughness Reynolds number, $(e/D)Re(\bar{f}/2)^{\frac{1}{2}}$ |
| $f$ | friction factor |
| $\bar{f}$ | average friction factor in a duct with two opposite ribbed walls |
| $\bar{f}/f$ | ratio of ribbed duct average friction factor to four sided smooth duct friction factor |
| $g_c$ | conversion factor |
| $G$ | mass flux, $\rho\bar{V}$ |
| $h$ | heat transfer coefficients |
| $H$ | heat transfer roughness function |
| $\bar{H}$ | average heat transfer roughness function |
| $K$ | thermal conductivity of fluid |
| $\ell$ | the distance between the wall and the position of zero shear stress |
| $L$ | test section length for friction pressure drop |
| $Nu$ | Nusselt number, $hD/K$ |
| $\bar{Nu}$ | average Nusselt number in a duct with two opposite ribbed walls |
| $\Delta p$ | pressure drop across the test section |
| $p$ | rib pitch |
| $\bar{P}/P$ | ratio of ribbed duct pumping power to four sided smooth duct pumping power, $(\bar{f}/f)/(\bar{St}/St)^3$ |
| $Pr$ | Prandtl number of fluid |
| $q''$ | heat transfer rate per unit surface area |

| | |
|---|---|
| $R$ | momentum transfer roughness function |
| $\bar{R}$ | average momentum transfer roughness function |
| Re | Reynolds number, $GD/\mu$ |
| Rav | average ray length of the duct |
| St | Stanton number, Nu/(Re Pr) |
| $\bar{St}$ | average Stanton number in a duct with two opposite ribbed walls |
| $\bar{St}/St$ | ratio of ribbed duct average Stanton number to four sided smooth duct Stanton number |
| $T$ | temperature |
| $T^+$ | dimensionless temperature |
| $\bar{T}^+$ | average dimensionless temperature |
| $T_b$ | bulk mean temperature of fluid |
| $T_w$ | local temperature at the wall |
| $\bar{T}_w$ | average lateral temperature at the wall |
| $u$ | velocity |
| $u^+$ | dimensionless velocity, $u/u^*$ |
| $\bar{u}^+$ | average dimensionless velocity |
| $u^*$ | friction velocity $(\tau/\rho)^{\frac{1}{2}}$ |
| $\bar{V}$ | average velocity of fluid |
| $X$ | the axial distance from the heated test duct |
| $Y$ | distance from the wall |
| $z$ | the lateral distance from the centerline of the duct |
| $\alpha$ | flow attack angle |
| $\rho$ | average density of fluid |
| $\mu$ | average viscosity of fluid |

$\tau$ wall shear stress

$\eta$ efficiency index of the ribbed duct, $(\bar{St}/St_{~})/(\bar{f}/f_{~})$

## Subscripts

s smooth side walls in a duct with two opposite ribbed walls

R ribbed side walls in a duct with two opposite ribbed walls

r four sided ribbed duct

LDE Long Duct Entrance

SCE Sudden Contraction Entrance

# HEAT TRANSFER AND PRESSURE DROP IN BLADE COOLING CHANNELS WITH TURBULENCE PROMOTERS

## 1.0 SUMMARY

This is the final report for the program of Heat Transfer and Pressure Drop in Blade Cooling Channels with Turbulence Promoters. This project was conducted by the Texas A&M University and was funded by Curtis Walker at the U.S. Army Research and Technology Laboratories (AVRADCOM). The project was monitored by Robert Boyle at the NASA-Lewis Research Center under NASA Grant No. NAG 3-311.

Repeated rib roughness elements have been used in advanced turbine cooling designs to enhance the internal heat transfer. Often the ribs are perpendicular to the main flow direction so that they have an angle-of-attack of 90 degrees. The objective of the project was to investigate the effect of rib angle-of-attack on the pressure drop and the average heat transfer coefficients in a square duct with two opposite rib-roughened walls for Reynolds number varied from 8,000 to 80,000. The rib height-to-equivalent diameter ratio (e/D) was kept at a constant value of 0.063, the rib pitch-to-height ratio (P/e) was varied from 10 to 20, and the rib angle-of-attack ($\alpha$) was varied from 90° to 60° to 45° to 30°, respectively. Two types of entrance conditions were examined, namely, long duct and sudden contraction. The heat transfer coefficients distribution on the smooth side wall and on the rough side wall at the entrance and the fully developed regions were measured.

For the long duct entrance the results showed that the heat transfer decreased monotonically with distance for all angles-of-attack. In the fully developed region, the heat transfer coefficients of the ribbed side wall was about 2.5 to 3.0 times that of the four sided smooth duct and the heat transfer coefficients of the smooth side wall was also enhanced by 30-80% due to the presence of the ribs on the adjacent walls; whereas the average friction factor was increased about 3 to 10 times depending upon the rib P/e ratio, angle $\alpha$, and Reynolds number. Best thermal performance was achieved at angles-of-attack of 30 and 45 degrees for both P/e ratios. At $\alpha = 30°$ the heat transfer was 5% greater than at $\alpha = 90°$, but the friction factor was reduced by approximately 30%. At $\alpha = 45°$ the heat transfer was 25% greater than at $\alpha = 90°$, and the friction factor remained the same. Semi-empirical correlations for friction factor and heat transfer coefficients were developed to account for rib spacing and rib angle over the range of Reynolds number. The correlations can be used in the design of turbine blade cooling passages.

For the sudden contraction entrance the results were different. The variation of heat transfer was a function of the P/e ratio. At a P/e of 10 the heat transfer did not decrease monotonically with distance for all angles-of-attack. At $\alpha = 60°$ for example, the heat transfer increased between an X/D of 3 and 8, reaching a maximum that was 50% greater than that for $\alpha = 90°$. Further away from the entrance the results were similar to the long duct entrance results. For a P/e of 20 the results were similar to the long duct entrance results at all angles-of-attack. The P/e = 10 had a slightly better performance than the P/e = 20.

## 2.0 INTRODUCTION

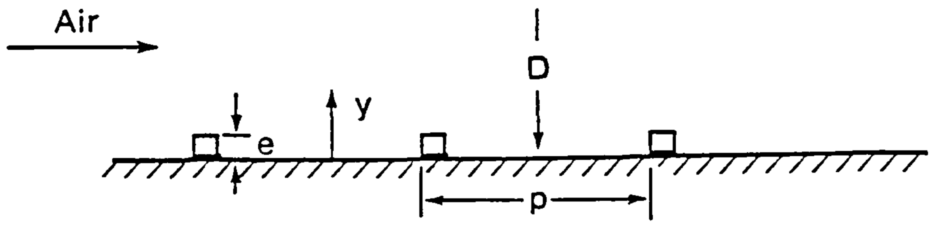
### 2.1 Background

One of the well known methods to enhance the heat transfer from a surface is to roughen the surface by the use of two-dimensional repeated-ribs on the surface. However, the increase in heat transfer is accompanied by an increase in the pressure drop of the fluid flow. Many investigations have been directed toward developing predictive correlations for a given rib geometry and establishing a geometry which gives the best heat transfer performance for a given pumping power.

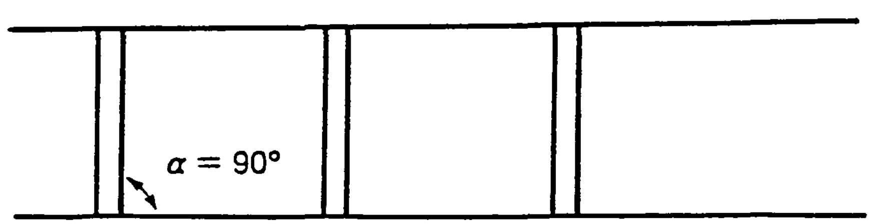
Fully developed turbulent heat transfer and friction in tubes with repeated-rib roughened have been studied extensively [1-7]. Considerable data also exists for repeated-rib-roughness in an annular flow geometry in which the inner annular surface is rough and the outer surface is smooth to simulate the geometry of fuel bundles in advanced gas-cooled nuclear reactor [8-12]. Based on those previous studies, the effects of rib height-to-equivalent diameter ratio, e/D, and rib pitch-to-height ratio, P/e, on the heat transfer coefficients and friction factor over a wide range of Reynolds number are well established. Recently, Han et al. [6] used a parallel-plate channel geometry to study the effect of rib height-to-equivalent diameter ratio, rib pitch-to-height ratio, and rib angle-of-attack (See Figure 1). They concluded that a 45° angle-of-attack provided superior performance at a given friction power when compared to ribs at a 90° angle-of-attack. The similar results had been reported by Gee and Webb [7] who conducted forced convection heat transfer in helically rib-roughened tubes. However, in some applications, such as gas turbine airfoil cooling design, the heat transfer enhancement is required on two opposite walls of the cooling passages in order to remove more heat transferred from airfoil external surface which is directly exposed to the hot gases flow. The current advanced gas turbine blade cooling system, as sketched in Figure 2, the turbulence promoters (i.e., repeated-ribs) with a 90° angle to the flow have been cast onto the two opposite walls of the shaped internal passages [13-15]. The internal passages can be approximately modeled as that the flow in a rectangular channels with two opposite rib-roughened walls. The heat transfer and friction characteristics in channels of this kind may be different from those of circular tubes, parallel-plates, or annuli. The only available data was reported by Burggraf [16] who studied the square duct with two opposite rib-roughened walls with a rib flow-attack-angle of 90°, rib pitch-to-height ratio of 10, and rib height-to-equivalent diameter ratio of 0.055. Air was the working fluid; constant wall temperature was the boundary condition. Three types of entrance conditions were tested over Reynolds numbers (Re) from $1.3 \times 10^4$ to $1.3 \times 10^5$, namely, downstream of a fully developed hydrodynamic flow (long duct entrance), downstream of a rounded entrance from a plenum (short duct entrance), and downstream of a 180° bend, respectively. For the long duct entrance case, Burggraf found the augmentation of the Nusselt number on the ribbed side wall was 2.38 times the fully developed smooth duct flow values when the characteristic dimension was taken as twice the plate spacing (twice the hydraulic diameter for a square duct). The augmentation of the friction factor was approximately 8.6 times that of the smooth duct results. There was also enhancement of the smooth side wall heat transfer by 19% over the all smooth correlations. He also reported similar trends for the case of a short duct entrance and for the 180° bend tests. In this study the emphasis was placed on the effect of entrance conditions on the heat transfer coefficients. Only one particular rib angle-of-attack (i.e., $\alpha$ = 90°) was tested. Since then, no study has been reported to optimize the rib angle-of-attack in the blade cooling channels in order to obtain the best heat transfer performance for a given flow pressure drop. No further study to investigate the effect of channel aspect ratio on the heat transfer and friction can be found in the open literature. Moreover, the data of the local heat transfer coefficient distributions on the smooth side wall and between the ribs of the rough side wall are lacking. Therefore, basic research in this area is warrentable.

## 2.2 Program Objective

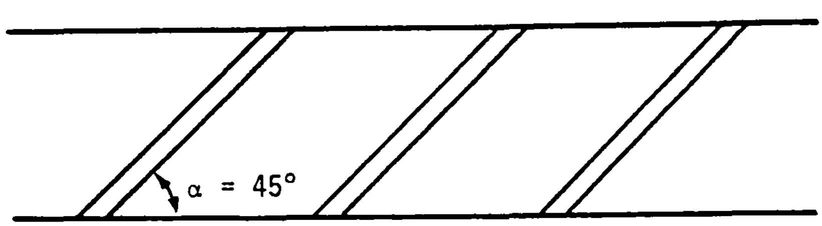
The objective of the project was to investigate the effect of rib angle-of-attack on the friction factor and the average heat transfer coefficients in a square duct with two opposite ribbed walls for Reynolds number varied from 8,000 to 80,000. The rib height-to-equivalent diameter ratio (e/D) was kept at a constant value of 0.063, the rib pitch-to-height ratio (P/e) was varied from 10 to 20, whereas the corresponding rib angle-of-attack ($\alpha$) was varied from 90° to 60° to 45° to 30°, respectively. Two types of entrance conditions were examined, namely, long duct and sudden contraction, respectively. The heat transfer coefficients distribution on the smooth side wall and between the ribs of the rough side wall at the entrance and the fully developed regions were measured. Thermal performance was compared, and the optimum rib flow-attack-angle was identified. Semi-empirical correlations for friction factor and heat transfer coefficients were developed to account for rib spacing and rib angle. The correlations can be used for gas turbine blade cooling passages.




End View




Front View




Front View

Figure 1. Rib geometry

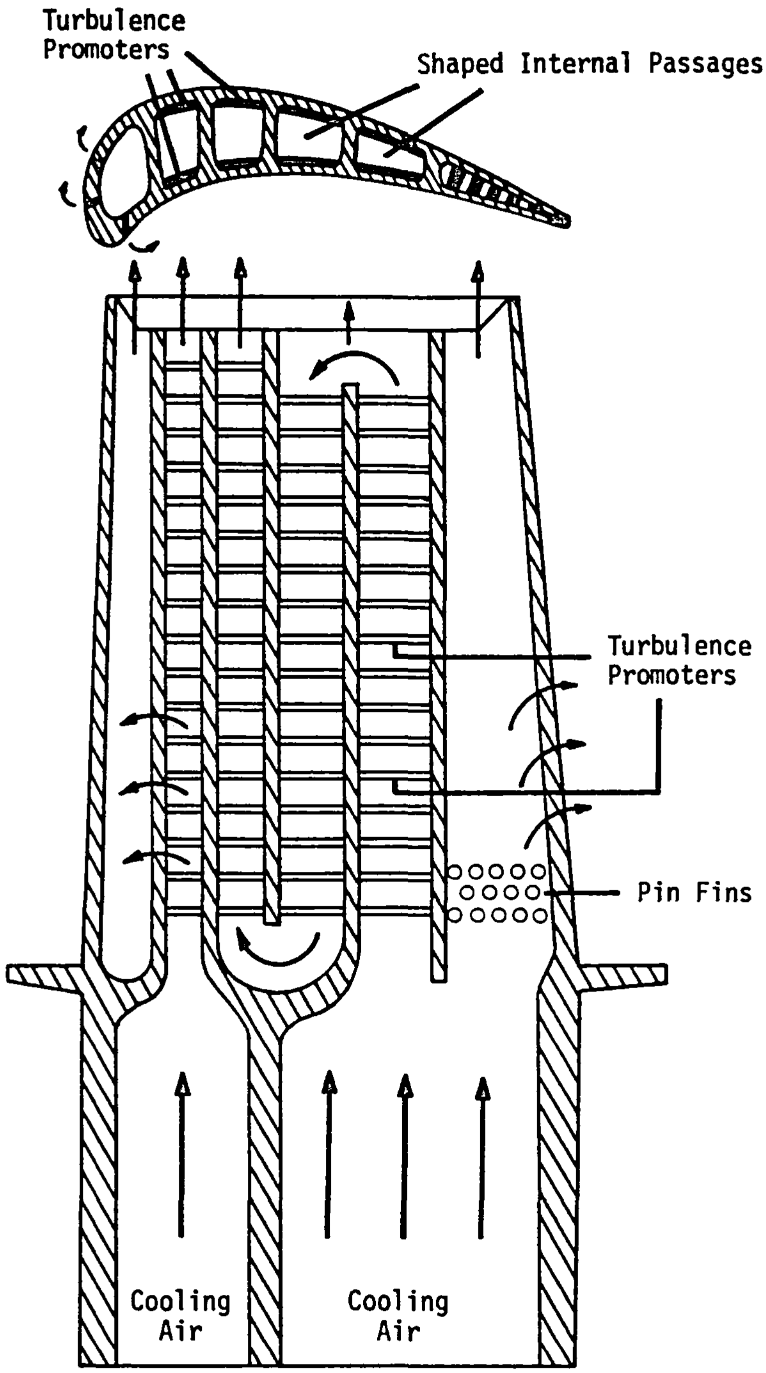



Figure 2. Design Concept of a Modern Internally-Cooled Gas Turbine Blade

# 3.0 SQUARE DUCT WITH LONG DUCT ENTRANCE

## 3.1 The Experimental Apparatus

The construction of the apparatus with a long duct entrance was completed before this project started on August, 1982. The purpose of this apparatus was to provide the friction factor and the average heat transfer coefficients data for flow in the fully developed region. Figure 3 shows a schematic, and Figure 4 shows a photograph of the test rig.

A blower forced air at room temperature and pressure through a 10.16 cm (4 in) diameter tube equipped with a 5.08 cm (2 in) diameter ASME square-edged orifice plate to measure flow rate. A transition section was used between the tube and the unheated entrance duct. At the end of the heated test duct, the air was exhausted into the atmosphere. The blower was capable of providing a range of air velocities so that the Reynolds number (Re) in the test duct varied between 7,000 and 90,000.

The test duct which consisted of four heated parallel aluminum plates, 0.635 cm (0.25 in) thick, as shown in Figure 5, had cross-sectional dimensions 7.6 cm by 7.6 cm (3 in by 3 in) and a heated length of 20 duct diameters. The duct orientation was such that the two opposite rib-roughened walls of the square cross section were vertical and the two opposite smooth walls horizontal. These ribbed walls were made by gluing square brass ribs to the plate surface in a required distribution. The ribs serve as turbulence promoters to trip the laminar sublayer of the turbulent flow. The glue thickness of the present study was estimated to be 0.0127 cm (0.005 in) or less. A 0.159 cm (0.0625 in) thick asbestos strip was adhered along the contact surface between the smooth and the ribbed walls to reduce the possible heat conduction effect. Woven heaters embedded in silicone rubber were glued uniformly between the aluminum plate and a wood panel to insure good contact. Each aluminum plate had one woven heater; each heater could be independently controlled by a variac transformer and provided a controllable constant heat flux for the entire test plate. The entire heated test duct, including unheated end duct, was mounted centrally in a long horizontal enclosure of cross-sectional dimensions 30.5 cm by 30.5 cm (12 in by 12 in). The enclosure was filled with fiberglass insulating material. The unheated entrance duct had the same cross-section and length as those of the test duct although the entrance duct was made of plexi-glass plates. This entrance duct served to establish hydrodynamically fully developed flow at the entrance to the heated duct. Additionally, the entrance duct was ribbed over its length on two opposite walls in the same way as the test duct. The test section was instrumented with 36, 36 gauge, copper-constantan thermocouples distributed along the length and across the span of the aluminum plates, as shown in Figure 6. Thermocouples were also used to measure the bulk mean air temperature entering and leaving the test section. Five pressure taps along the test duct (three on the smooth side and two on the ribbed side) were used for the static pressure drop measurements across the test duct.

## 3.2 Analysis of Data

The pressure drop across the test section was measured by a micromanometer and checked by an inclined manometer. In fully developed duct flow, the friction factor can be determined by measuring the pressure drop across the flow channel and the mass flow rate of the air. The friction factor can be calculated from:

$$\bar{f} = \frac{\Delta p}{4(L/D)(G^2/2\rho g_c)} \tag{1}$$

During the experiments, it was seen that the magnitude of the pressure drop was about the same when measured from the pressure taps on the smooth side or on the ribbed side wall. Therefore, the friction factor, calculated from equation (1) was an average value (i.e., average friction factor) over the smooth side wall and the ribbed side walls. The average friction factor of the present investigation was based on the adiabatic conditions (tests without heating). The maximum uncertainty in the average friction factor was estimated to be less than 6.6% for Reynolds number greater than 10,000 by using the uncertainties estimation method of reference [17].

For the longitudinally constant heat flux boundary condition of the present investigation, the thermally fully developed region is characterized by wall and fluid temperatures that increase linearly as a function of longitudinal position. The longitudinal distribution of the fluid bulk mean temperature was represented as a straight line connecting the measured values at inlet and exit. Typically, at downstream distances ranging from 3 to 5 hydraulic diameters from the start of heating the wall temperature data paralleled the aforementioned bulk temperature straight line. During the tests, it was found that the ribbed surface heat transfer capability was higher than that of the smooth surface. Consequently, the ribbed wall temperature was lower than the smooth one. In order to reduce the possible heat conduction effect between the smooth wall and the rough wall, the heat input to the smooth wall was controlled at about 2/3 to 4/5 that of the rough wall. Therefore the temperature difference between the adjacent walls was maintained between 0.6°C to 1.8°C (1°F to 3°F) in all tests. Additionally, in order to reduce the thermocouple inaccuracy, which strongly affects the calculated heat transfer coefficient, the temperature rise of air was maintained between 11°C and 17°C (20°F and 30°F), and the temperature difference between the wall and fluid was maintained between 22°C and 33°C (40°F and 50°F) in all tests.

The heat transfer coefficients to be reported here will be termed spanwise-average since they describe the average value of the full 7.6 cm (cross-sectional) span of the heated wall. The spanwise-average Nusselt numbers in the fully developed region (for example X/D = 11.5) can be calculated from:

$$Nu_S = [q''_S/(\bar{T}_w - T_b)_S](D/K), \tag{2}$$

$$Nu_R = [q''_R/(\bar{T}_w - T_b)_R]/(D/K), \tag{3}$$

$$\bar{N}u = \tfrac{1}{2}\,(Nu_S + Nu_R) \tag{4}$$

The $q''_S$ and $q''_R$ represent the net heat flux from the smooth side wall and the ribbed side wall to the fluid, respectively, whereas $(\bar{T}_w - T_b)_S$ and $(\bar{T}_w - T_b)_R$ are the thermal driving forces averaged over the span of the smooth wall and the ribbed wall in the fully developed region, respectively. The net heat flux is the heat flux generated from heater subtracting from heat loss to outside and from axial heat conduction in the test section, i.e., q" (net) = q" (heater) - q" (loss) - q" (net heat conduction). The maximum heat loss from the smooth side wall and the ribbed side wall was estimated to be less than 5% and 3% for Reynolds number greater than 10,000, respectively, while the maximum net heat conduction inside the smooth wall and the ribbed wall in the fully developed region was estimated to be less than 4% and 2% under the lower heat generation conditions. It is noted that the amount of the net heat conduction was not taken into account for the Nusselt number calculations because they were not enough thermocouples distributed in the neighborhood of X/D = 11.5 for the accurate temperature gradient calculations. Equation (2) was used for the smooth side wall Nusselt number calculation and equation (3) was for the ribbed side wall while equation (4) was for the average Nusselt number in a duct with two opposite ribbed walls. Notice that the ribbed side heat flux, $q''_R$, was based on the projected heat transfer area (not including the increased rib surface area). The maximum uncertainty in the Nusselt number was estimated to be less than 6.8% for Reynolds number greater than 10,000.

## 3.3 Experimental Results

### 3.3.1 Friction and Heat Transfer for Smooth Duct

Before initiating experiments with rib-roughened walls, the friction factor and heat-transfer coefficients were measured for a four sided smooth duct and compared with the results given in the literature, as shown in Figure 7. As seen by the figure there is good agreement between an existing correlation and the experimental results for the present smooth duct with 7.6 cm by 7.6 cm cross-section. The friction factor differs by up to 9.0% from the modified Karman-Prandtl equation [18], and the Nusselt number differs by up to 9.5% from the Petukhov-Popov equation [19]. This showed that accurate data would be expected for the cases with ribbed walls. The modified Karman-Prandtl equation for the four sided smooth duct friction factor by Brundrett (18] is:

$$1/(f)^{\frac{1}{2}} = 4.0 \log_{10}[Re(f)^{\frac{1}{2}}] - 0.4 + 4.0 \log_{10}(2Rav/D) \quad (5)$$

Where

$$2Rav/D = 1.156 \text{ for square duct}$$

The Petukhov-Popov equation for the four sided smooth duct heat transfer [19] is:

$$Nu = (f/2)Re\,Pr/[1.07 + 12.7\,(f/2)^{\frac{1}{2}}(Pr^{2/3} - 1)] \quad (6)$$

3.3.2 Friction and Heat Transfer for Ribbed Duct

The ribs had a square cross-section and were glued onto the surfaces in patterns to achieve the desired spacing and angle-of-attack. Table 1

Table 1. Rib Geometry Tested for Long Duct Entrance

| | P/e = 10 | | P/e = 20 | |
|---|---|---|---|---|
| | Friction | Heat Transfer | Friction | Heat Transfer |
| $\alpha$ = 90° | X | X | X | X |
| = 75° | X | X | X | X |
| = 60° | X | X | | |
| = 45° | X | X | X | X |
| = 30° | X | X | X | X |
| = 15° | X | | X | |

Note: For All Tests: e/D = 0.063, Re = 7,000 to 90,000.

shows a total of 11 rib geometries tested for the square duct with long duct entrance. The tabulated data is given in section 7.1 Appendix. Only the most representative results will be discussed here.

The average friction factor vs Reynolds number for the different rib angle is shown in Figures 8-9. For the $\alpha$ = 90°, 75°, 60°, and 45°, the friction factor approaches an approximately constant value as the Reynolds number increases while the friction factor decreases with Reynolds number when the $\alpha$ = 30° and 15°. For the case of P/e = 10, the friction factor with $\alpha$ = 90° is about 3-10 times higher than the four sided smooth duct over the range of Reynolds number. The friction factor with $\alpha$ = 45° is about the same as $\alpha$ = 90°, however, it decreases by 20-40% when the $\alpha$ changes from 90° to 30°. It is noted that the friction factor with $\alpha$ = 60° (or 75°) is about 50% higher than $\alpha$ = 90°. The results with P/e = 20 has the similar trends as P/e = 10, however, the friction factor is relatively reduced as shown in Figure 9.

Figures 10-13 are the typical temperature distribution of the ribbed side wall and smooth side wall along the test section. It is seen that the ribbed side wall heat flux is higher than the smooth side wall. Therefore the Nusselt number of the ribbed side wall is higher than that of the smooth side wall as shown in Figures 14-17. It is seen that the Nusselt number approaches a constant value for X/D greater than 5.

The Nusselt number shown in Figures 18-23 were based on the fully developed region results (i.e., X/D = 11.5). The data show that the Nusselt number (therefore the heat transfer coefficients) increases with increasing Reynolds number as in conventional turbulent pipe flow.

Figures 18-20 show the results for P/e = 10. As indicated in Figure 18, the Nusselt number of the ribbed side wall with $\alpha = 90°$ is about 2.5 times higher than that of the four sided smooth duct. The Nusselt number with $\alpha = 30°$ is about the same as $\alpha = 90°$; whereas the Nusselt number with $\alpha = 45°$ (60°, and 75°) is about 25% higher than that $\alpha = 90°$. As seen from Figure 19, the Nusselt number of the smooth side wall is also higher than that of the four sided smooth duct by 30-80% due to the presence of the ribs on the adjacent walls. It is observed that the ribs with an oblique angle to the flow has more influence on the smooth side walls. Therefore the average Nusselt number (average of the ribbed side and the smooth side walls) for the ribs with an oblique angle to the flow is higher than that the rib with a 90° angle to the flow, as shown in Figure 20. The results for P/e = 20 has the similar trends as P/e = 10, however, the heat transfer is relatively reduced as shown in Figures 21-23.

The orientation of the ribs with respect to the thermocouples in the fully developed region (X/D = 9.7 - 15.3) is shown in Figures 24-27. It is noted that the thermocouples under ribs read close to the other thermocouples because of the aluminum plate. The local Nusselt number variation in both streamwise and spanwise directions is less than 6% for $\alpha = 90°$ and 30°. The Nusselt number of the ribbed side wall is greater than the smooth side wall. The heat transfer of P/e = 10 is greater than P/e = 20 and $\alpha = 30°$ is greater than $\alpha = 90°$. The heat transfer increases with increasing Reynolds number.

3.4 Thermal Performance Comparison

Figures 28-29 show the friction factor and Stanton number vs the rib angle-of-attack. The data of the 0° angle-of-attack was obtained from the present smooth duct results. Both the friction and heat transfer increase with decreasing $\alpha$, and reach a maximum value at $\alpha$ approximately 70°-60°, then decrease with further decreasing $\alpha$. It is noted that the amount of the friction factor decrease is relatively larger than that of the Stanton number when the rib angle-of-attack changes from 90° to 30°. This suggests that the best thermal performance may be obtained at the rib flow-attack-angle around 30°.

Figures 30-37 show the thermal performance vs average roughness Reynolds number ($\bar{e}^+$). The $\bar{f}/f$ increases with increasing $\bar{e}^+$ while the $\bar{St}/St$ is insensitive to $\bar{e}^+$ as seen from Figures 30-33. These considerations suggest that the preferred operating condition is for smaller $\bar{e}^+$. This is illustrated in Figures 34-35 which show the efficiency index ($\eta$) vs $\bar{e}^+$. However, it should be noted that the $\bar{e}^+$ is estimated to be varied from 200 to 500 in the gas turbine cooling application. It is clearly seen that the best $\eta$ is obtained with the 30° flow-attack-angle. It should be noted that the best performance angle was reported about 45° for flow between parallel-plates and in tubes (i.e., four sided ridded duct) by the previous investigations [6-7]. Based on these observations, it may be concluded that the best rib angle is shifted from a 45° to a smaller angle of 30° when the square duct has only two opposite ribbed walls.

One of the performance evaluation criteria was to compare the reduced pumping power for equal heat transfer load and surface area operating at fixed total flow rate and entering fluid conditions [7]. Figures 36-37 show the reduced pumping power ($\bar{P}/P$, pumping power for ribbed duct relative to pumping power for smooth duct) vs $\bar{e}^+$ for the data of this study. Again the 30° oblique ribs provide the highest performance (i.e., the lowest pumping power required for a given heat load and surface area) for P/e = 20, but the difference between 30° and 45° is reduced when P/e = 10.

3.5 Friction and Heat Transfer Correlations

For the results of rib-roughened surfaces to be most useful, general correlations are required for both the friction factor and the heat transfer coefficients which cover a wide range of parameters (e/D, Re, P/e, $\alpha$).

Since Nikuradse [20] found the law of the wall and developed the so-called friction similarity law to correlate the friction data for fully developed turbulent flow in tubes with sand roughness, the method has been successfully extended to correlate the friction data for turbulent flow in tubes with repeated-ribs roughness [2]. Assuming that the same method can be applied to flow in a four sided ribbed duct, the law of the wall can be expressed by the dimensionless velocity profile normal to the wall:

$$u^+ = 2.5 \ \ell n \ (y/e) + R(e^+) \tag{7}$$

Integration of equation (7) across the cross-sectional area of a flow channel gives:

$$\bar{u}^+ = -2.5 + 2.5 \ \ell n \ (\ell/e) + R(e^+) \tag{8}$$

Where $\ell$ is the distance between the ribbed wall and the position of zero shear stress (i.e., $\ell$ = 1/2 D). The dimensionless average velocity across the channel in a four sided ribbed duct can be written in terms of the friction factor, $f_r$, as:

$$\bar{u}^+ = (2/f_r)^{\frac{1}{2}} \tag{9}$$

Inserting equation (9) into equation (8), the friction similarity law for flow in a four sided ribbed square duct yields

$$R(e^+) = (2/f_r)^{\frac{1}{2}} + 2.5 \ln (2e/D) + 2.5 \quad (10)$$

Assuming that equation (10) can be applied for flow in a square duct with two opposite ribbed walls, by replacing $\bar{R}$ and $\bar{f}$ for R and $f_r$, the friction similarity law of the present study becomes

$$\bar{R}(\bar{e}^+) = (2/\bar{f})^{\frac{1}{2}} + 2.5 \ln (2e/D) + 2.5 \quad (11)$$

It should be noted that $R(e^+)$ and $f_r$ is for flow in a four sided ribbed duct, whereas $\bar{R}(\bar{e}^+)$ and $\bar{f}$ is for flow in a two opposite ribbed duct. It is expected that $\bar{R}(\bar{e}^+)$ is larger than $R(e^+)$ for a given e/D ratio because $\bar{f}$ is smaller than $f_r$. Han and Lei [22] found that all the data of the different e/D ratios (e/D ≅ 0.021 to 0.063) can be correlated into one value of $\bar{R}$ ($\bar{R}$ ≅ 5.2) in fully rough regime for a given rib angle-of-attack ($\alpha$ = 90°), and rib pitch-to-height ratio (P/e = 10). This is why we only need to study one value of e/D ratio (i.e., e/D = 0.063) in order to determine $\bar{R}$. Once $\bar{R}$ is experimentally determined, the friction factor can be predicted from equation (11) for a given e/D ratio.

Correlation of the present friction data is shown on Figures 38-39. The data for the non-geometrically similar roughness are displaced due to their different value of P/e and $\alpha$. The $\bar{R}$ is independent of $\bar{e}^+$ for $\alpha$ = 90° to 45° while the $\bar{R}$ increases with increasing $\bar{e}^+$ (because $\bar{f}$ decreases with increasing Reynolds number) for $\alpha < 45°$. The dependence of $\bar{R}$ on P/e and $\alpha$ shown in Figure 40 is

$$\bar{R}/[(P/e/10)^{0.35} (0.003\ \bar{e}^+)^n] = 15.6 - 31.6(\alpha/90°) + 21.1(\alpha/90°)^2 \quad (12)$$

Where $n = 0$ if $\alpha \geq 45°$, $n = 0.17$ if $\alpha < 45°$. It is noted that the discontinuity of equation (12) at $\alpha$ slightly smaller than 45° is estimated to be less than ± 8% when the $\bar{e}^+$ is varied from 200 to 500 in the gas turbine cooling design. The friction factor can be found by combining equations (11) and (12). The correlation can be used for blade internal cooling design.

Dipprey and Sabersky [21] developed the heat transfer similarity law to correlate heat transfer data for fully developed turbulent flow in tubes with sand roughness. This similarity method has been extended to correlated heat transfer data for turbulent flow in rib-roughened tubes [2]. It is assumed that the same method can be applied for flow in a four sided ribbed duct using the heat and momentum transfer analogy, giving a dimensionless temperature profile normal to the ribbed wall as:

$$T^+ = 2.5 \ln (y/e) + H (e^+, Pr) \quad (13)$$

Integrating equation (13) over the flow channel cross section and combining with equations (8) and (9), produces:

$$\bar{T}^+ = (2/f_r)^{\frac{1}{2}} - R(e^+) + H (e^+, Pr) \quad (14)$$

Where the dimensionless average temperature profile can be expressed by

$$\bar{T}^+ = (f_r/2)^{\frac{1}{2}}/St_r \quad (15)$$

Substituting equation (15) into equation (14), the heat transfer similarity law for flow in a four sided ribbed duct yields

$$H(e^+, Pr) = R(e^+) + [f_r/(2St_r) - 1]/(f_r/2)^{\frac{1}{2}} \quad (16)$$

Assuming that equation (16) can be applied for flow in a square duct with two opposite ribbed walls by replacing $\bar{H}$, $\bar{R}$, $\bar{f}$, $\bar{St}$ for $H$, $R$, $f_r$, and $St_r$, respectively, the heat transfer similarity law of the present study becomes

$$\bar{H}\ (\bar{e}^+, Pr) = \bar{R}(\bar{e}^+) + [\bar{f}/(2\bar{S}t) - 1]/(\bar{f}/2)^{\frac{1}{2}} \tag{17}$$

Correlation of the present heat transfer data is shown in Figure 41. No significant dependence of $\bar{H}$ on P/e is observed. For a Prandtl number of 0.7 of the present study, the dependence of $\bar{H}$ on $\alpha$ and $\bar{e}^+$ can be represented by

$$\bar{H}\ (\bar{e}^+) = 3.74\ (\alpha/90°)^{0.3}\ (\bar{e}^+)^{0.28} \tag{18}$$

If $\bar{H}$, $\bar{R}$, and $\bar{f}$ are known, then the average Stanton number can be found as

$$\bar{S}t = \bar{f}/[(\bar{H} - \bar{R})(2\bar{f})^{\frac{1}{2}} + 2] \tag{19}$$

The correlation can be used for blade internal cooling design.

In design consideration, correlations for the ribbed side wall Stanton number ($St_R$) and the smooth side wall Stanton number ($St_s$) may be necessary. Assuming that equation (17) can be used to correlate the ribbed side wall heat transfer data by replacing $H_R$ and $St_R$ for $\bar{H}$ and $\bar{S}t$, one obtains

$$H_R(\bar{e}^+, Pr) = \bar{R}\ (\bar{e}^+) + [\bar{f}/(2St_R) - 1]/(\bar{f}/2)^{\frac{1}{2}} \tag{20}$$

Heat transfer correlation of the ribbed side wall is shown in Figure 42, the best curve fit can be represented by

$$H_R/(P/e/10)^{0.14} = 2.83(\alpha/90°)^{0.3}\ (\bar{e}^+)^{0.28} \tag{21}$$

If $H_R$, $\bar{R}$, and $\bar{f}$ are known, the ribbed side wall Stanton number can be determined as

$$St_R = \bar{f}/[(H_R - \bar{R})(2\bar{f})^{\frac{1}{2}} + 2] \quad (22)$$

After obtaining $\bar{S}t$ and $St_R$ from equations (19) and (22), the smooth side wall Stanton number can be found by

$$St_s = 2\ \bar{S}t - St_R \quad (23)$$

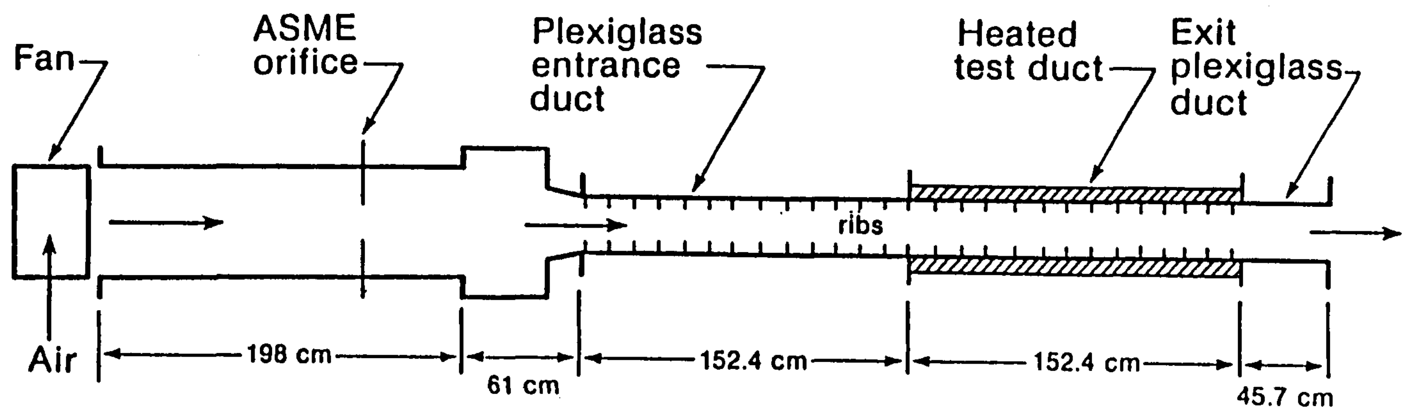
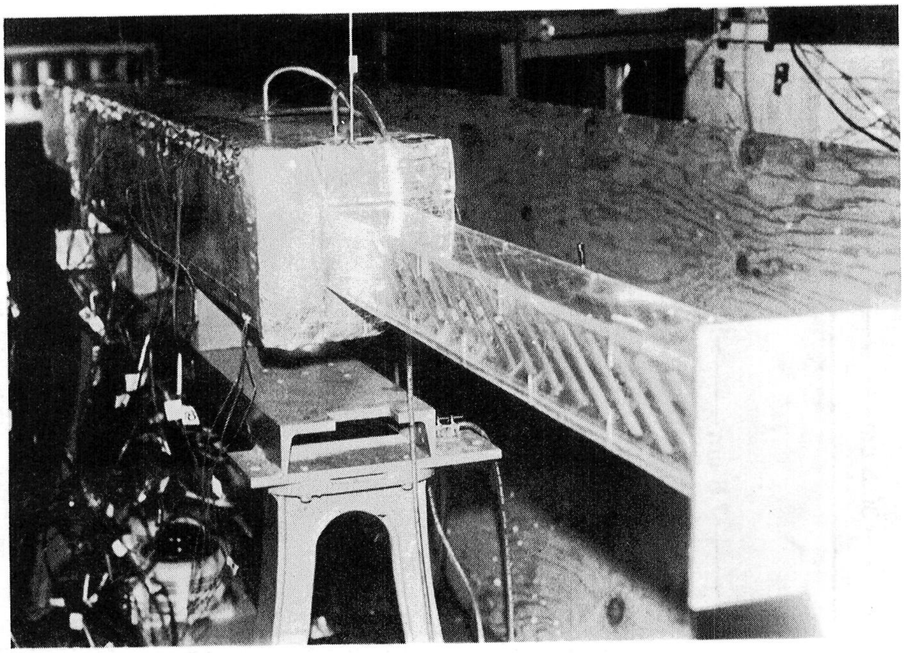



Figure 3. Test rig with Long Duct Entrance (LDE)



Upper photo: Test rig with long duct entrance

Lower photo: Opposite ribs at $\alpha = 30°$

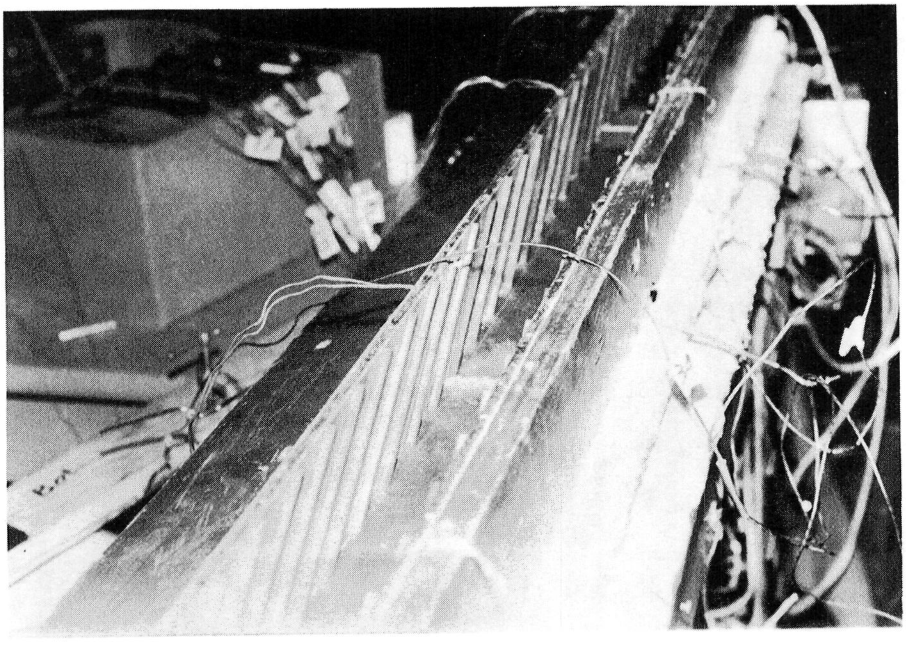


Figure 4. Photograph of test rig with long duct entrance

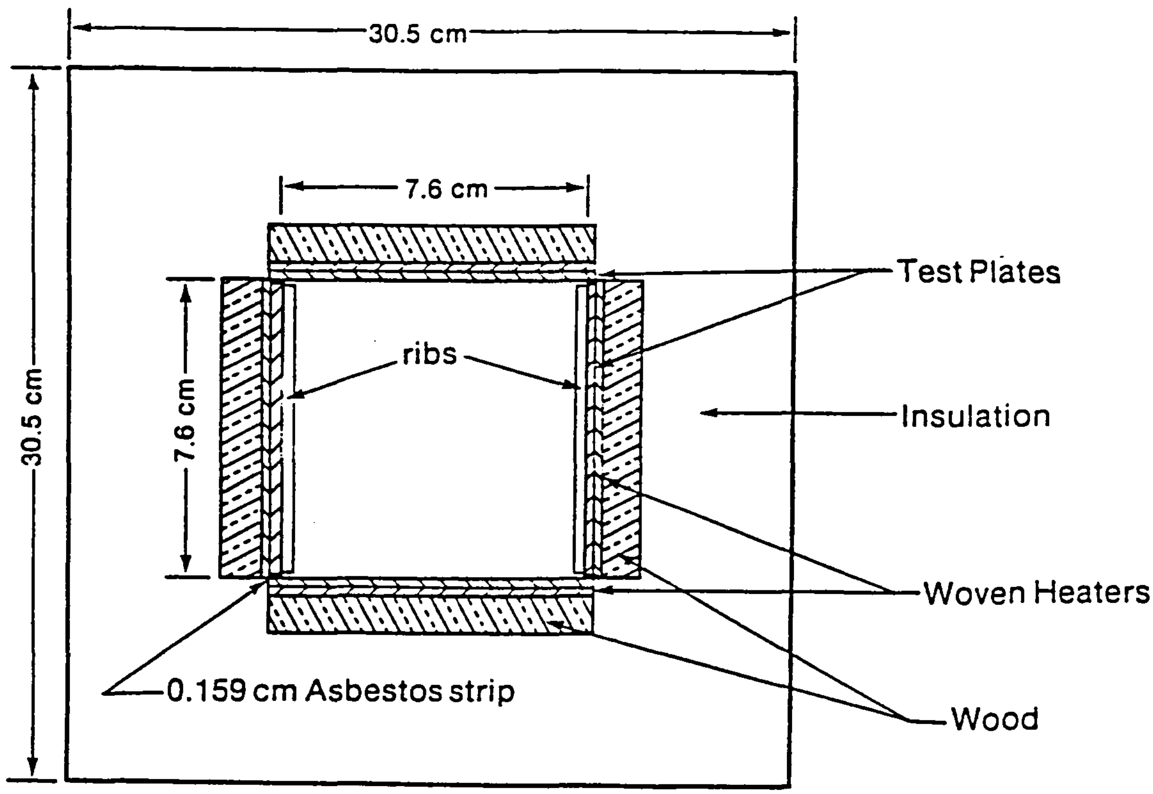



Figure 5. Cross-section of test duct

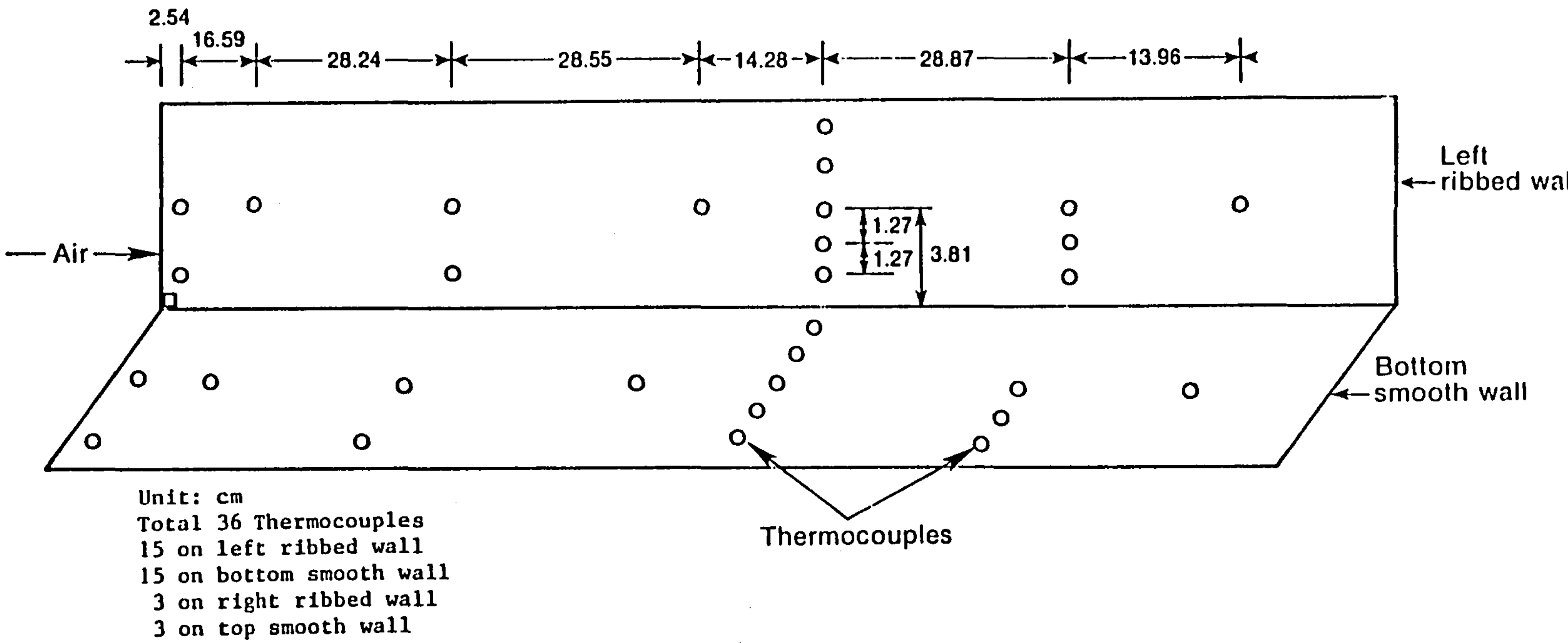



Figure 6. Thermocouples distributions on test plates (LDE)

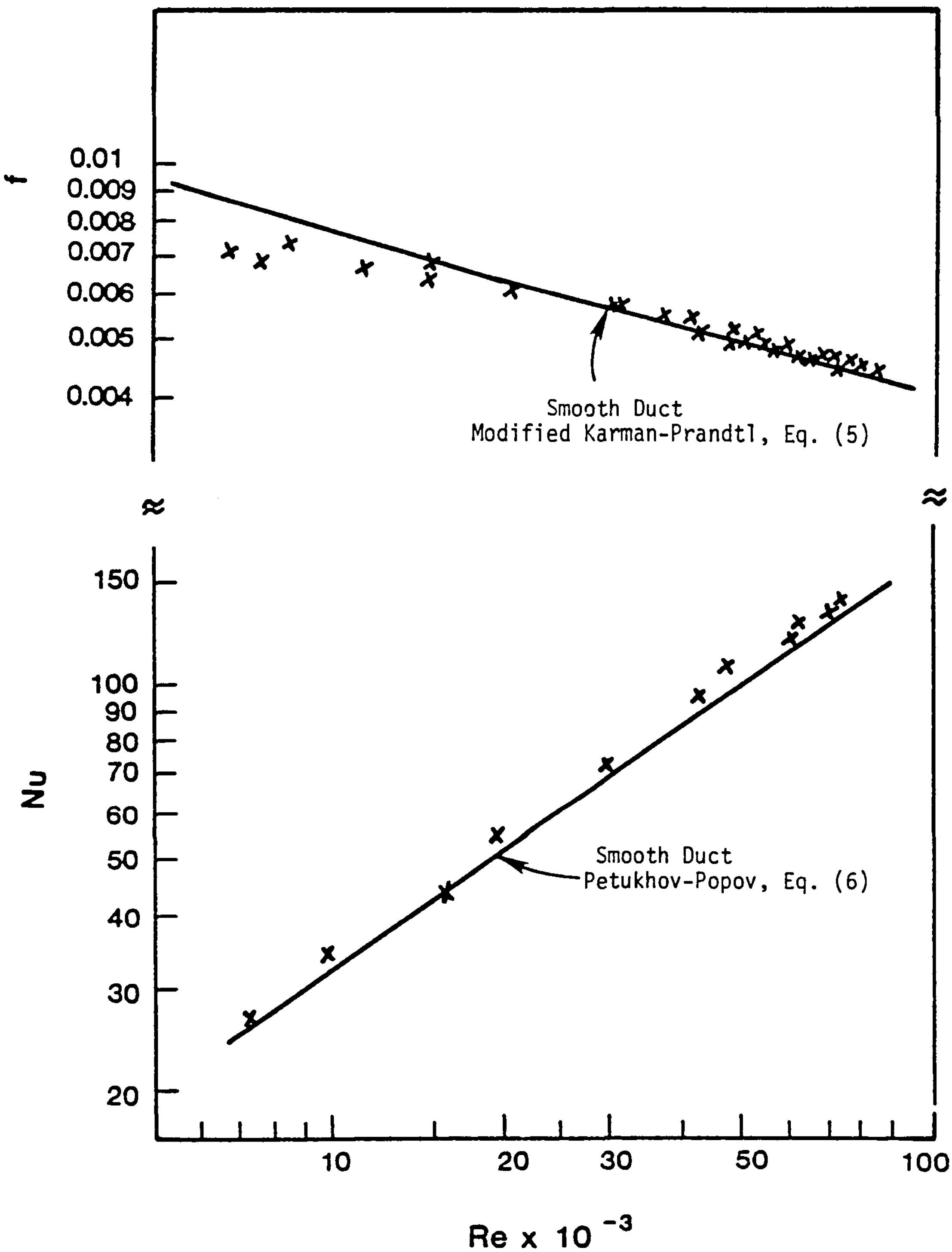



Figure 7. Friction and heat transfer results for smooth duct (LDE)

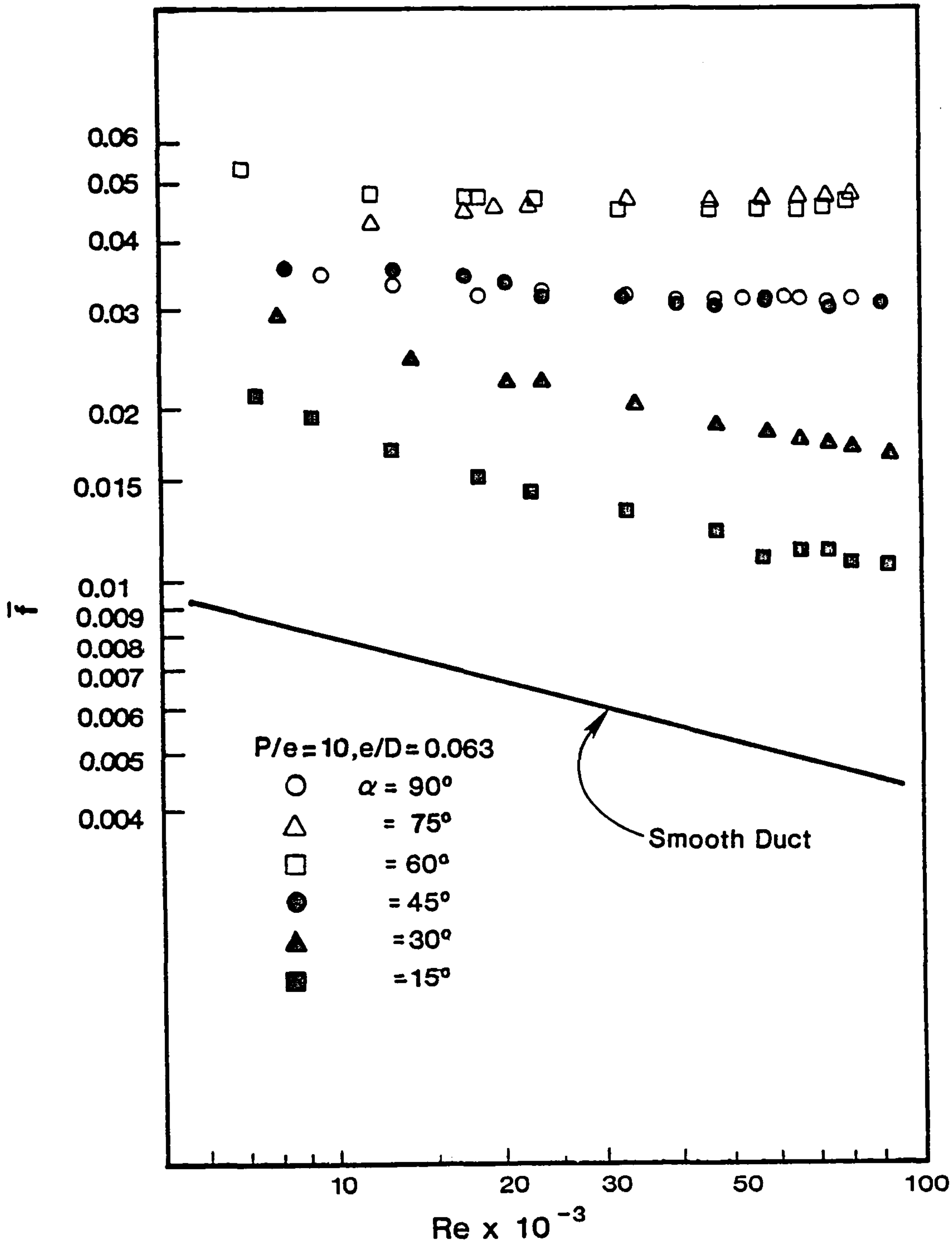



Figure 8. Average friction factor with different α for P/e = 10 (LDE)

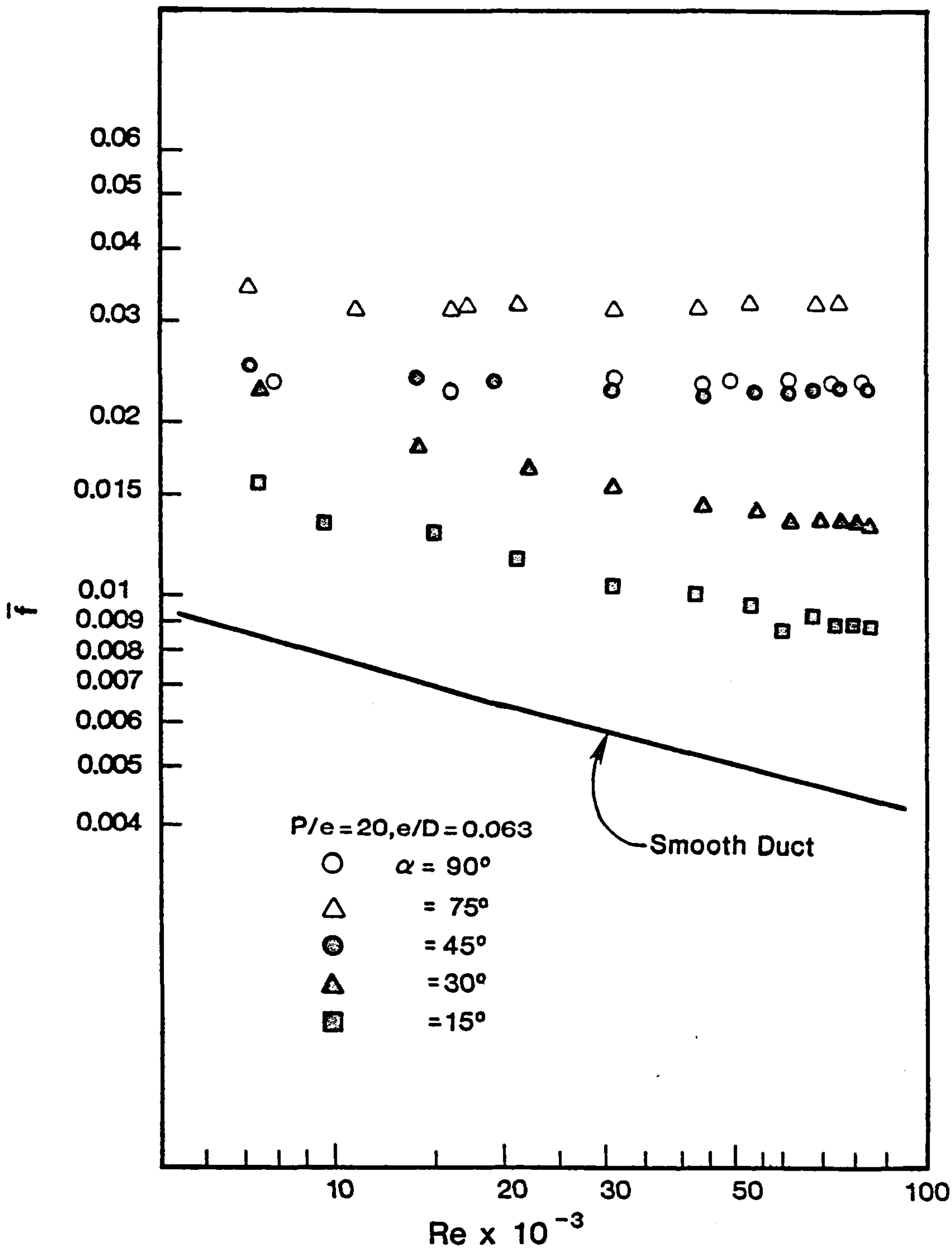



Figure 9. Average friction factor with different α for P/e = 20 (LDE)

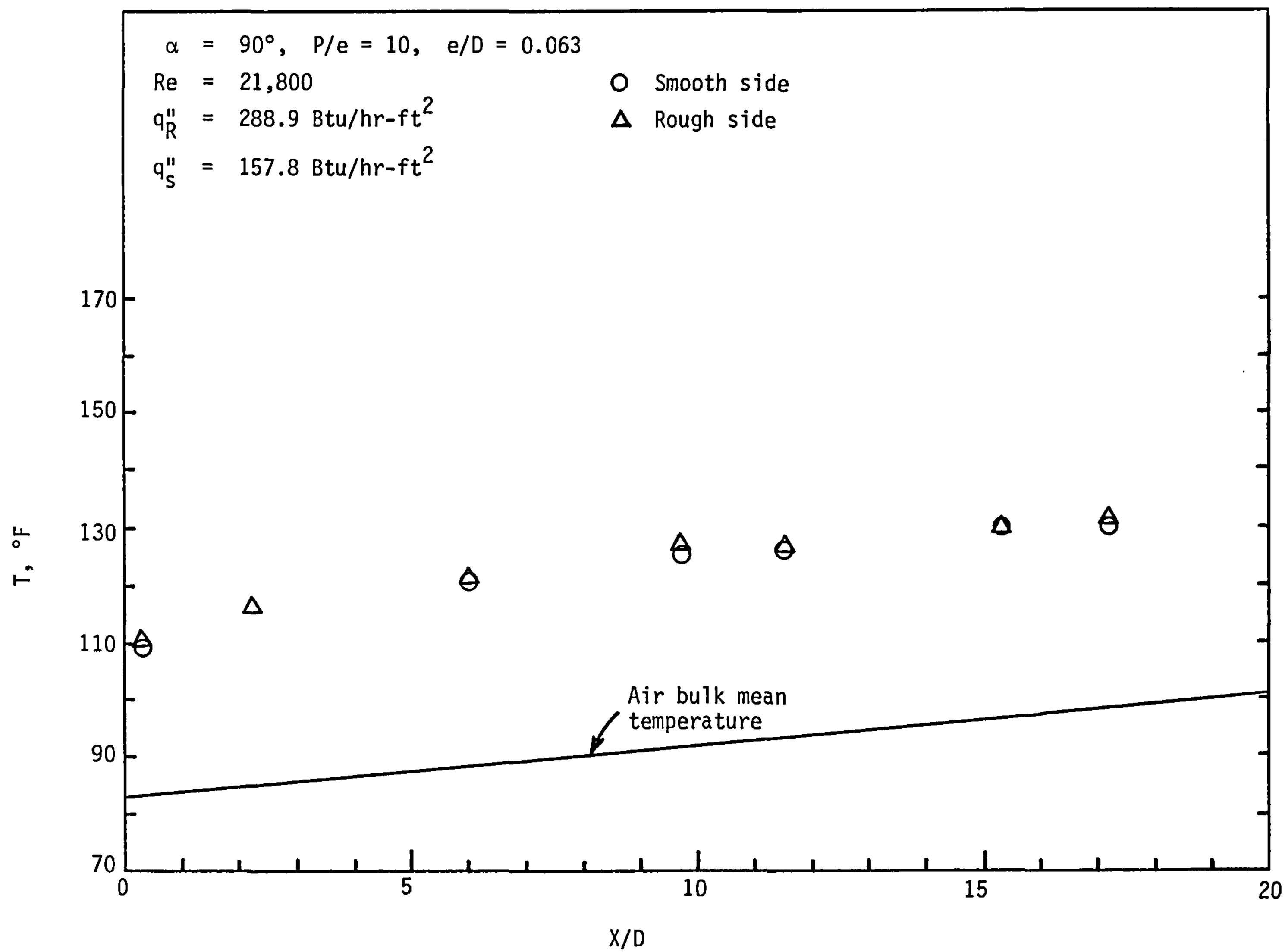



Figure 10. Temperature distributions for α = 90°, P/e = 10, Re = 21,800 (LDE)

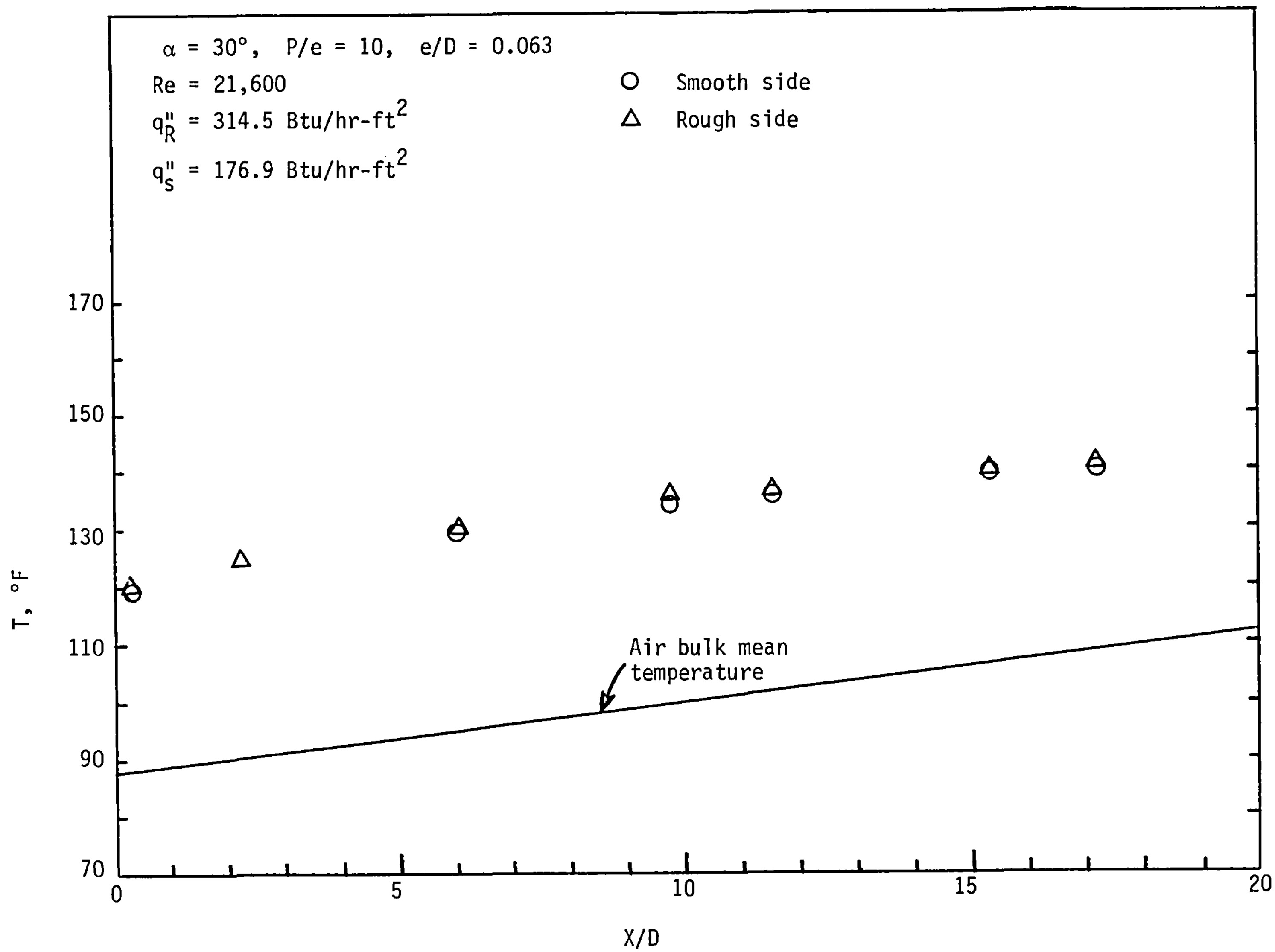



Figure 11. Temperature distributions for $\alpha$ = 30°, P/e = 10, Re = 21,600 (LDE)

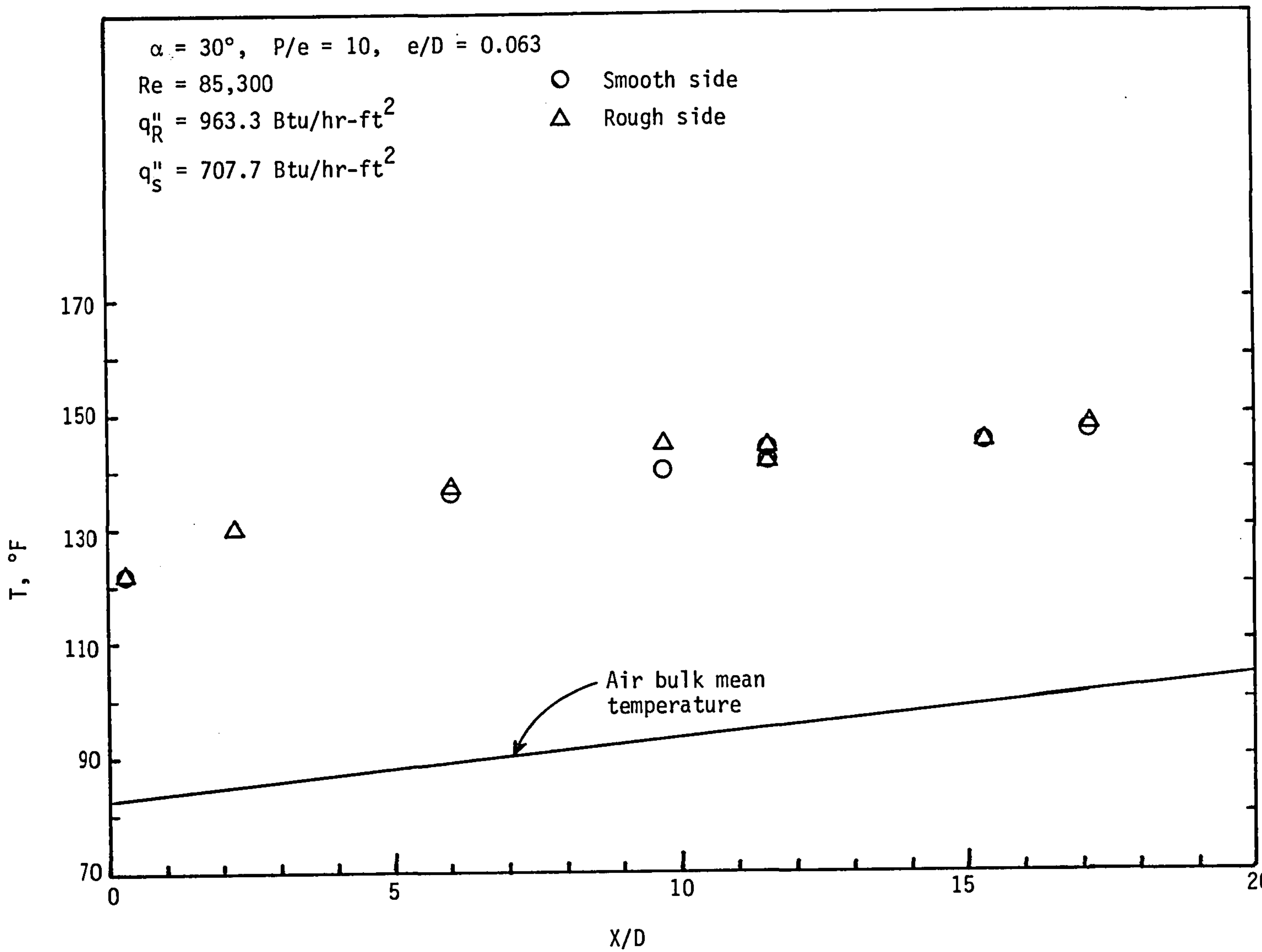



Figure 12. Temperature distributions for $\alpha = 30°$, P/e = 10, Re = 85,300 (LDE)

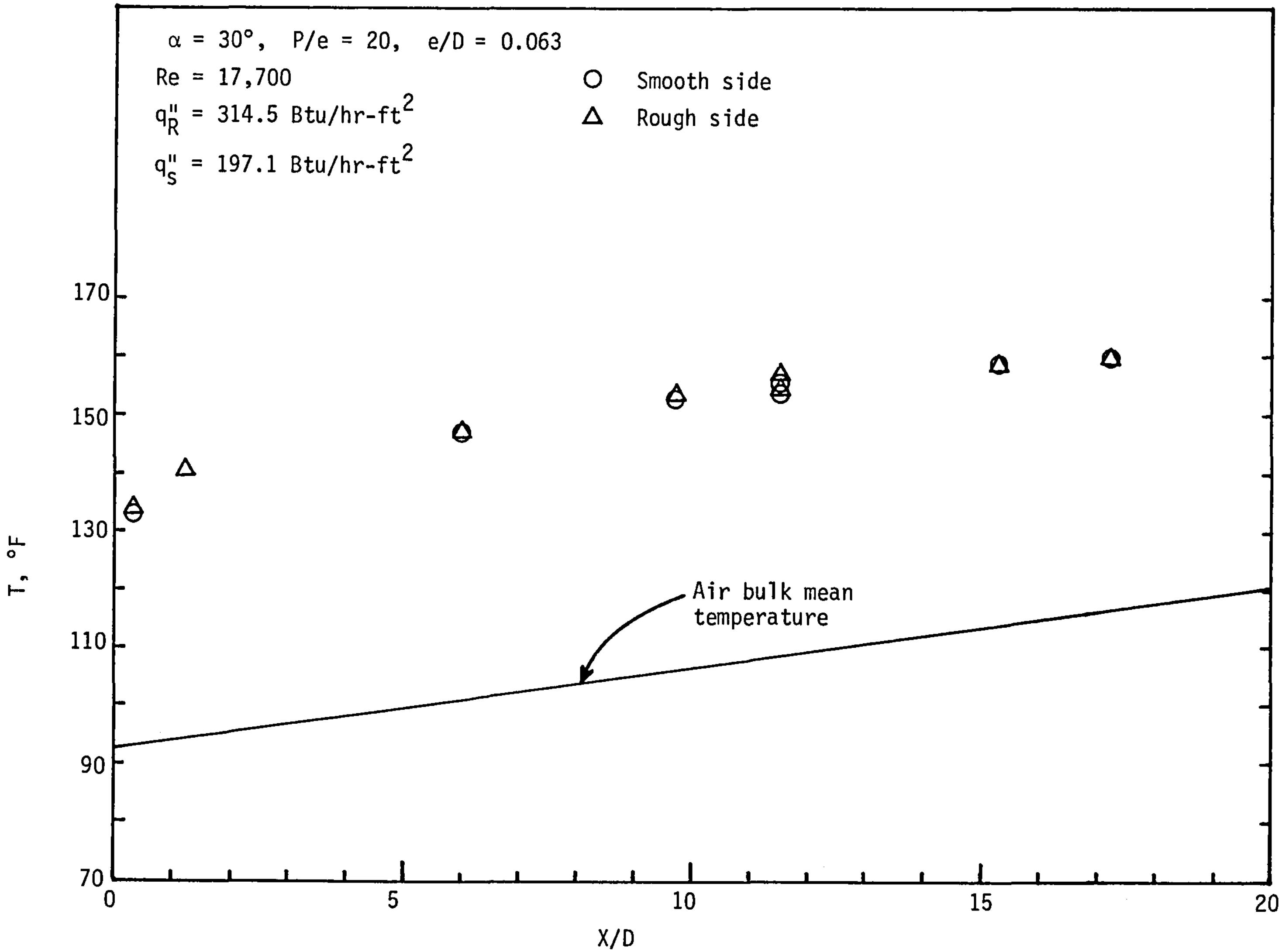



Figure 13. Temperature distributions for α = 30°, P/e = 20, Re = 17,700 (LDE)

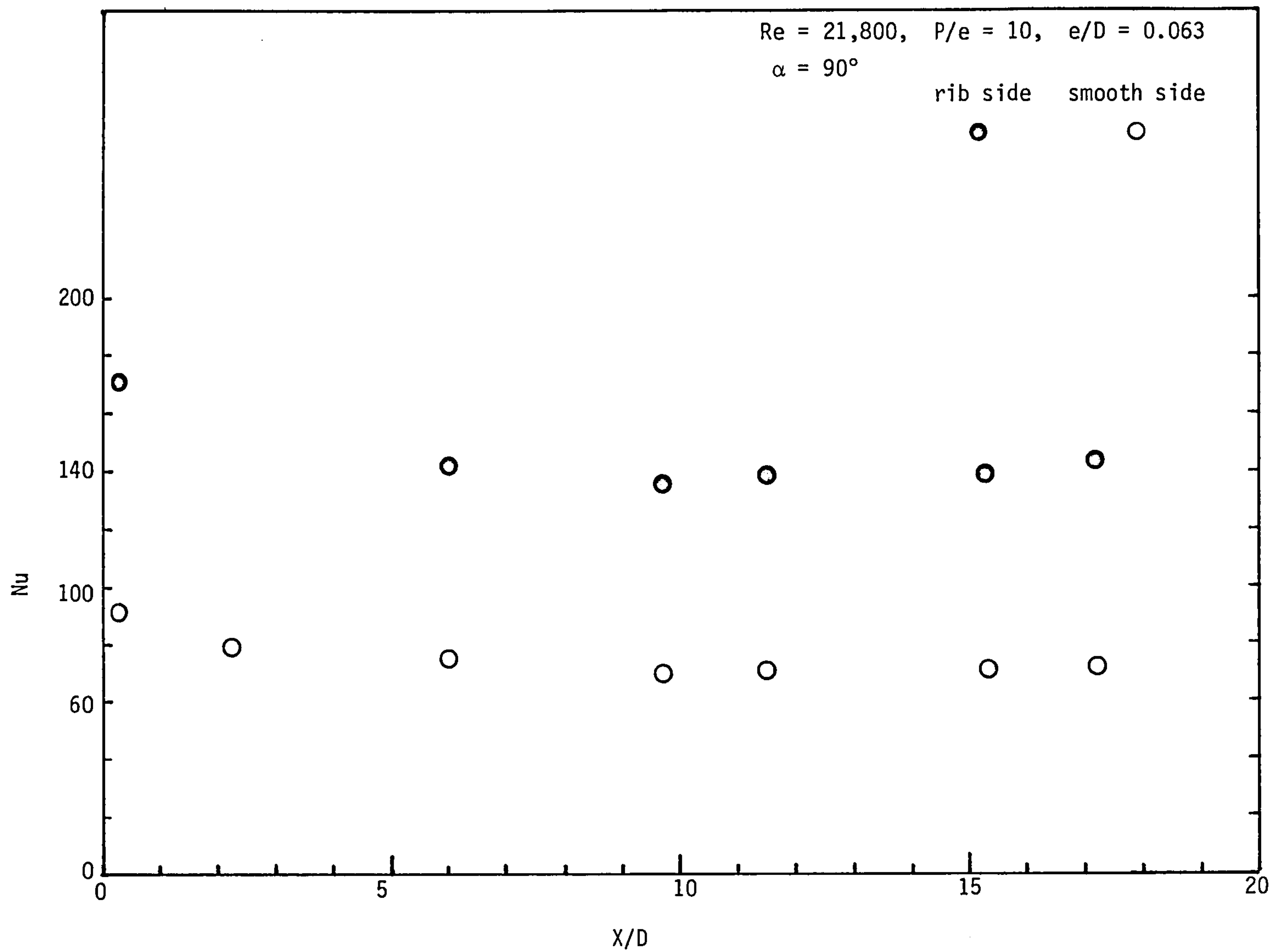



Figure 14. Nusselt number distributions for $\alpha = 90°$, P/e = 10, Re = 21,800 (LDE)

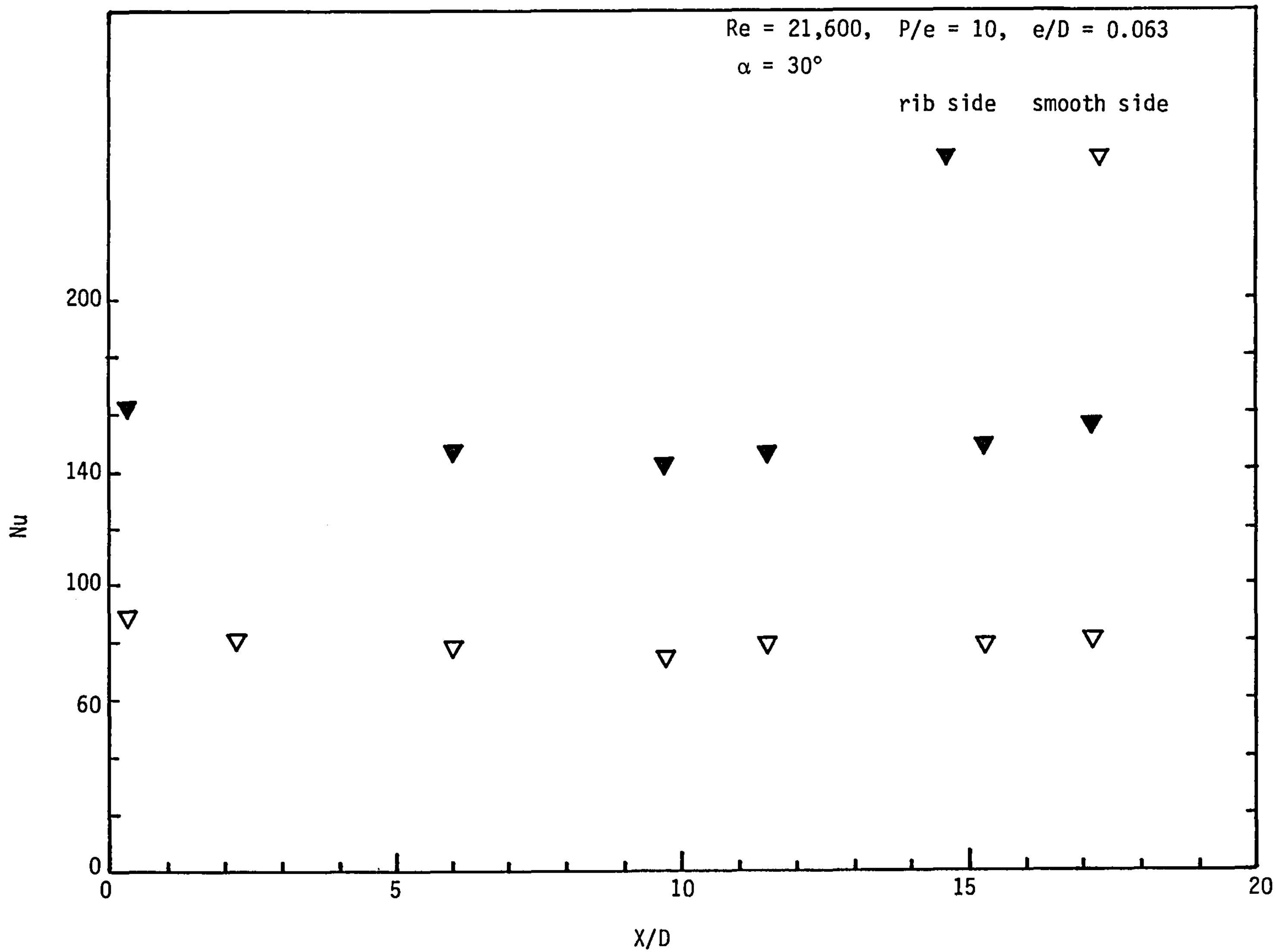



Figure 15. Nusselt number distributions for α = 30°, P/e = 10, Re = 21,600 (LDE)

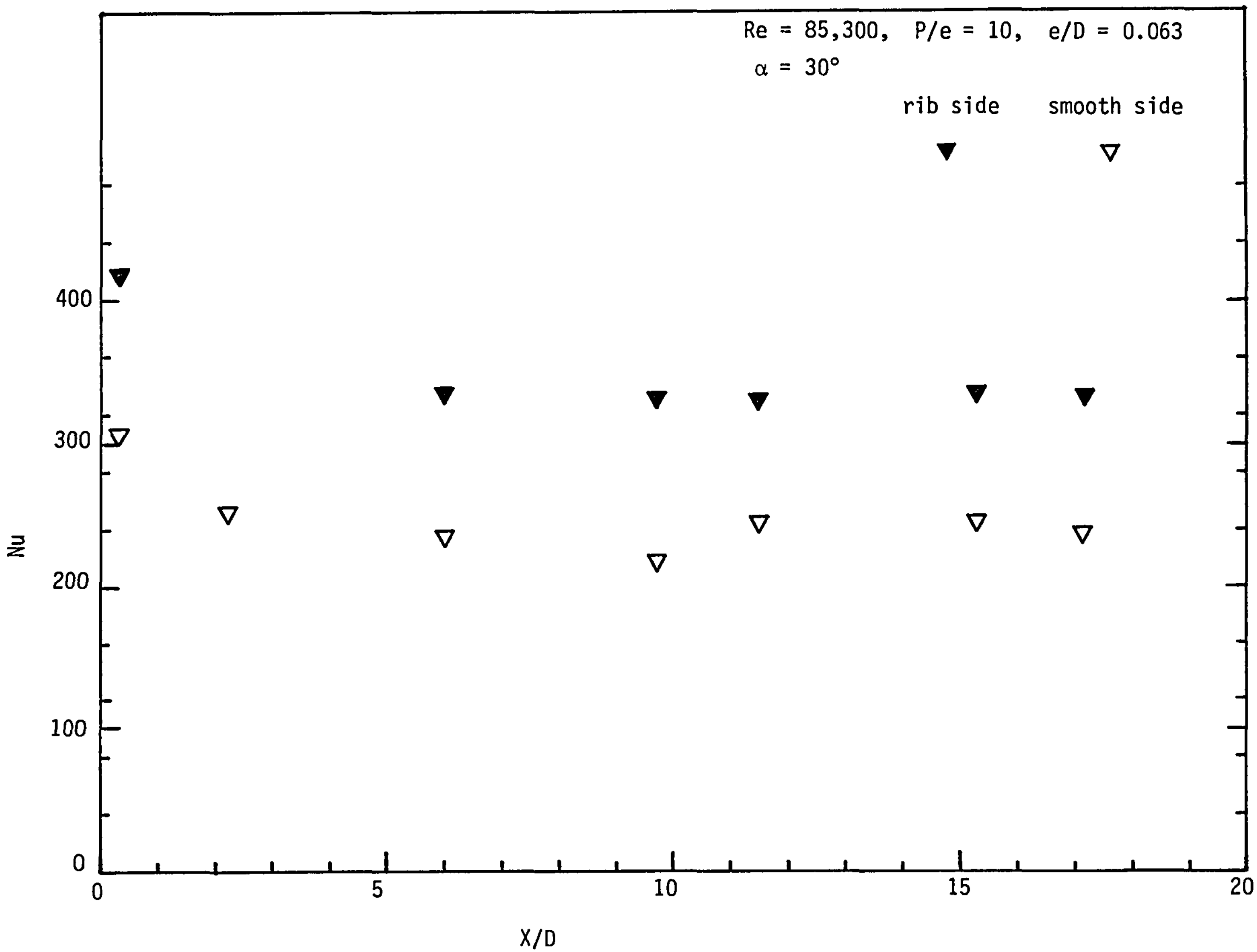



Figure 16. Nusselt number distributions for $\alpha = 30°$, P/e = 10, Re = 85,300 (LDE)

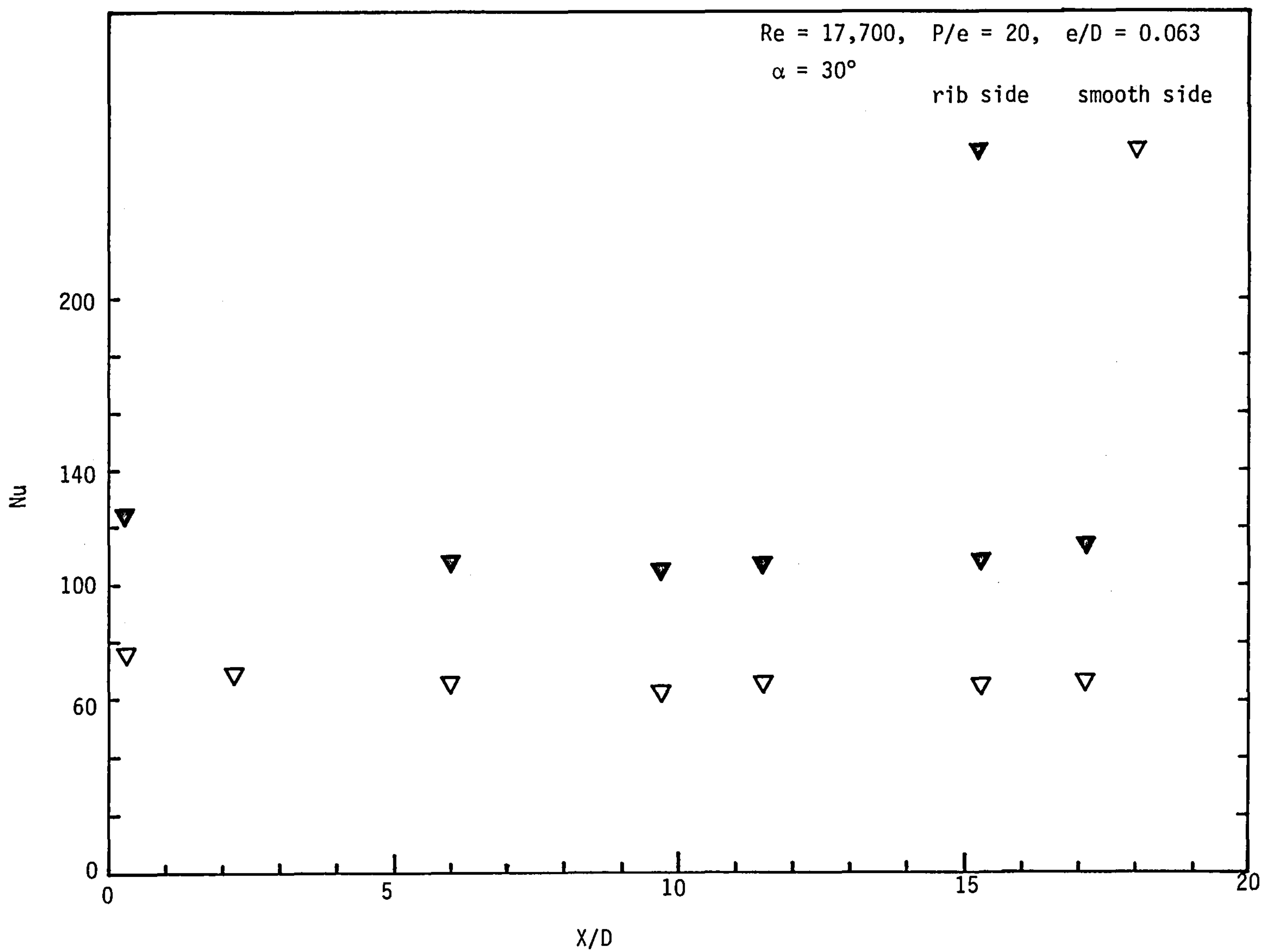



Figure 17. Nusselt number distributions for α = 30°, P/e = 20, Re = 17,700 (LDE)

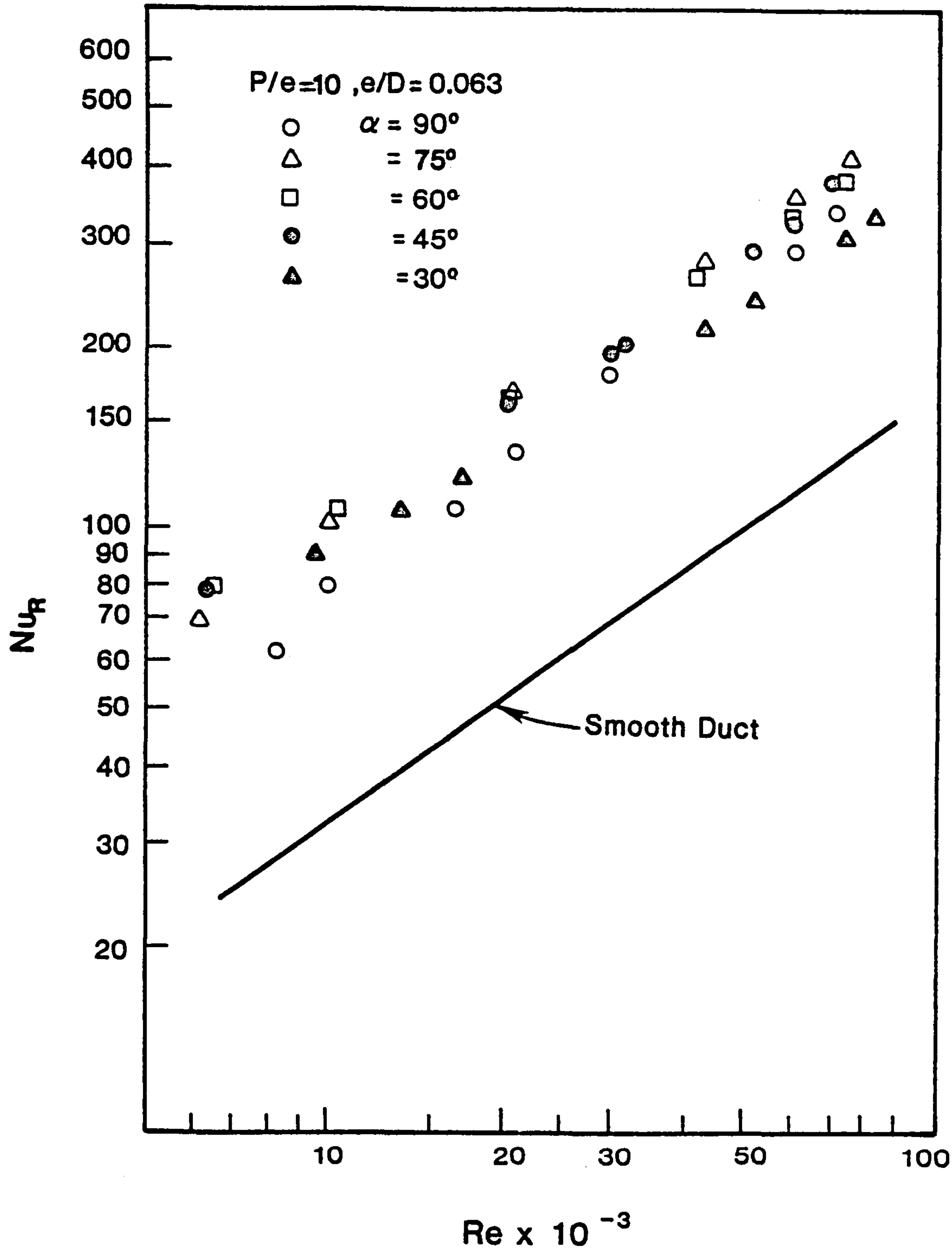



Figure 18. The ribbed side Nusselt number with different α for P/e = 10 (LDE)

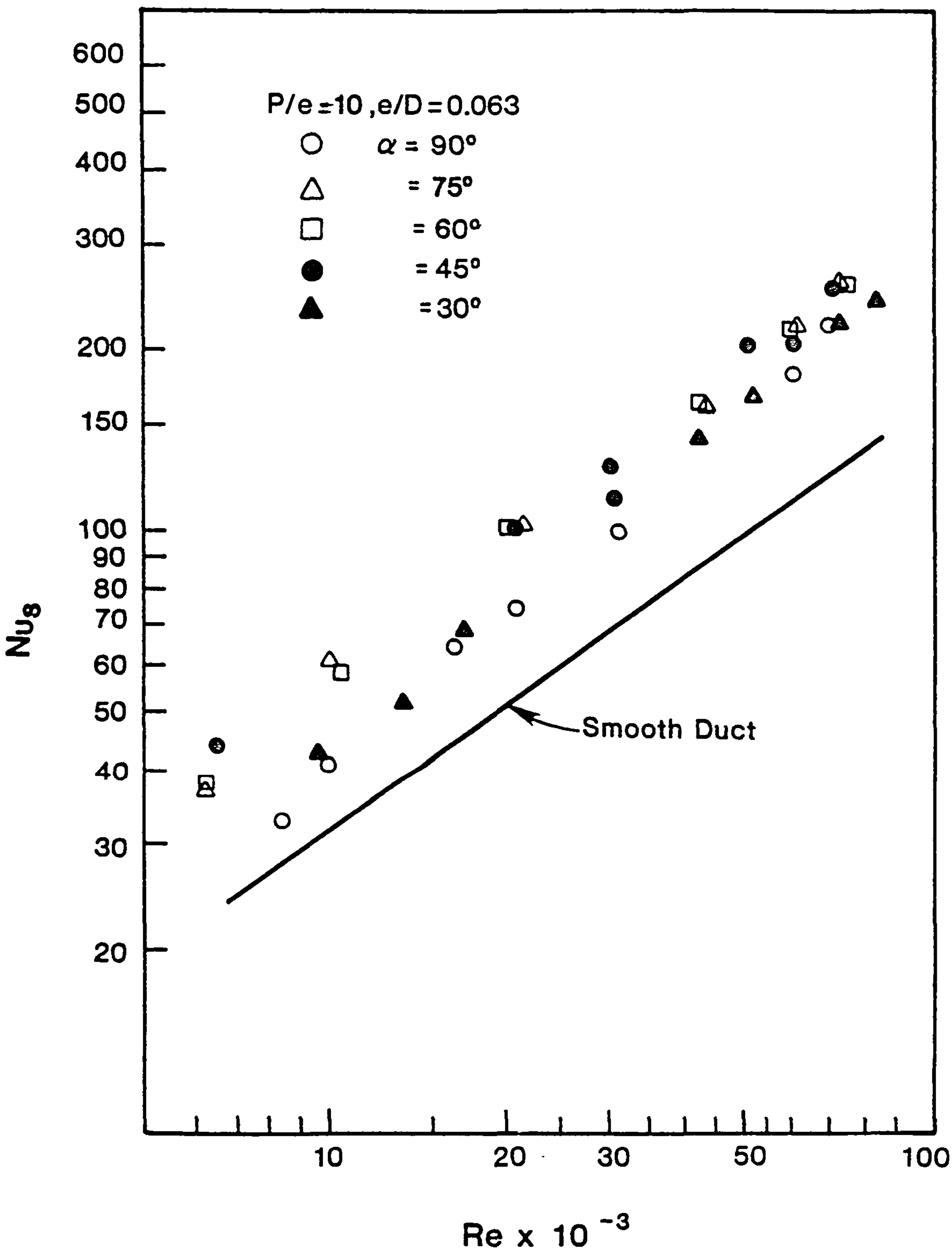



Figure 19. The smooth side Nusselt number with different α for P/e = 10 (LDE)

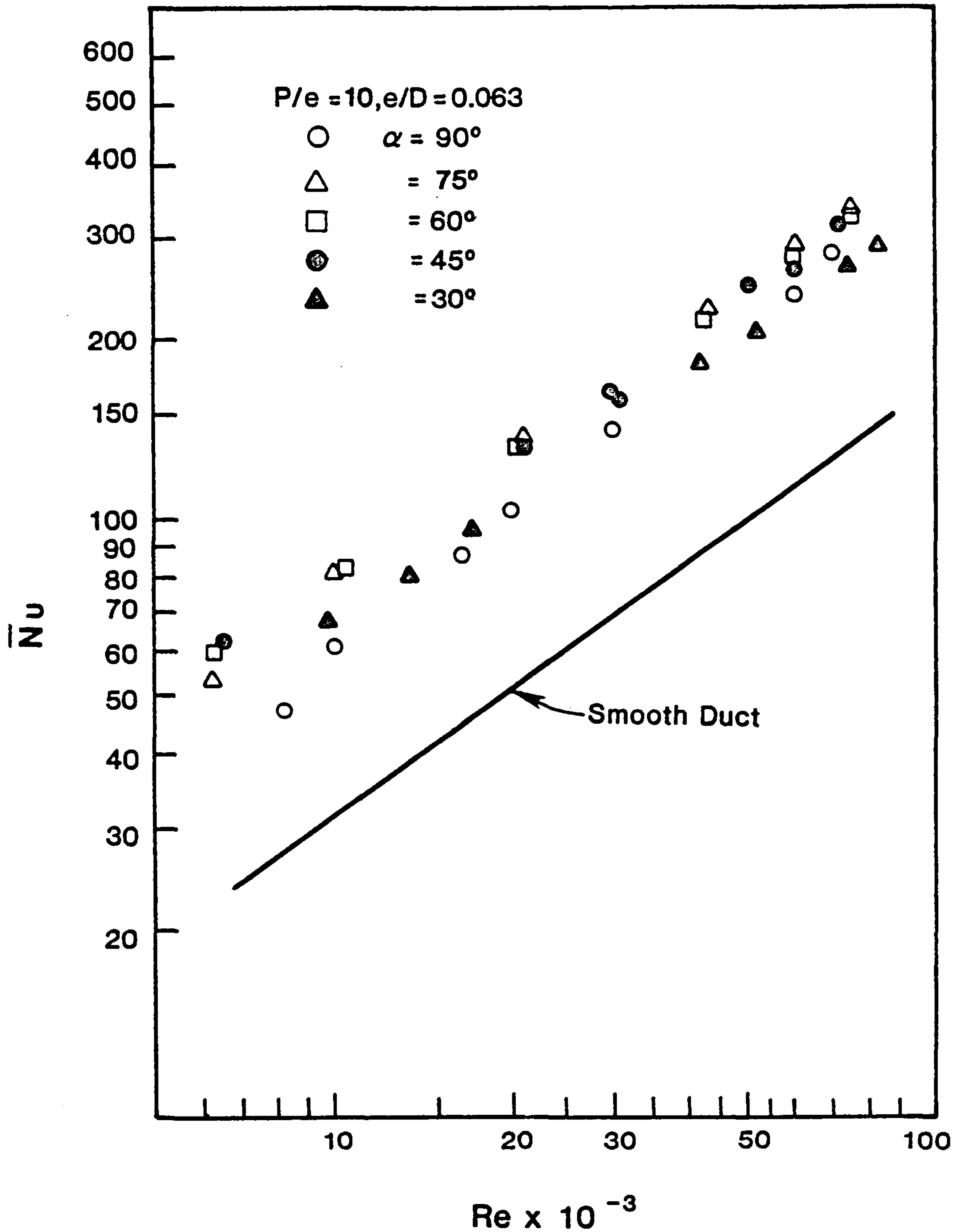



Figure 20. The average Nusselt number with different α for P/e = 10 (LDE)

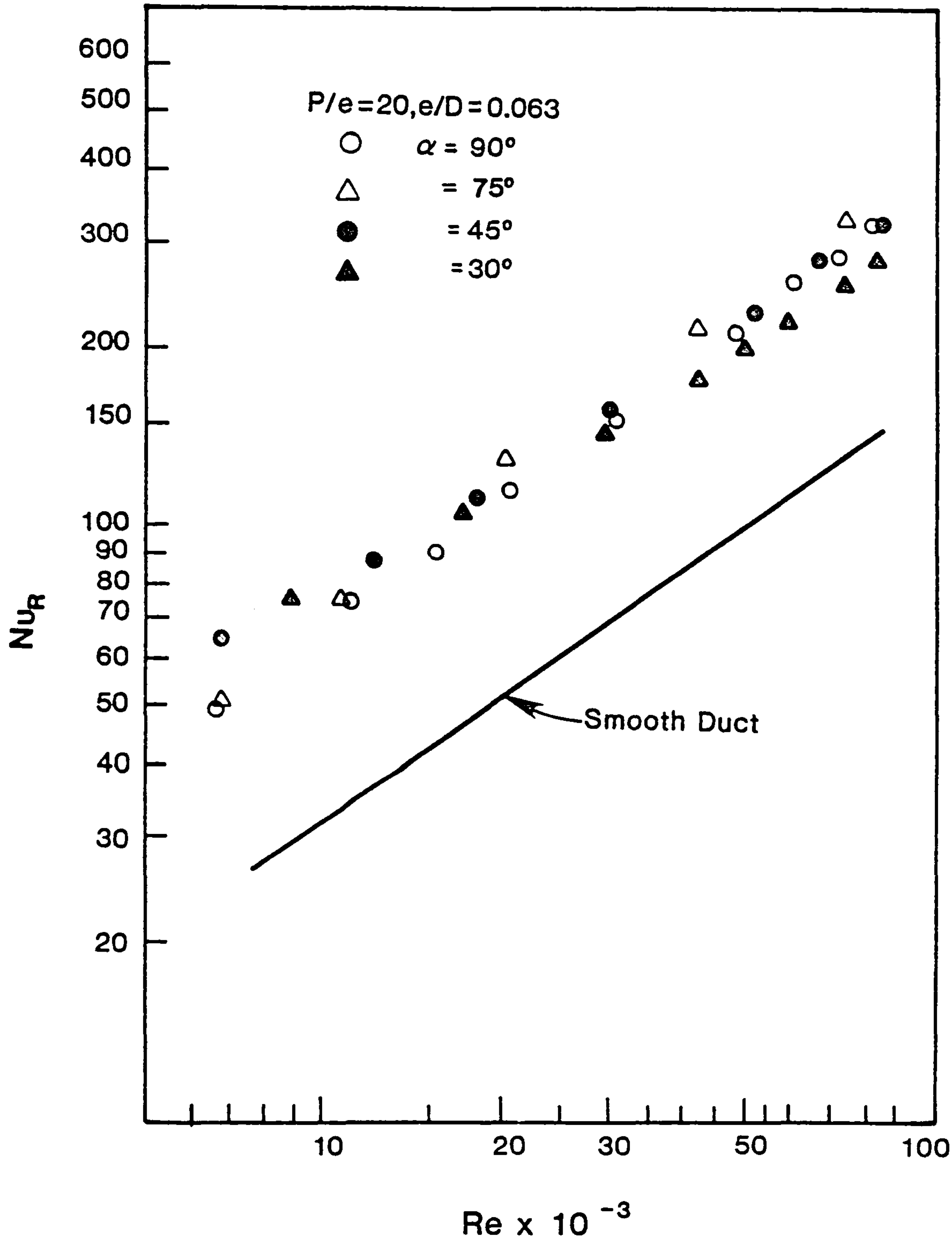


Figure 21. The ribbed side Nusselt number with different α for P/e = 20 (LDE)

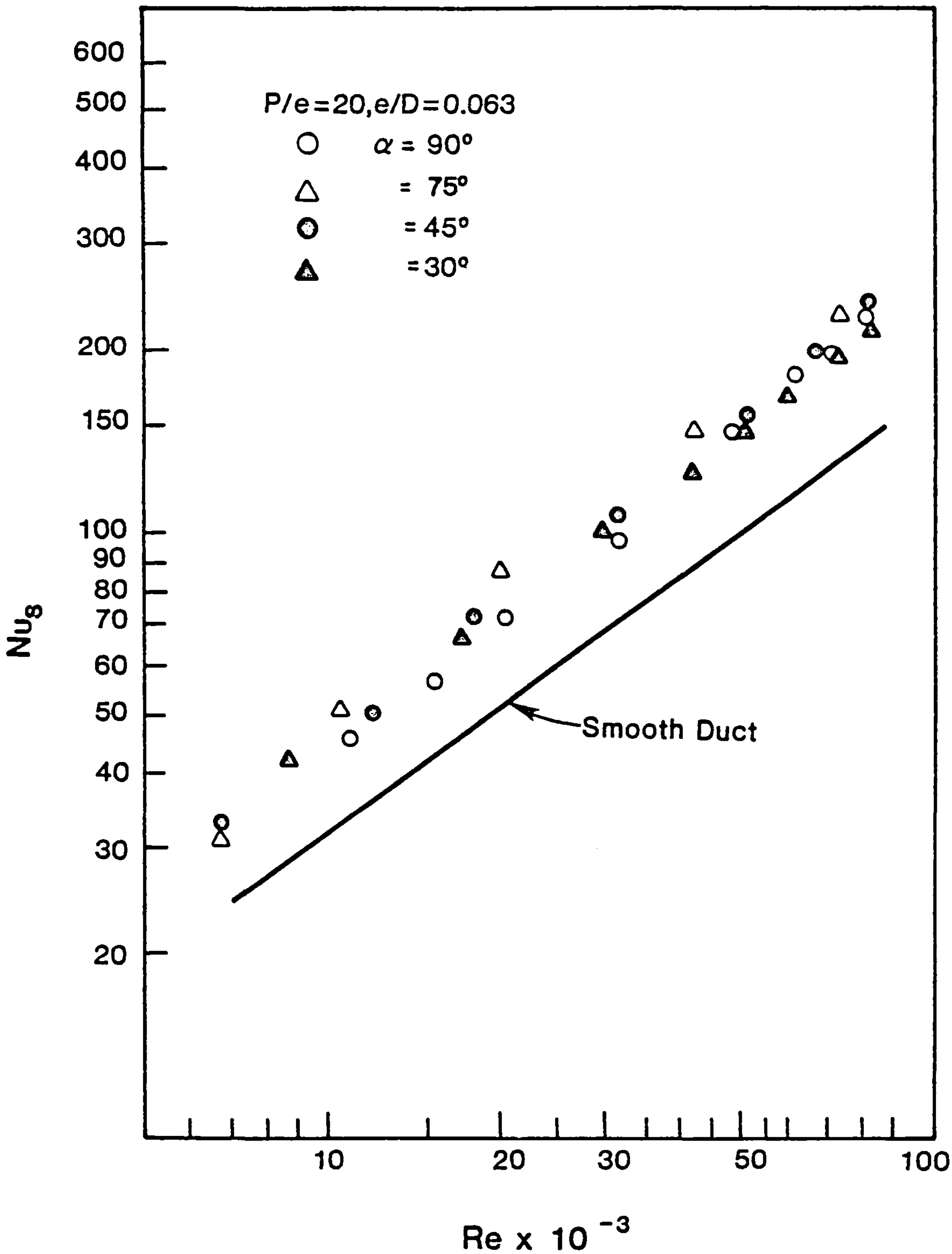



Figure 22. The smooth side Nusselt number with different α for P/e = 20 (LDE)

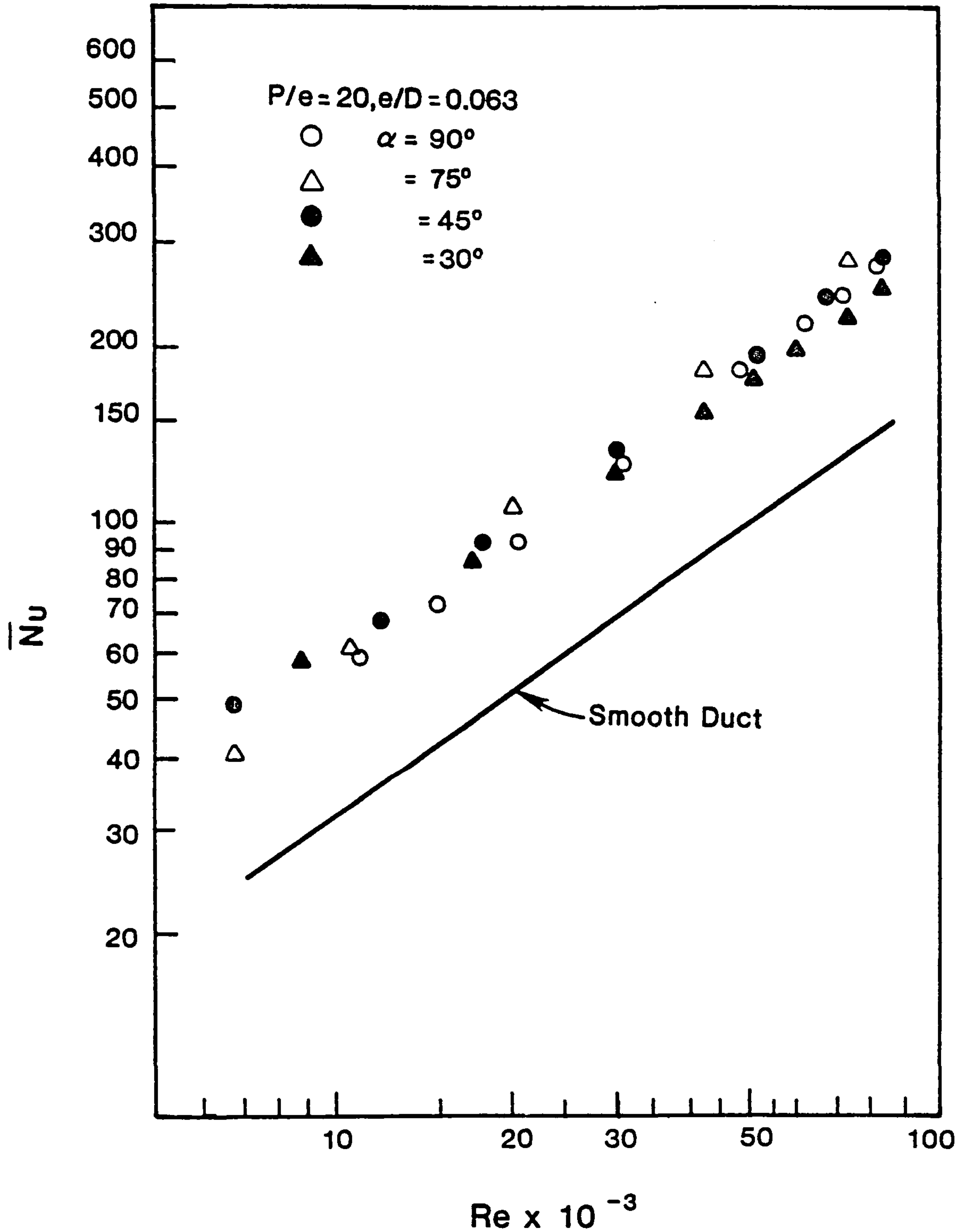



Figure 23. The average Nusselt number with different α for P/e = 20 (LDE)

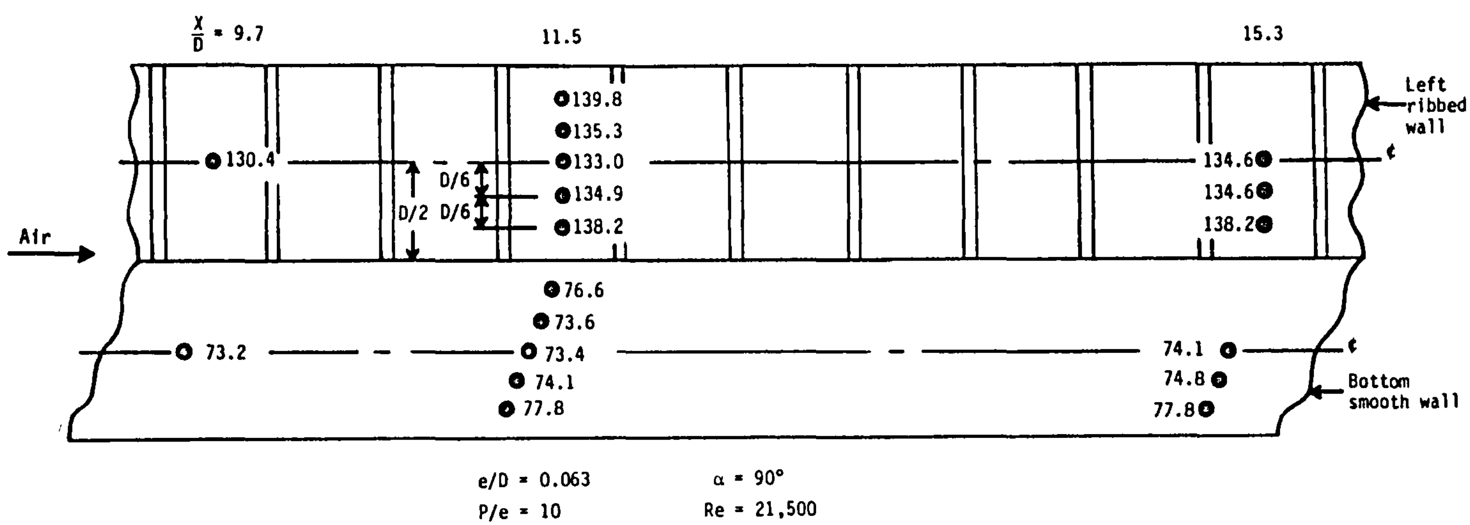



Figure 24. The local Nusselt number for P/e = 10, $\alpha$ = 90°, and Re = 21,500

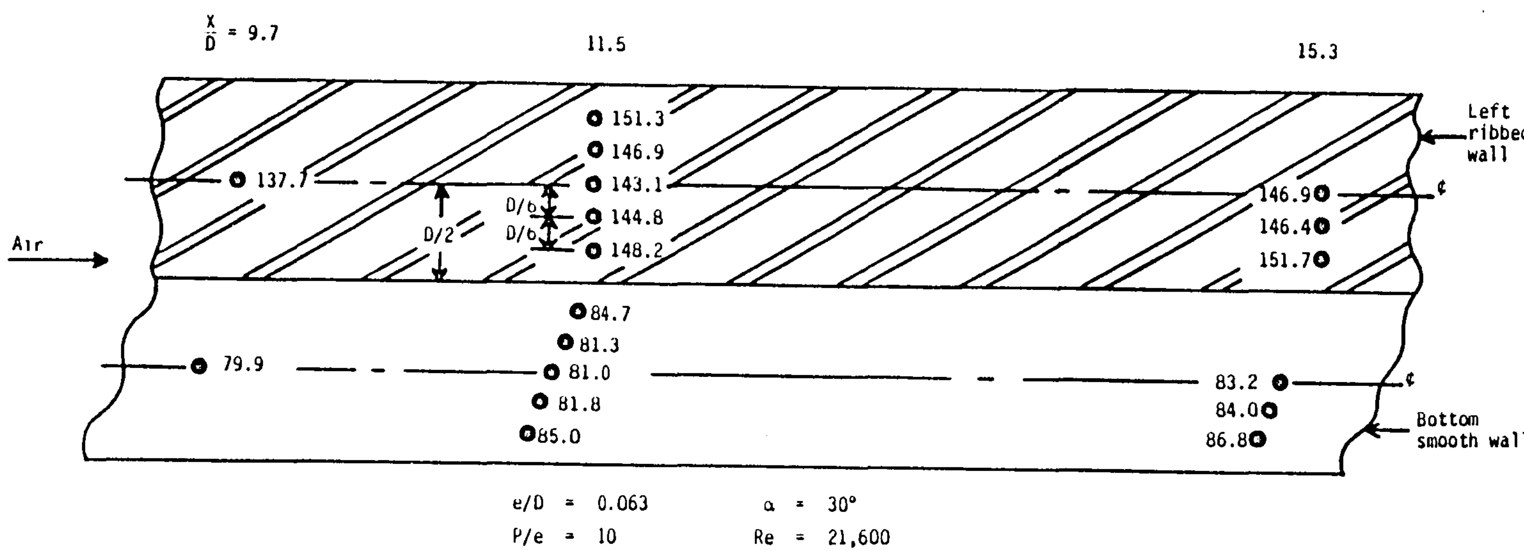



Figure 25. The local Nusselt number for P/e = 10, $\alpha$ = 30°, and Re = 21,600

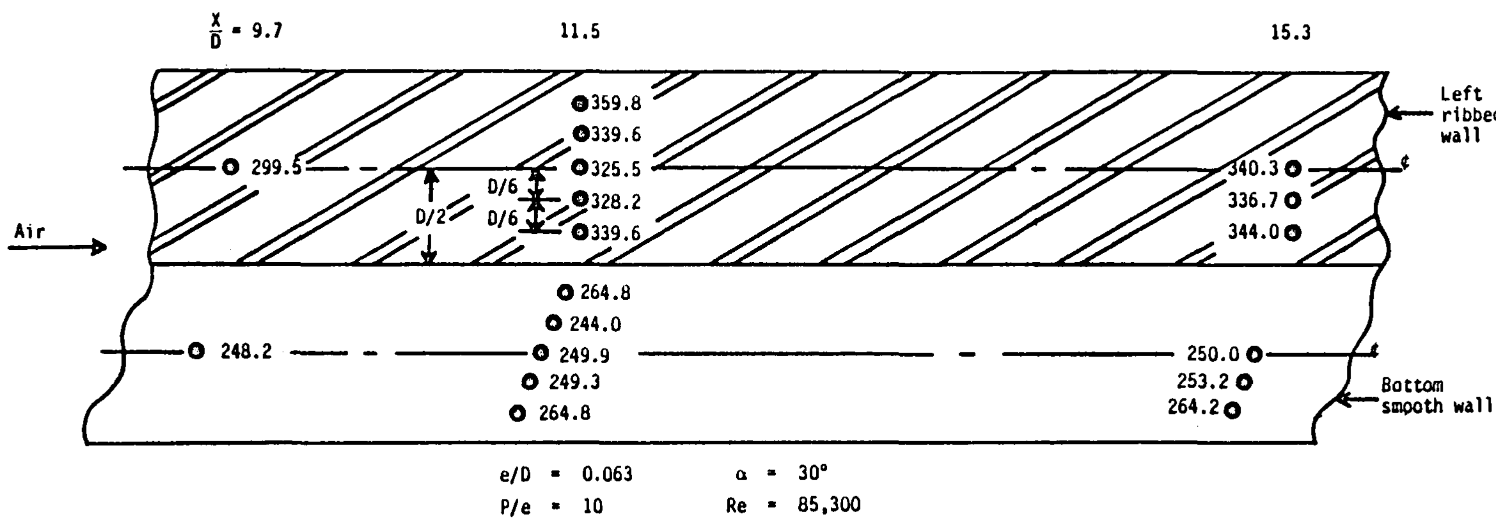



Figure 26. The local Nusselt number for P/e = 10, $\alpha$ = 30°, and Re = 85,300

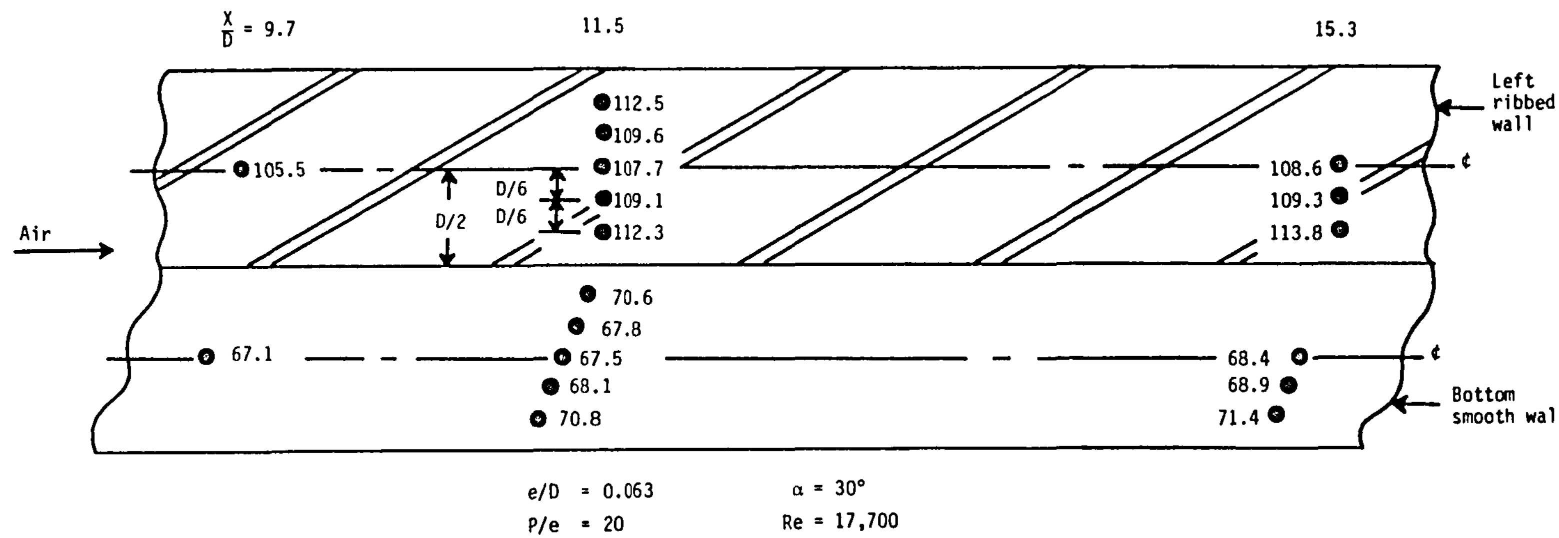



Figure 27. The local Nusselt number for P/e = 20, $\alpha$ = 30°, and Re = 17,700

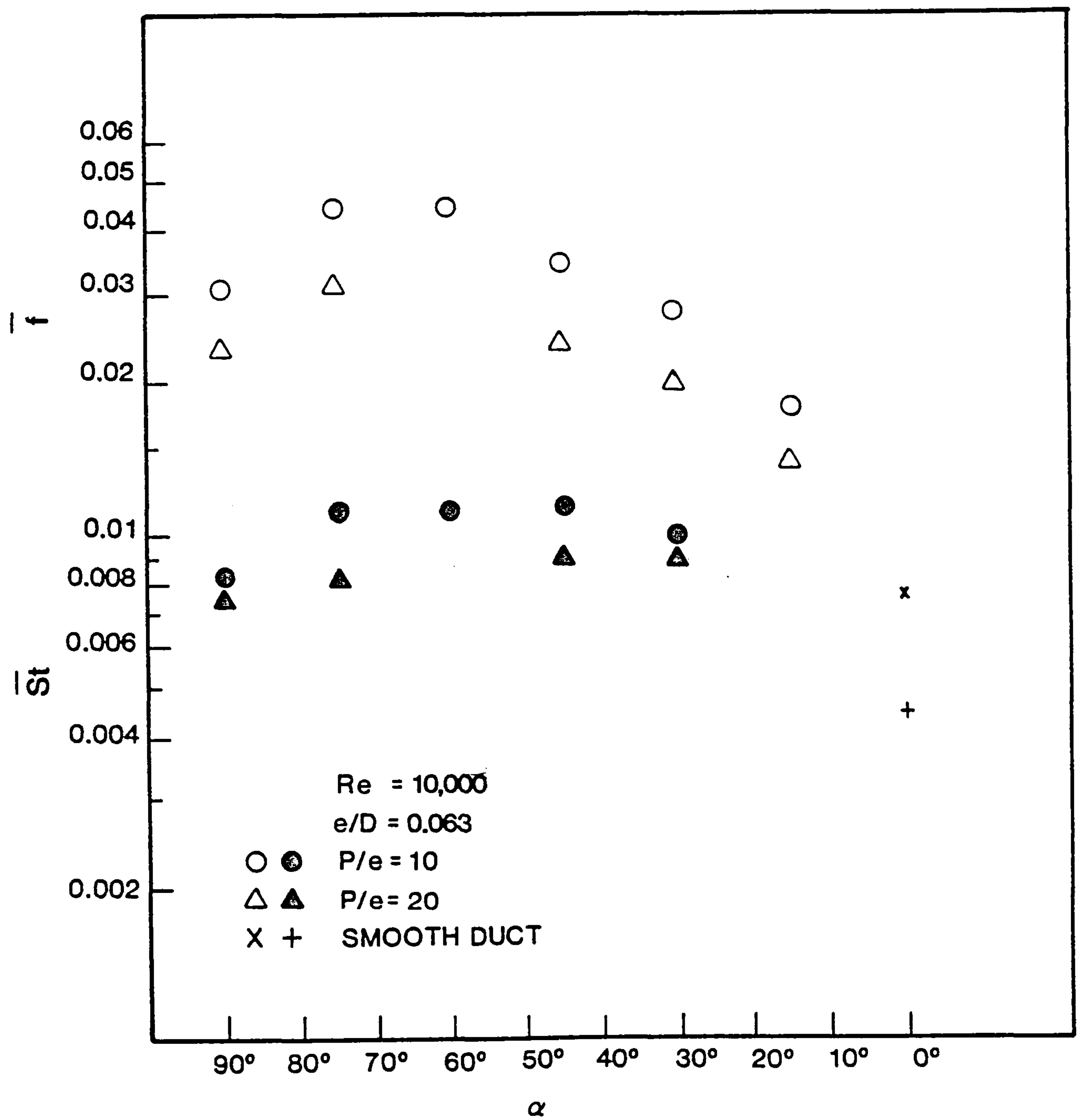



Figure 28. Friction and Stanton number vs α for Re = 10,000 (LDE)

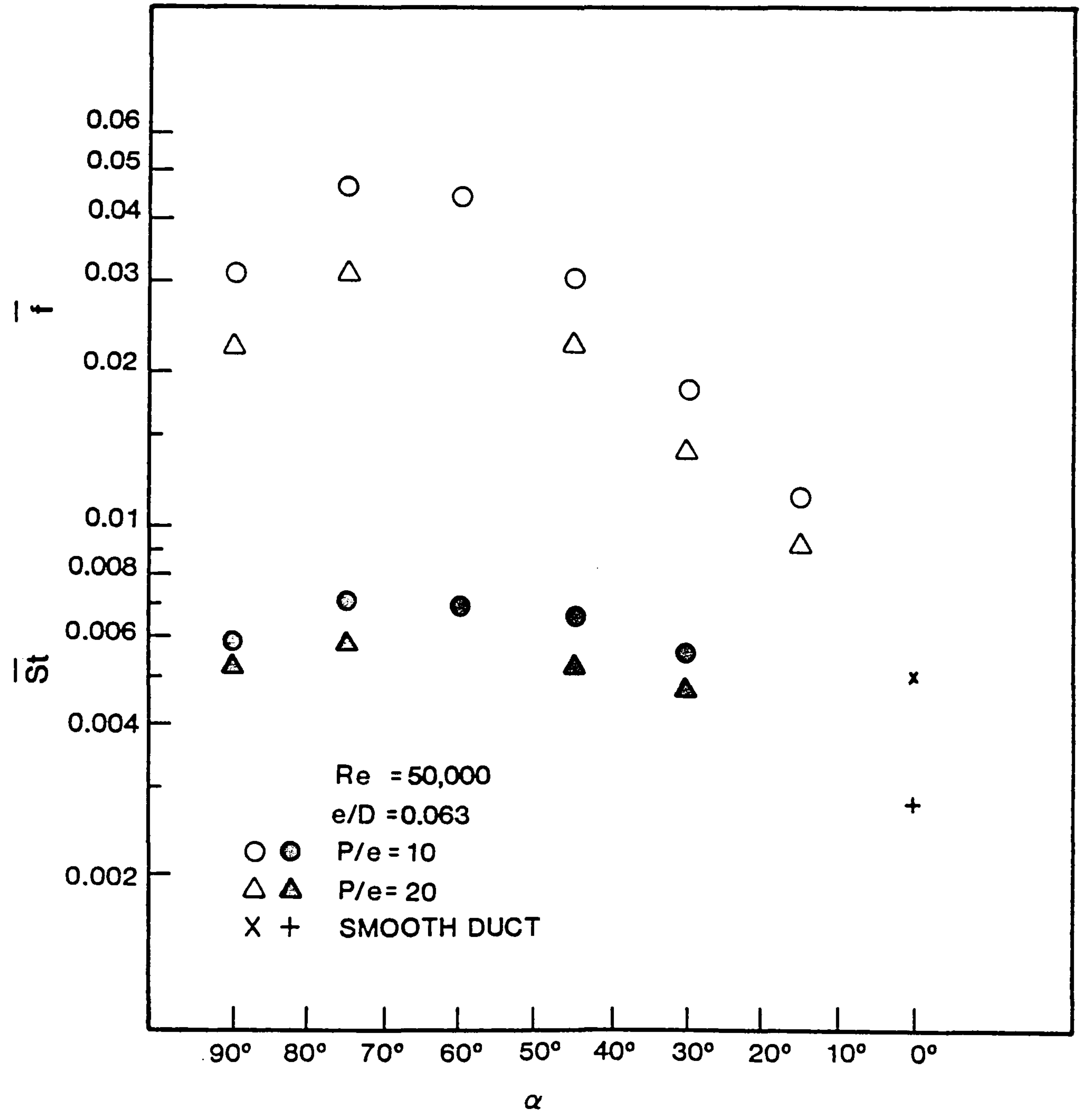



Figure 29. Friction and Stanton number vs α for Re = 50,000 (LDE)

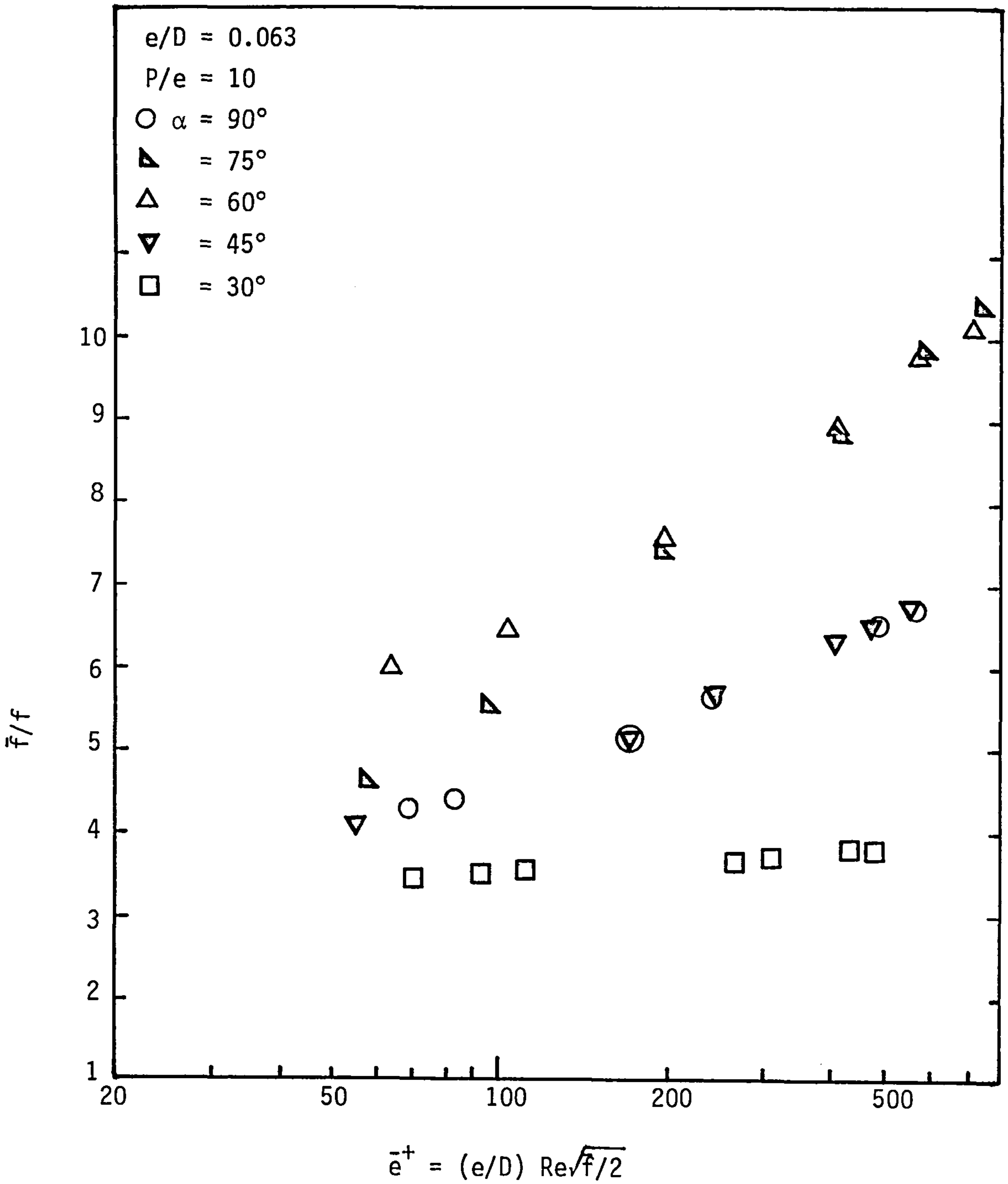



Figure 30. Increased friction factor with different α for P/e = 10 (LDE)

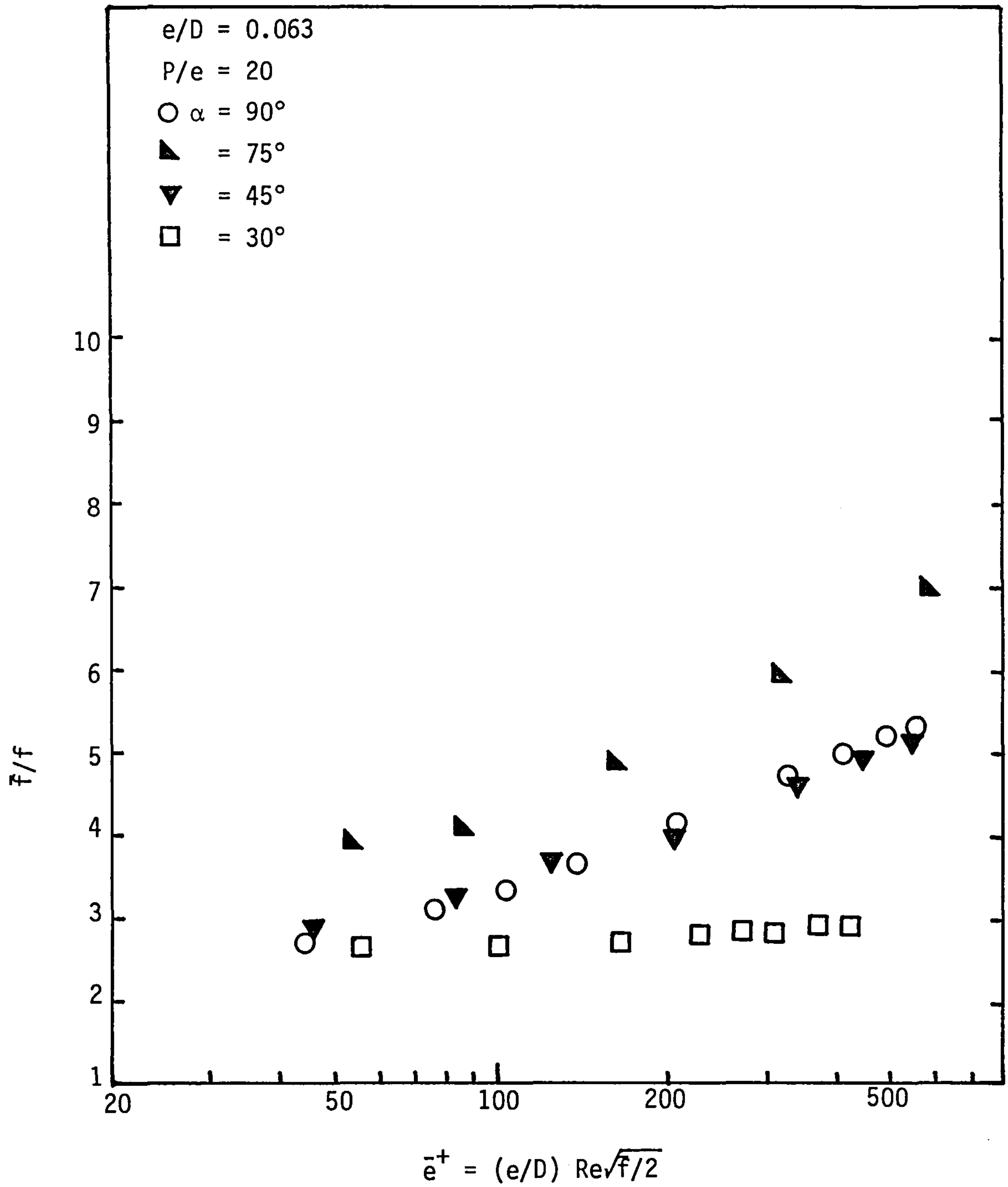



Figure 31. Increased friction factor with different α for P/e = 20 (LDE)

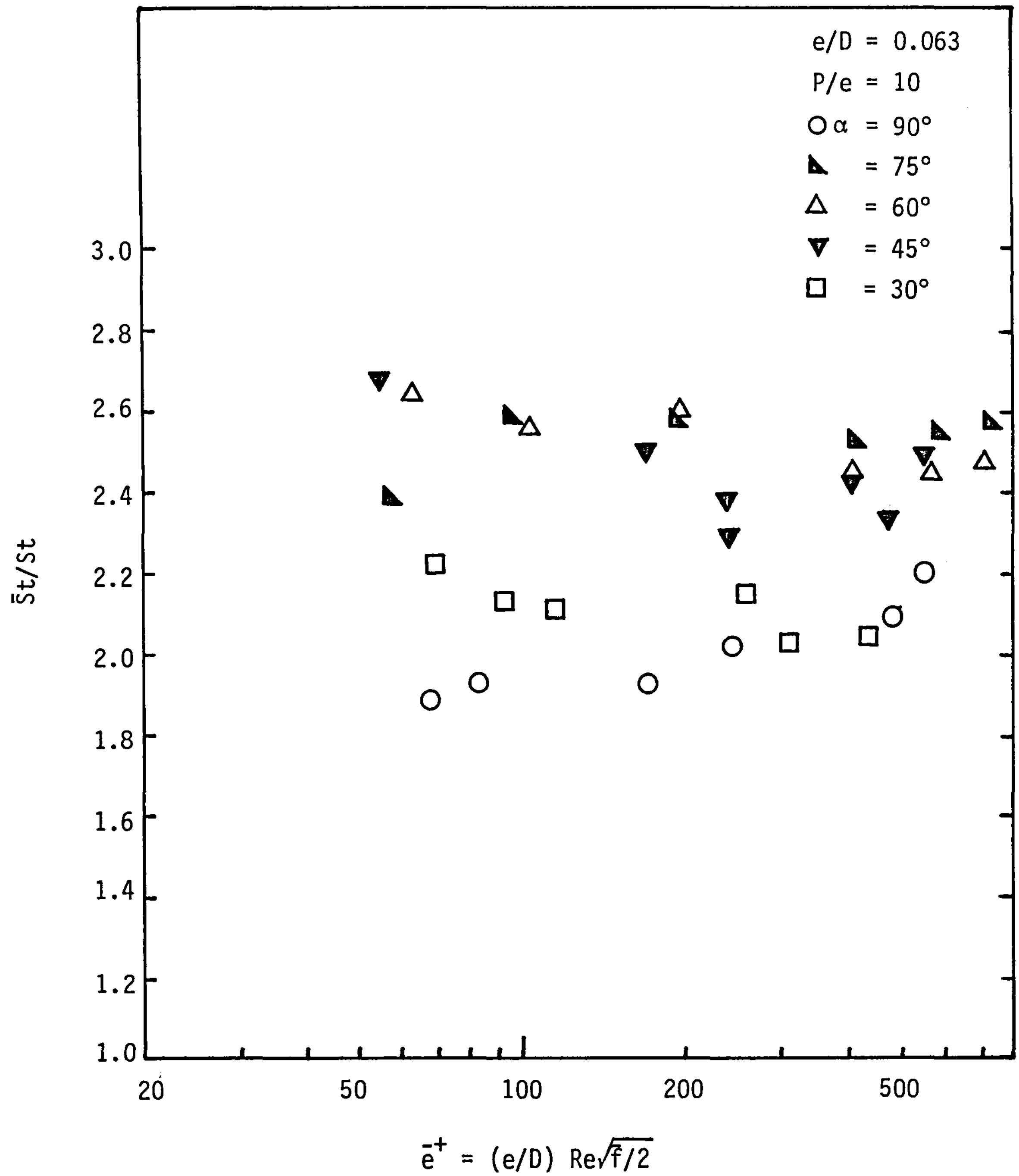



Figure 32. Increased Stanton number with different α for P/e = 10 (LDE)

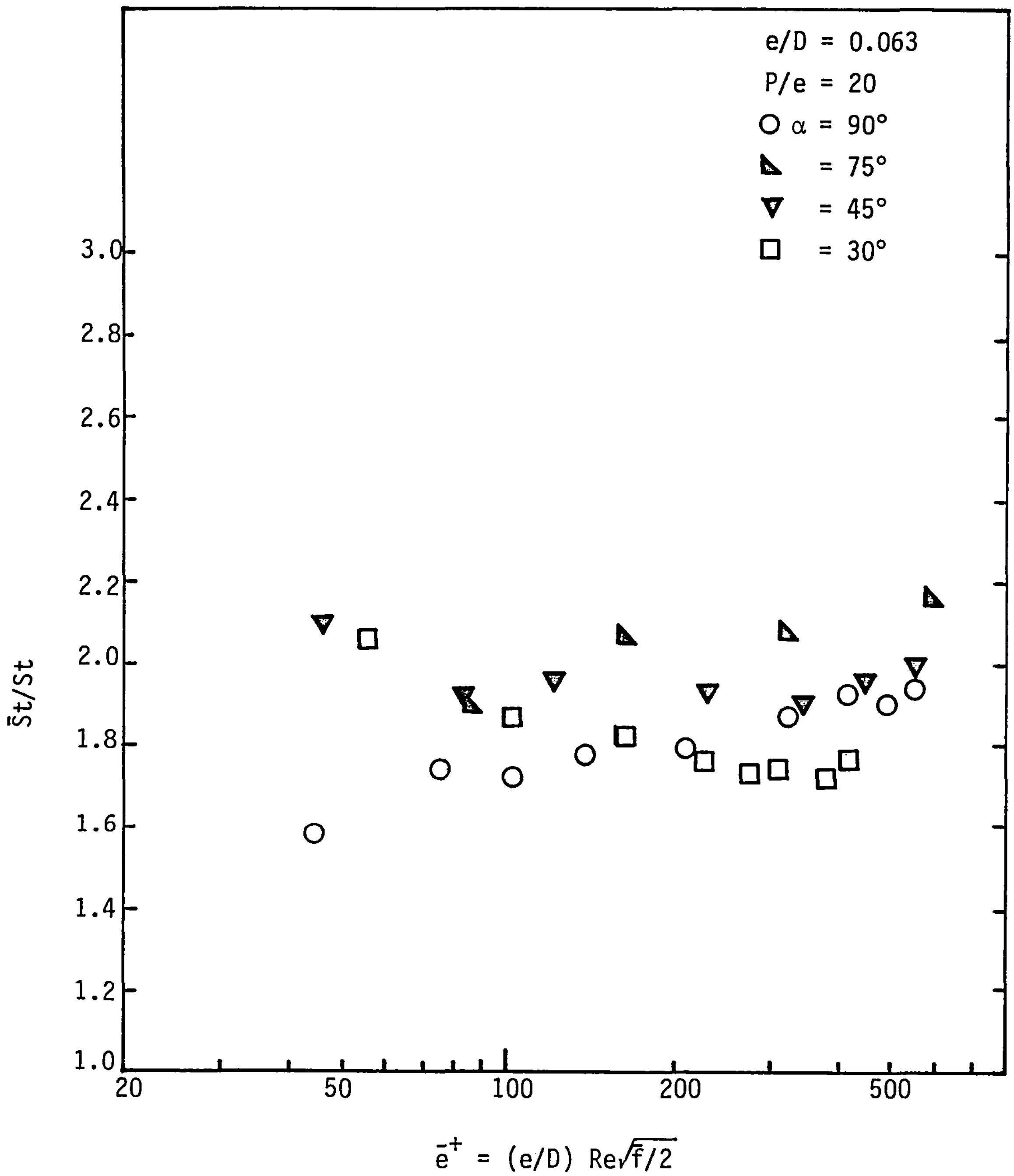



Figure 33. Increased Stanton number with different α for P/e = 20 (LDE)

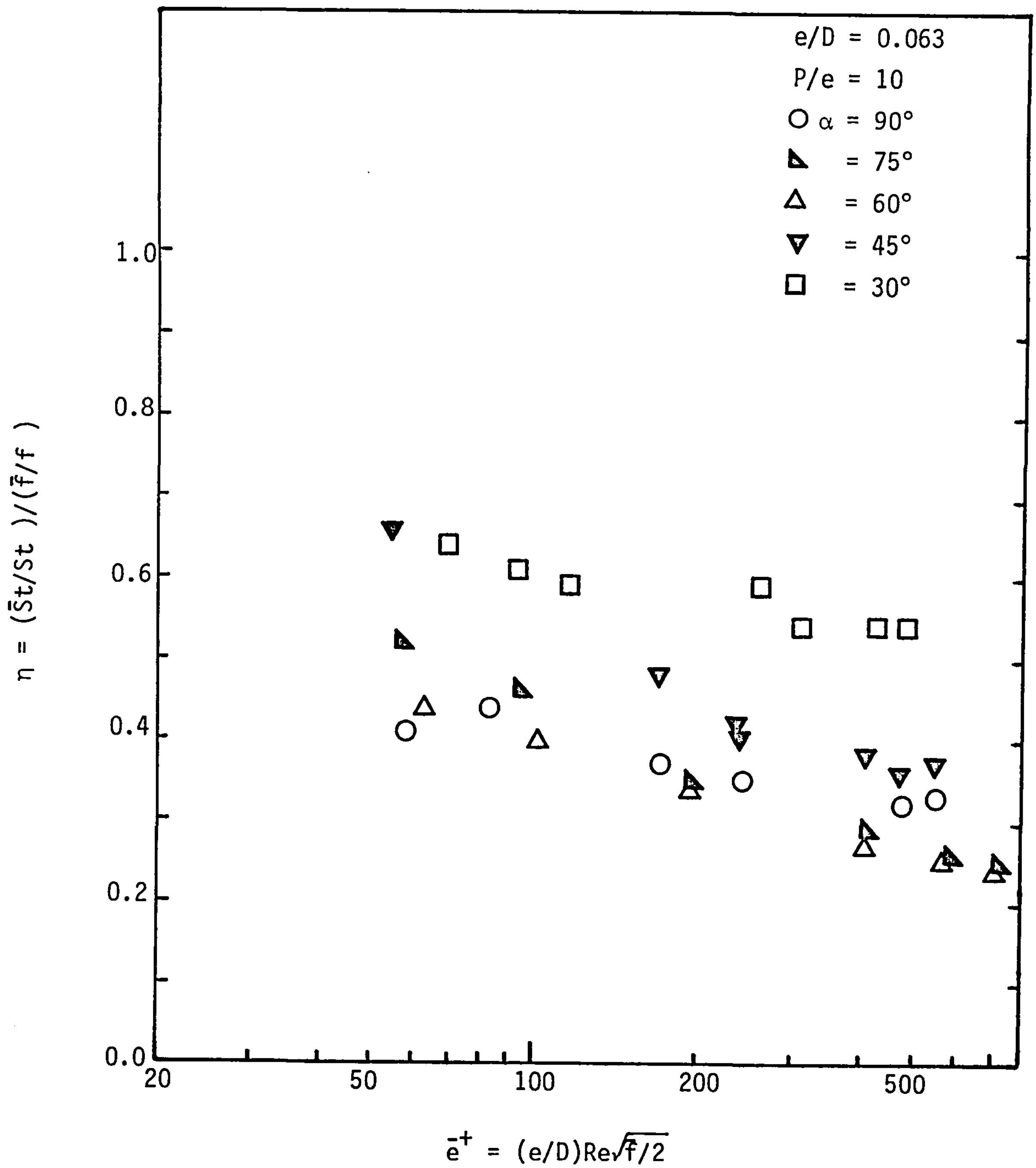



Figure 34. Efficiency index with different α for P/e = 10 (LDE)

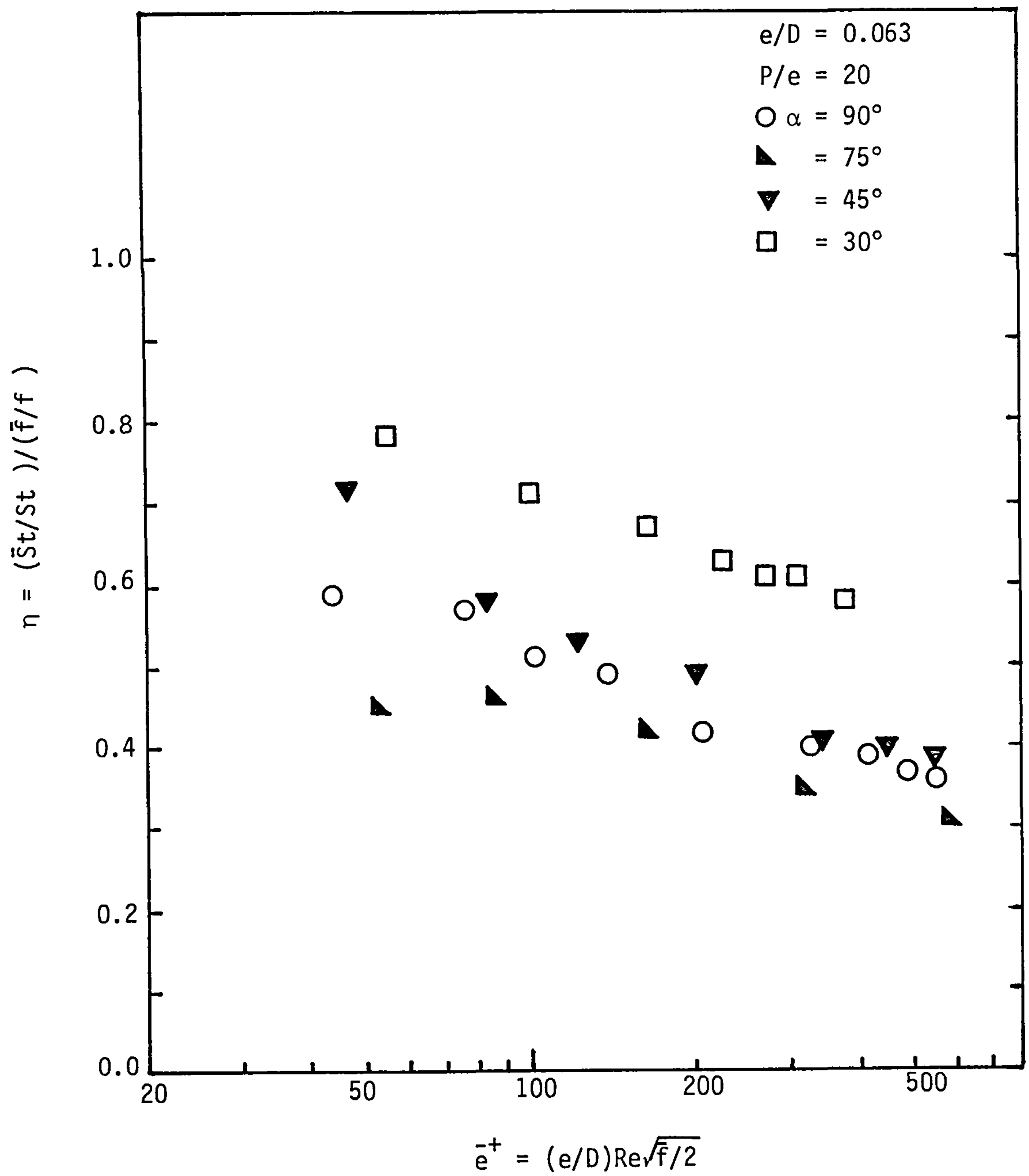



Figure 35. Efficiency index with different α for P/e = 20 (LDE)

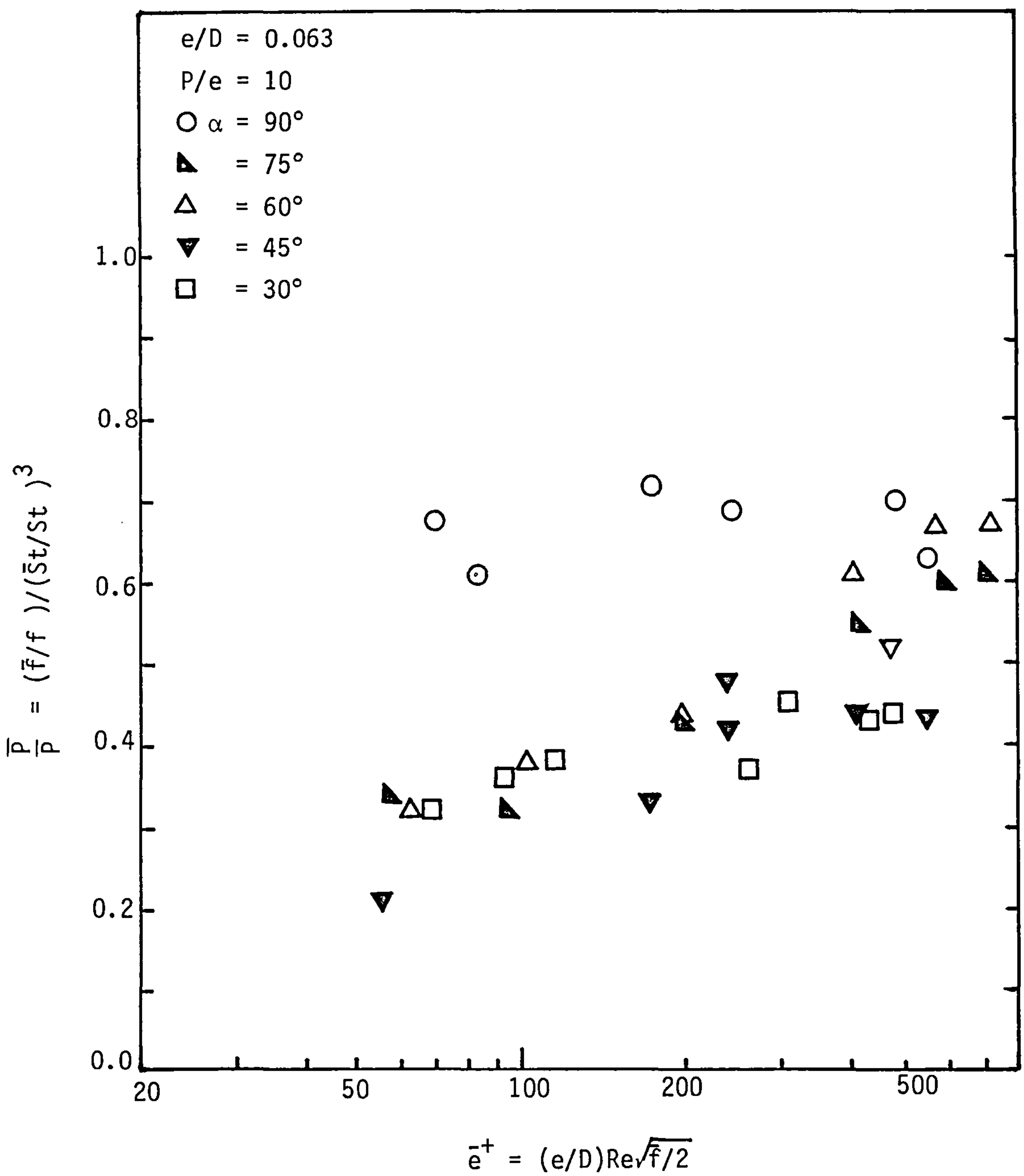



Figure 36. Reduced pumping power with different α for P/e = 10 (LDE)

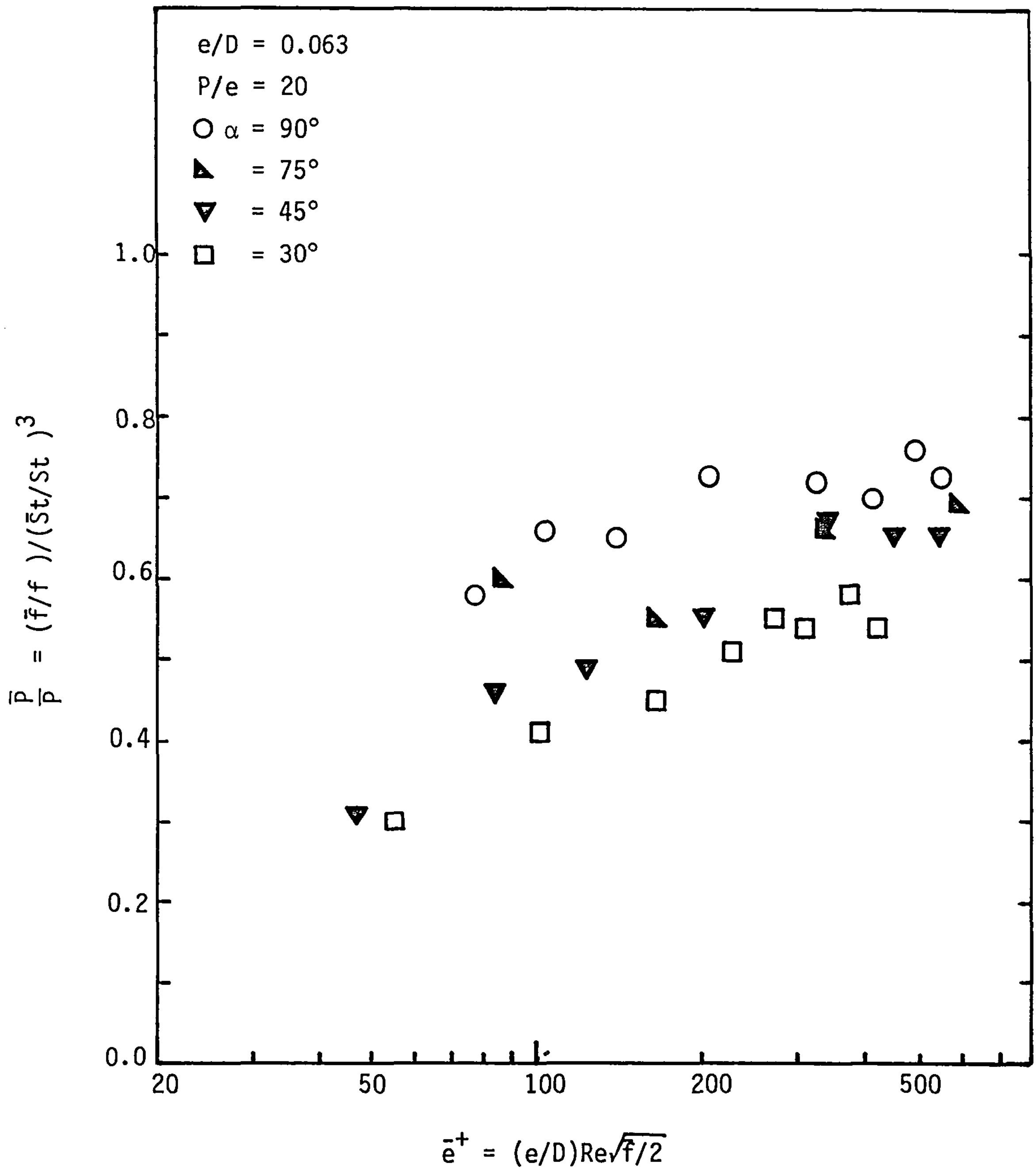



Figure 37. Reduced pumping power with different α for P/e = 20 (LDE)

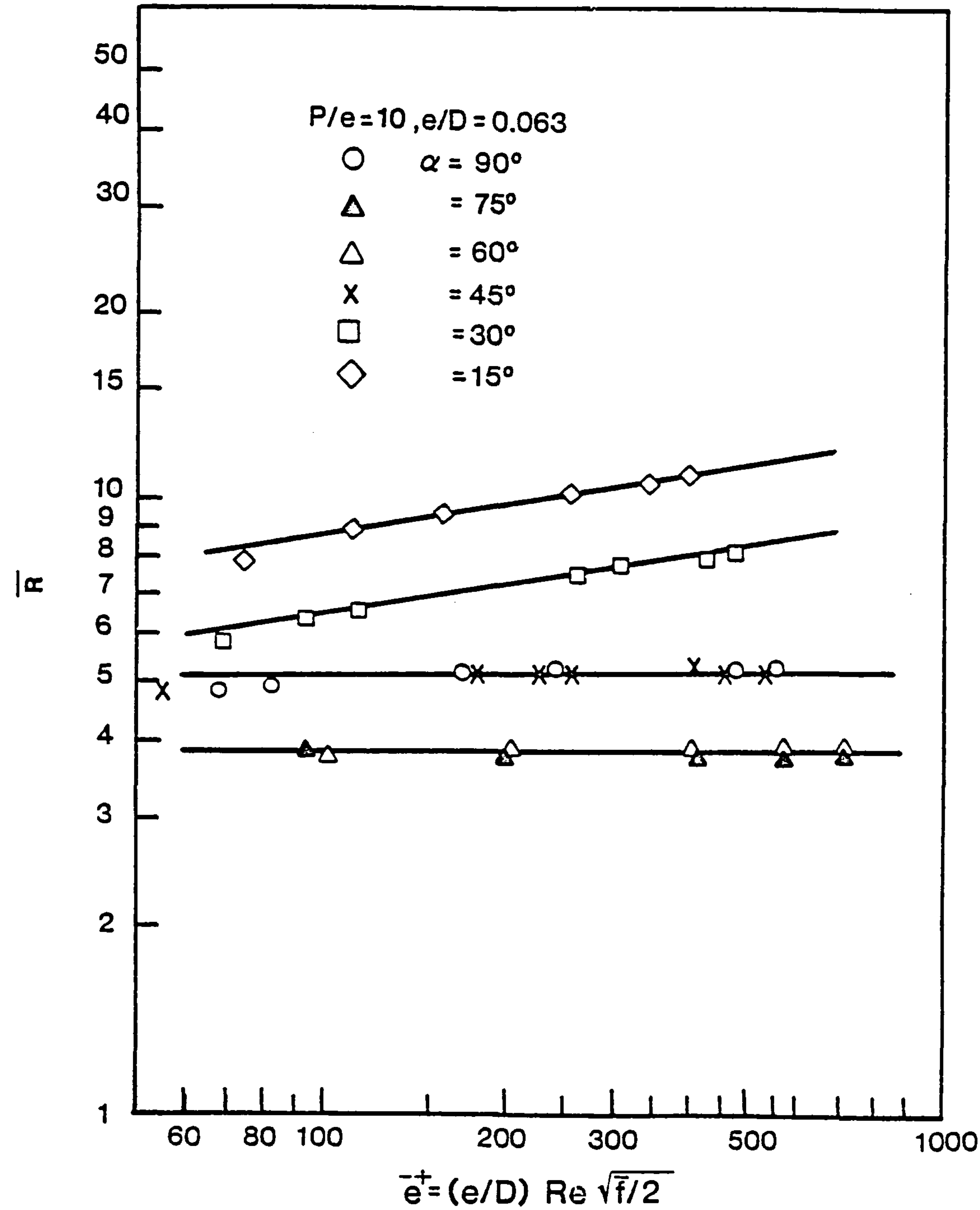



Figure 38. Momentum roughness function for P/e = 10 (LDE)

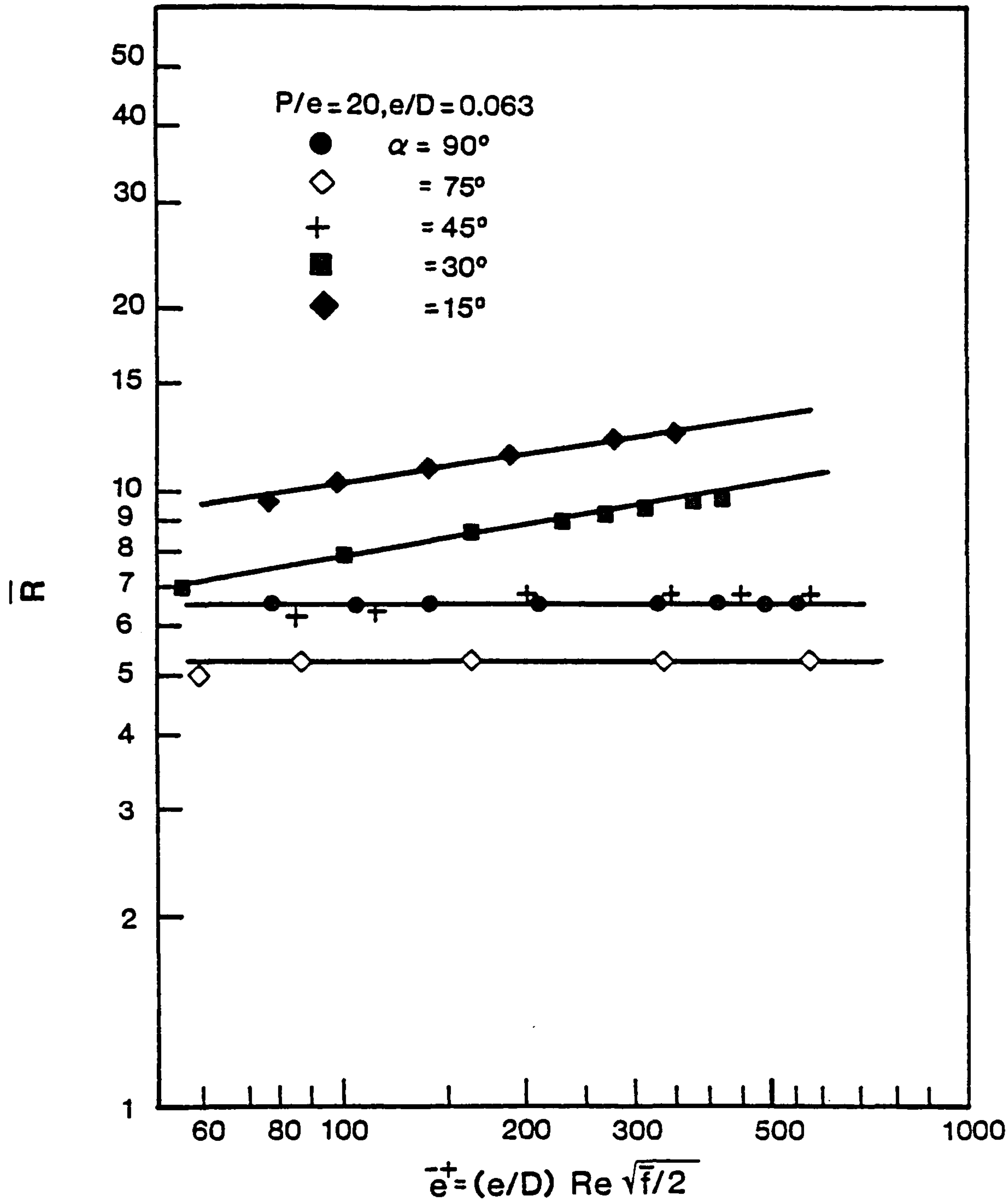



Figure 39. Momentum roughness function for P/e = 20 (LDE)

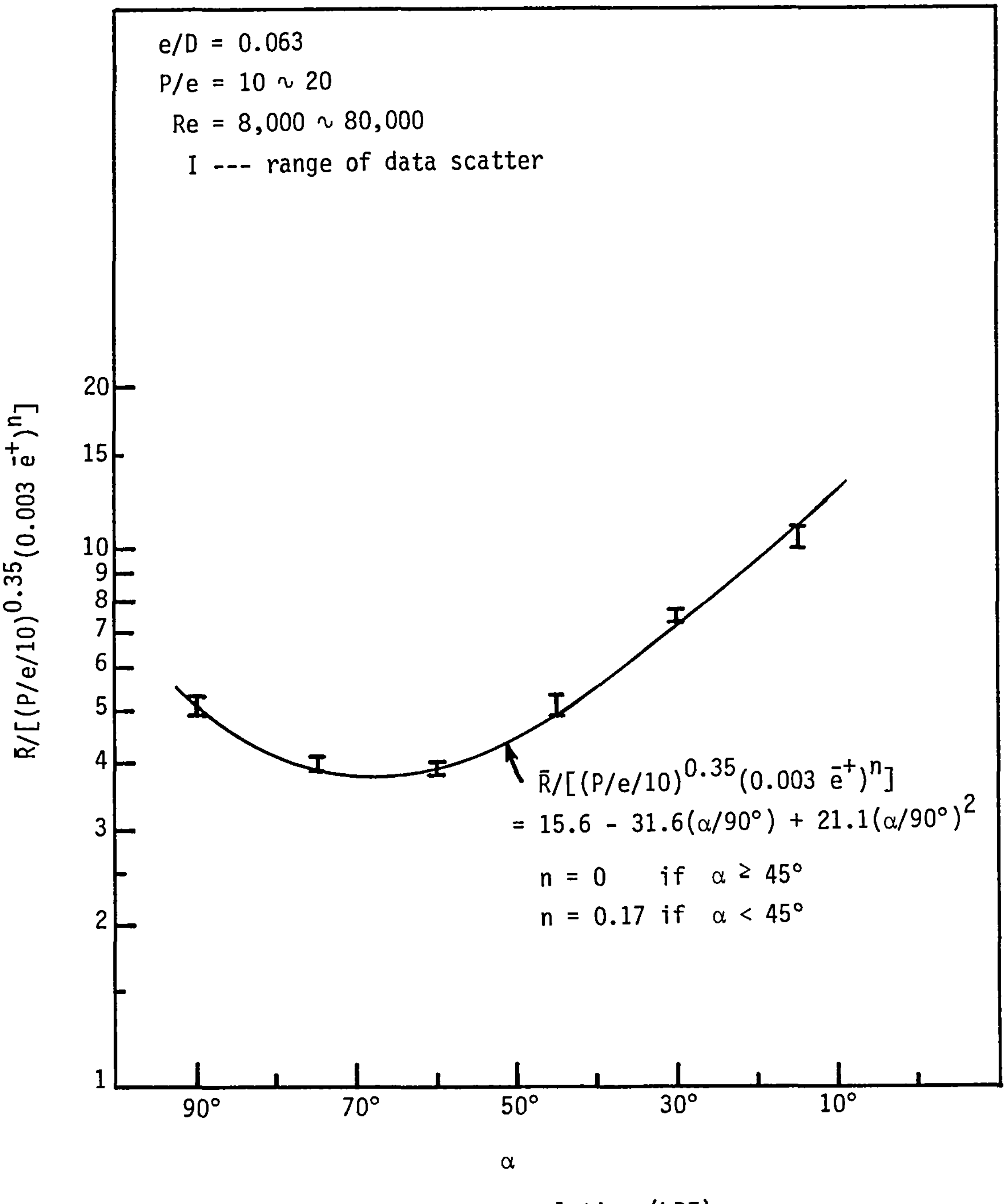



Figure 40. Friction factor correlation (LDE)

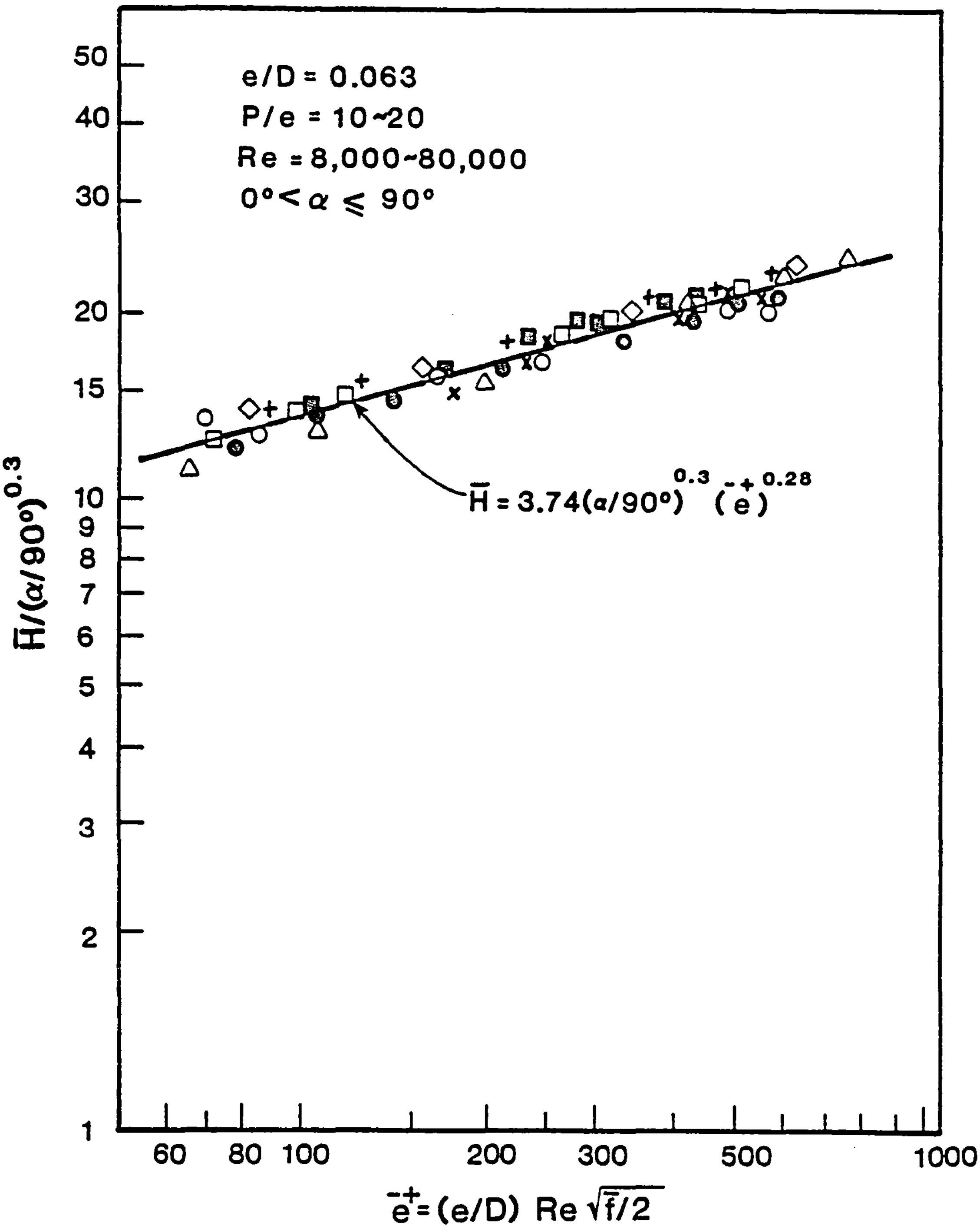



Figure 41. Heat transfer coefficients correlation (LDE)

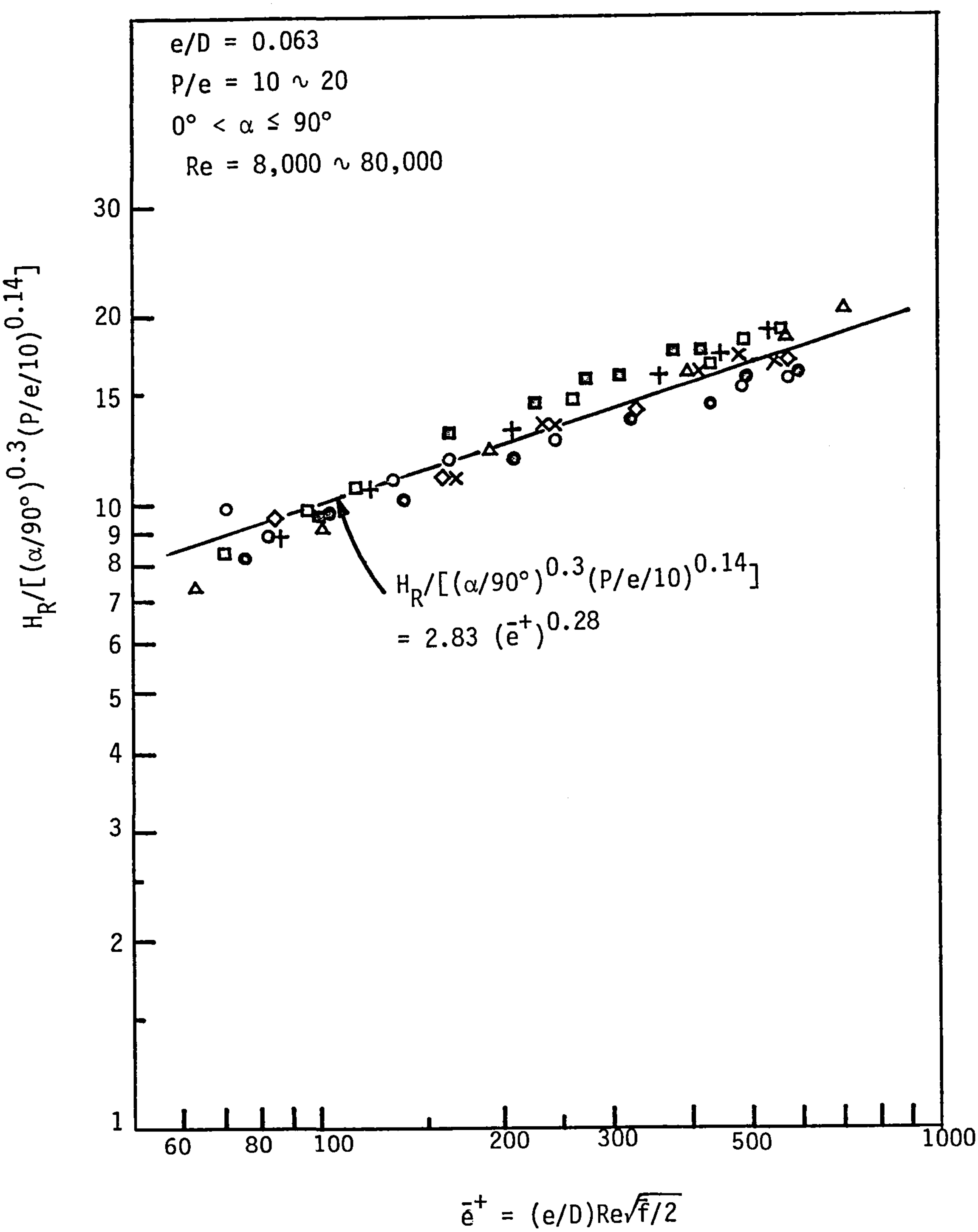



Figure 42. Ribbed side wall heat transfer correlation (LDE)

# 4.0 SQUARE DUCT WITH SUDDEN CONTRACTION ENTRANCE

## 4.1 The Experimental Apparatus

The construction of the apparatus with a sudden contraction entrance was completed by November, 1982. The purpose of this apparatus was to provide data of the pressure drop and the local heat transfer coefficients on the smooth side wall and between the ribs of the rough side wall for flow in the entrance and in the fully developed regions. Figure 43 shows a schematic, and Figure 44 shows a photograph of the test rig.

A 5 HP blower forced air through a 10.16 cm (4 in) diameter pipe equipped with a 3.8 cm (1.5 in) diameter orifice plate to measure flow rate. A plexiglass plenum with a cross section of 38 cm by 38 cm (15 in by 15 in) and a length of 76 cm (30 in) was connected between the pipe and the test duct to ensure that the air entering the test duct was uniform and had a sudden contraction condition. The contration ratio was 5:1. A round corner with a radius of 0.63 cm (0.25 in) was provided between the plenum and the test duct. The test section was designed to simulate the inlet condition of the cooling flow in the turbine blade. At the end of the test section, the air was exhausted into the atmosphere. The Reynolds number in the test duct was varied between 8,000 and 80,000.

The test duct which consisted of four parallel stainless steel plates was constructed in the same way as that of the long duct entrance condition. The detail description of the test duct can be referred to paragraph 3.1. The stainless steel plates were used to replace aluminum because of their low thermal conductivity, so that the local temperature distributions (therefore the local heat transfer coefficient distributions) on the smooth side wall and between the ribs of the rough side wall at the entrance and the fully developed regions could be measured. The test section was instrumented with 78 thermocouples distributed along the length and cross the span of the stainless steel plates, as shown in Figure 45. Thermocouples were also used to measure the bulk mean air temperature entering and leaving the test duct. Six pressure taps (two on the plenum and four on the test duct) were used for the static pressure drop measurements, as shown in Figure 46. The air flow, pressure drop, electrical heat input, and temperature measurements systems are shown in Figure 47.

## 4.2 Analysis of Data

Equation (1) can be used to determine the friction factor for flow in the fully developed region. The average friction factor, $\bar{f}$, was based on the adiabatic conditions. The maximum uncertainty of $\bar{f}$ was estimated to be less than 6.5% for Reynolds number greater than 10,000.

In heat transfer measurements, the local wall temperature distributions were measured by thermocouples. The heat transfer rate into the test duct can be calculated from Watts meters. The local bulk mean air temperature can be calculated for the given heat input. Then the local Nusselt number can be determined by:

$$Nu_s = \frac{q''_s}{Tw_s - T_b} \frac{D}{K} \qquad (24)$$

$$Nu_R = \frac{q''_R}{Tw_R - T_b} \frac{D}{K} \quad (25)$$

$$\bar{N}u = \frac{1}{2} (Nu_s + Nu_R) \quad (26)$$

The $q''_s$ and $q''_R$ represents the local net heat flux from the smooth side and the ribbed side walls to the fluid, respectively; whereas $Tw_s$ and $Tw_R$ is the local wall temperatures on the smooth side and on the ribbed side, respectively. The net heat flux is the heat flux generated from heater substracting from heat loss to outside and from axial heat conduction in the test duct, i.e., q" (net) = q" (heater) - q" (loss) - q" (net heat conduction). A computer program was developed to account for the heat loss and axial conduction effects. The maximum heat loss from the smooth side and the ribbed side wall was estimated to be less than 5% and 3% for Reynolds number greater than 10,000; whereas the axial conduction could be up to 8% at the entrance region in some operation conditions. Equation (24) was used for the smooth side wall local Nusselt number calculation and equation (25) was for the ribbed side wall while equation (26) was for the local average Nusselt number in a duct with two opposite ribbed walls. Notice that the ribbed side heat flux, $q''_R$, was based on the projected heat transfer area (not including the increased rib surface area). The maximum uncertainty in the Nusselt number was estimated to be less than 6.0% for Reynolds number greater than 10,000.

## 4.3 Experimental Results

### 4.3.1 Friction and Heat Transfer for Smooth Duct

Before initiating experiments with ribbed walls, the pressure drop and heat transfer were calibrated for a four sided smooth duct and compared with the results given in the literature. Figure 48 shows the friction factor and heat transfer coefficients vs Reynolds number for flow in the fully developed region. The agreement between the accepted correlation and the present data is reasonably well. The friction factor differs by up to 8.5% from the modified Karman-Prandtl equation [18], and the Nusselt number differs by up to 8.0% from the Petukhov-Popov equation [19]. Based on these smooth duct results, the apparatus was ready to reproduce data for flow in the same duct with two opposite ribbed walls.

4.3.2 Friction and Heat Transfer for Ribbed Duct

Table 2 shows a total of 9 rib geometries tested for the square duct with sudden contraction entrance. The tabulated data is given in 7.2 Appendix. Only the most representative results will be discussed as follows.

Table 2. Rib Geometry Tested for Sudden Contraction Entrance

| | P/e = 10 | | P/e = 20 | |
|---|---|---|---|---|
| | Friction | Heat Transfer | Friction | Heat Transfer |
| $\alpha$ = 90° | X | X | X | X |
| = 60° | X | X | X | X |
| = 45° | X | X | X | X |
| = 30° | X | X | X | X |
| = 15° | X | | | |

Note: For All Tests: e/D = 0.063, Re = 8,000 to 80,000.

Figures 49-52 show the pressure drop ($\Delta P = P - P_{atm}$) along the duct (X/D). The 60° rib flow-attack-angle produces a higher pressure drop than 90°, 30°, and smooth duct for P/e = 10 or 20 and for Re = 20,000 or 56,000. It is noted that the pressure distribution is approximately a linear when X/D ≥ 3 for all tests. Those figures also indicate that the sharp pressure drop between the plenum and the duct entrance is about a constant value for a given Reynolds number regardless the rib angle in the square duct.

Figures 53-54 show the average friction factor vs Reynolds number for flow in the region with X/D ≥ 3. For the $\alpha$ = 90°, 60°, and 45°, the friction factor approaches an approximately constant value as the Reynolds number increases while the friction factor decreases with Reynolds number when the $\alpha$ = 30° and 15°. For the P/e = 10, the friction factor with $\alpha$ = 90° is about 3-10 times higher than the four sided smooth duct over the range of Reynolds number. The friction factor with $\alpha$ = 45° is slightly less than $\alpha$ = 90°, however, it decreases by 30-40% when the $\alpha$ changes from 90° to 30°. The friction factor with $\alpha$ = 60° is about 50% higher than $\alpha$ = 90°. The results for P/e = 20 generally agrees with that for P/e = 10 except with a relatively lower values as shown in Figure 54. It is noted that the friction data in X/D ≥ 3 with sudden contraction entrance are almost identical to those with long duct entrance as discussed in paragraph 3.3.2 (Figures 8-9).

Figures 55-58 show the typical temperature distribution of the ribbed side wall and the smooth side wall along the test section. The ribbed side wall heat flux is higher than the smooth side wall which means that the ribbed side Nusselt number is larger than the smooth side. It is noted that the wall temperature distribution for the smooth duct and the $\alpha$ = 90° is very similar to that the conventional turbulent pipe flow, indicating the smooth transition from the entrance to the fully developed region. However, the wall temperature distribution (ribbed or smooth side) for the $\alpha$ = 60°, and 30° has "overshoot" at X/D about 3 then decreases to a minimum value at X/D about 9, then increases again along the test duct. This wall temperature "overshoot" characteristics found for all tests of $\alpha$ = 60°, 45°, 30°, P/e = 10, and Re = 8,000 to 80,000. These wall temperature profiles were used for heat loss and wall heat conduction calculations in order to obtain the local net heat flux into the cooling air, then the local Nusselt number could be determined from equations (24) and (25).

Figures 59-62 show the typical local Nusselt number distribution along the centerline in both ribbed side and smooth side walls for different rib flow-attack-angle at different P/e and Re. It is noted that every thermocouple was located at the middle between two adjacent ribs along the centerline of the ribbed side wall. The local Nusselt number of the four sided smooth duct is included for comparison. It is seen that the local Nusselt number distribution for $\alpha$ = 90° decreases monotonically with distance for all Reynolds numbers, this is similar to that the smooth duct results except that the former has a larger values (both ribbed side and smooth side walls). However, the Nusselt number for $\alpha$ = 60° (and 30°) reaches a minimum at X/D = 3 then increases to reach a maximum value at X/D $\simeq$ 9 and decreases with further increasing X/D. The minimum Nusselt number occurs at X/D = 3, while the maximum Nusselt number occurs at X/D = 8.9. This overshoot distribution is diminished when the P/e changes from 10 to 20, or when the test section connecting with a long duct entrance, as shown in Figure 62 and Figure 63, respectively.

The data shown in Figures 64-69 were based on the average value of the local Nusselt number as X/D = 2.85 to 16.81. The data show that the Nusselt number increases with increasing Reynolds number as the conventional turbulent pipe flow. Nusselt number of the ribbed side wall with $\alpha = 90°$ is about 2.5 times higher than the four sided smooth duct as shown in Figure 64 for P/e = 10. The Nusselt number with $\alpha = 30°$ is about 20% higher than $\alpha = 90°$, while the Nusselt number with $\alpha = 45°$ and 60° is about 25% and 33% higher, respectively. Figure 65 shows that the Nusselt number of the smooth side wall is also enhanced by 50-100% due to the presence of the ribs on the adjacent walls when $\alpha$ changes from 90°-30°-45°-60°. It is noted that the ribs with an oblique angle to the flow has more enhancement on the smooth side walls. Figure 66 shows that the average Nusselt number for the ribs with an oblique angle to the flow is higher than $\alpha = 90°$. The results for P/e = 20 has the similar trends as P/e = 10 except that the enhanced value is lower as shown in Figures 67-69. It is noted that the heat transfer data for sudden contraction entrance has the same trends as those for long duct entrance, however, the former has about 5-15% more enhancement when the ribs have an oblique angle to the flow.

The local Nusselt number augmentation on the smooth side wall and between the ribs of the rough side wall at the entrance and the fully developed regions is shown in Figures 70-74. The numerator represents the local Nusselt number in either the ribbed side wall or the smooth side wall, whereas the denominator represents the local Nusselt number in the four sided smooth duct at the same corresponding locations. It is seen that the ribbed side wall has a much higher enhancement than the smooth side wall. In general, the local Nusselt number enhancement decreases with increasing the Reynolds number because the denominator increases with increasing Re, the fully developed region has more enhancement than the entrance region because the denominator in the entrance region is higher, the ribs with an oblique angle has more augmentation than the transverse ribs ($\alpha$ = 90°), and the P/e = 10 has more enhancement than P/e = 20. It is seen that there are no significant Nusselt number variations as shown in these figures. This is because the heat conduction inside the ¼" thickness stainless steel wall of the present investigation. In the actual gas turbine engine, it is expected that the Nusselt number variations between two adjacent ribs will be larger than those indicated in Figures 70-74 because the wall heat conduction in turbine blade is relatively smaller than the present test duct.

4.4 Thermal Performance Comparison

Figures 75-76 show the average friction factor and average Stanton number vs the rib angle-of-attack. The data of the 0° angle-of-attack was obtained from the present smooth duct results. Both the friction and heat transfer increase with decreasing $\alpha$, and reach a maximum value at $\alpha$ about 60°, then decrease with further decreasing $\alpha$. It is noted that the amount of the friction factor decrease is relatively larger than that of the Stanton number when the rib angle-of-attack changes from 90° to 30°. This suggests that the best thermal performance may be obtained at the $\alpha$ around 30°.

Figures 77-84 show the performance vs average roughness Reynolds number. The $\bar{f}/f$ increases with increasing $\bar{e}^+$ while the $\bar{St}/St$ is almost independent of $\bar{e}^+$ as shown in Figures 77-80. These considerations suggest that the preferred operating condition is for smaller $\bar{e}^+$. Again, the real application range of $\bar{e}^+$ is about 200 to 500. Figures 81-82 show the efficiency index, $\eta$, vs $\bar{e}^+$. It is seen that the best $\eta$ is obtained at $\alpha = 30°$. This is the same optimum operating rib angle as discussed in paragraph 3.4 for square duct with long duct entrance condition.

Figures 83-84 show the reduced pumping power vs $\bar{e}^+$. Again the ribs with an oblique angle to the flow require the lowest pumping power for a given heat load and surface area at fixed total flow rate and entering fluid conditions.

It should be noted that the thermal performance comparisons was based on the flow in the region where $X/D \geq 3$. The plenum related pressure drop for sudden contraction entrance was not taken into account for comparisons. Therefore the results with sudden contraction showed a better performance than that with long duct entrance at the same $\alpha$, as seen from Figures 36-37 and 83-84. The existing correlations of equations (5) and (6) were employed for the smooth surface calculation of the friction factor and Stanton number in both of long duct and sudden contraction entrances. It is expected that the thermal performance for two types of entrance conditions should be the same for a given flow rate and rib geometry if the pressure drop caused by sudden contraction is considered.

4.5 Friction and Heat Transfer Correlations

Equation (11) was employed to correlate the average friction data. Figures 85-86 show that the non-geometrically similar roughness are displaced due to their different value of P/e and $\alpha$. The $\bar{R}$ is independent of $\bar{e}^+$ when $\alpha \geq 45°$ while it increases with increasing $\bar{e}^+$ when $\alpha < 45°$.

The correlations between $\bar{R}$, P/e, and $\alpha$ shown in Figure 87 is

$$\bar{R}/[(P/e/10)^{0.3}(0.0009\ \bar{e}^{+})^{n}] = 21.9 - 47.9(\alpha/90°) + 31.6(\alpha/90°)^{2} \quad (27)$$

Where

$n = 0$ if $\alpha \geq 45°$

$n = 0.14$ if $\alpha < 45°$

It is noted that the discontinuity of equation (27) at $\alpha = 45°$ can be up to 10% at $\bar{e}^{+} = 500$. The average friction factor can be found by combining equations (11) and (27). It is noted that equation (27) is very similar to equation (12).

Equation (17) was employed to correlate the average heat transfer data. The correlation as shown in Figure 88 is

$$\bar{H}(\bar{e}^{+}) = 2.12\ (P/e/10)^{0.17}\ (\alpha/90°)^{0.3}\ (\bar{e}^{+})^{0.37} \quad (28)$$

compare equation (28) to equation (18), it is seen that $\bar{H}$ slightly depends on P/e and higher slope of $\bar{e}^{+}$ for sudden contraction condition, although the slope of $\alpha$ is the same. If $\bar{H}$, $\bar{R}$, and $\bar{f}$ are known, then the average Stanton number can be found as from equation (19).

The correlations between $H_R$, P/e, and $\alpha$ shown in Figure 89 is

$$H_R = 1.58\ (P/e/10)^{0.17}\ (\alpha/90°)^{0.3}\ (\bar{e}^{+})^{0.37} \quad (29)$$

Equation (22) can be employed to determine the ribbed side wall Stanton number ($St_R$), whereas equation (23) can be used for computing the smooth side wall Stanton number ($St_s$).

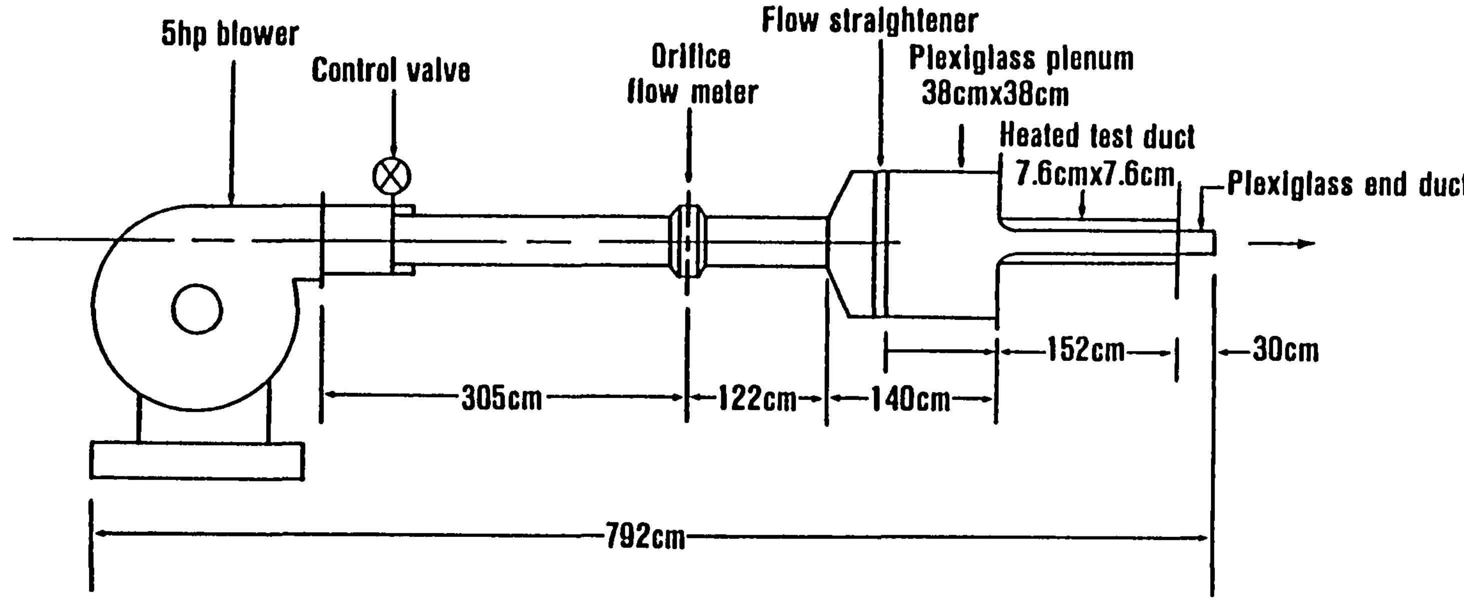
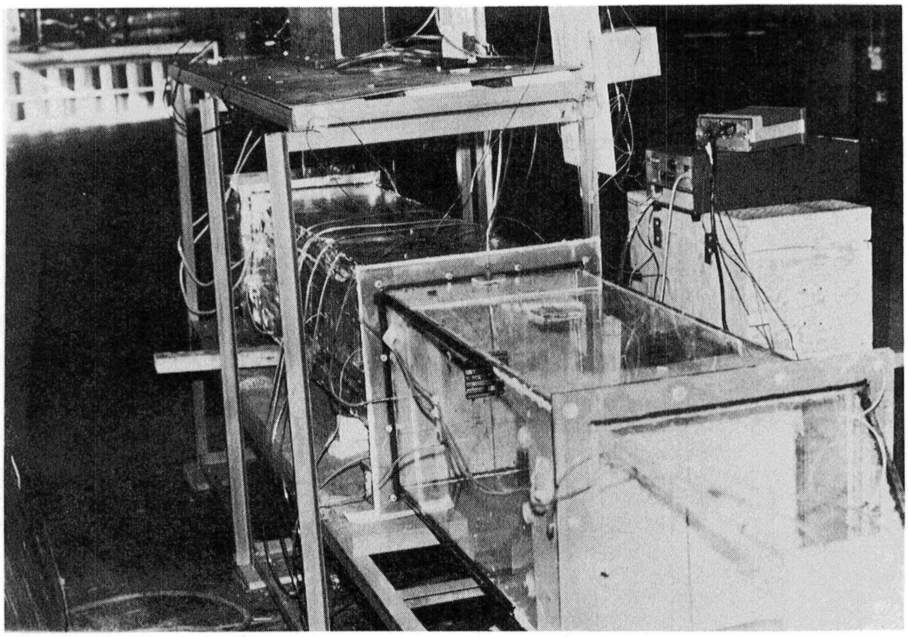



Figure 43. Test rig with Sudden Contraction Entrance (SCE)



Upper photo: Test rig with sudden contraction entrance

Lower photo: Instrumentations and measurements facilities

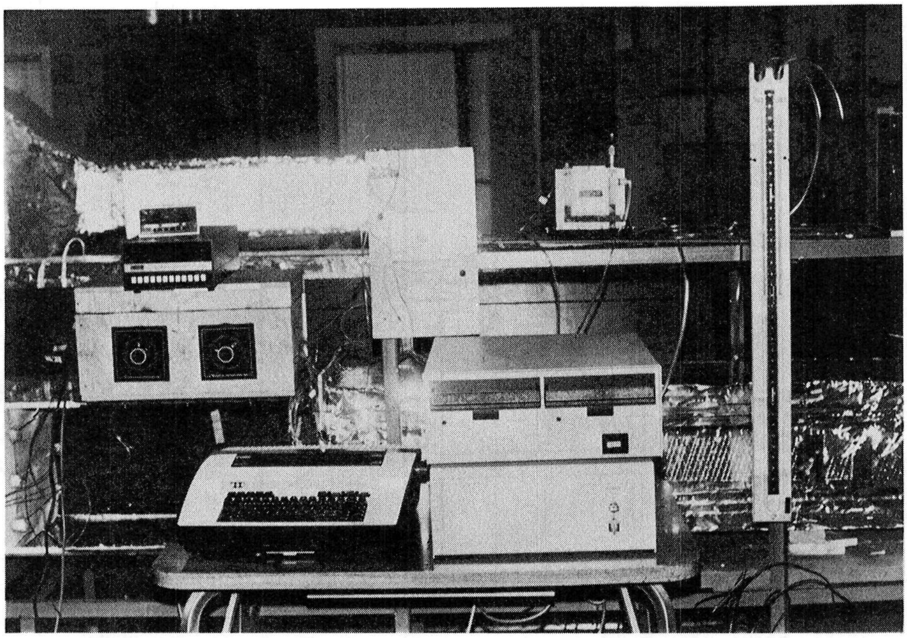


Figure 44. Photograph of test rig with sudden contraction entrance

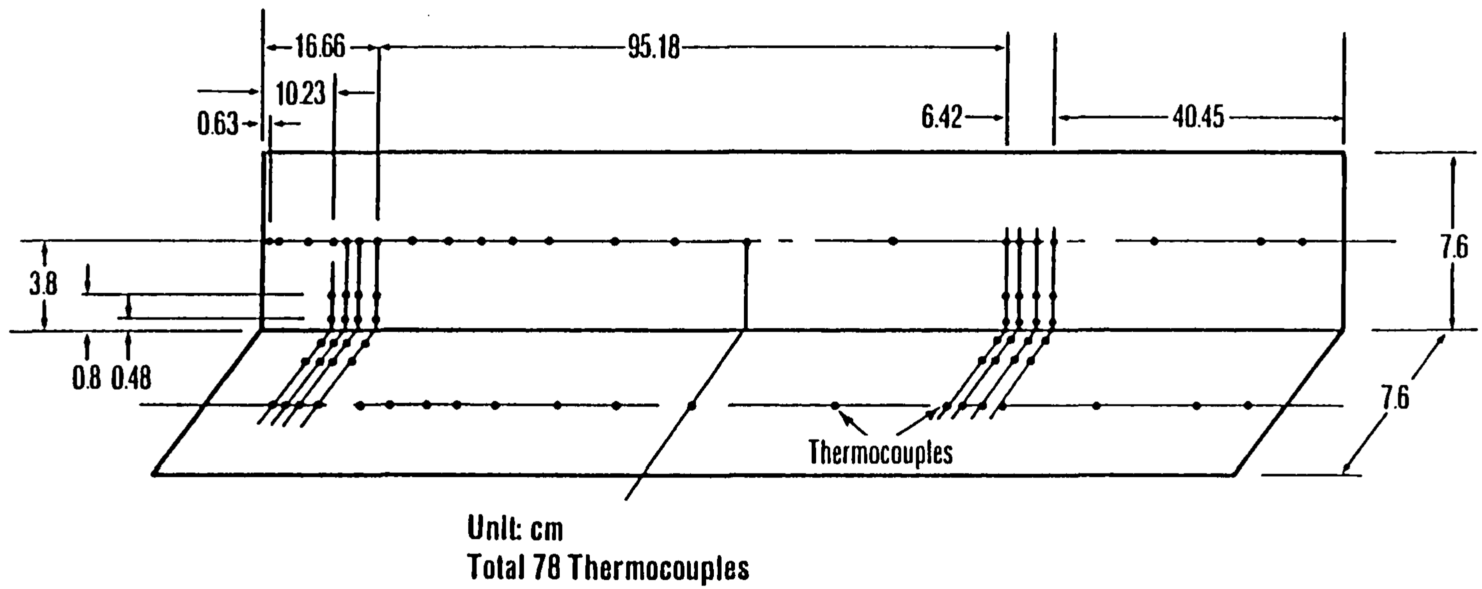



Figure 45. Thermocouples distributions on test plates (SCE)

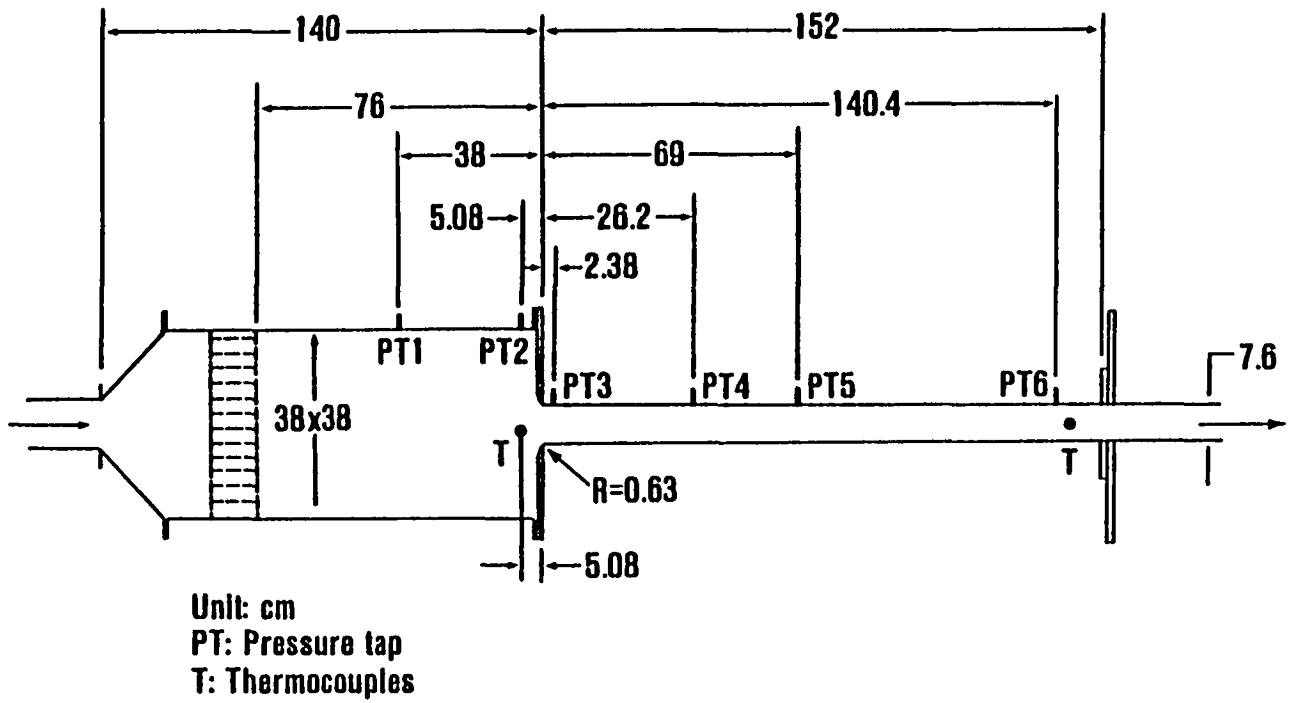



Figure 46. Pressure taps locations (SCE)

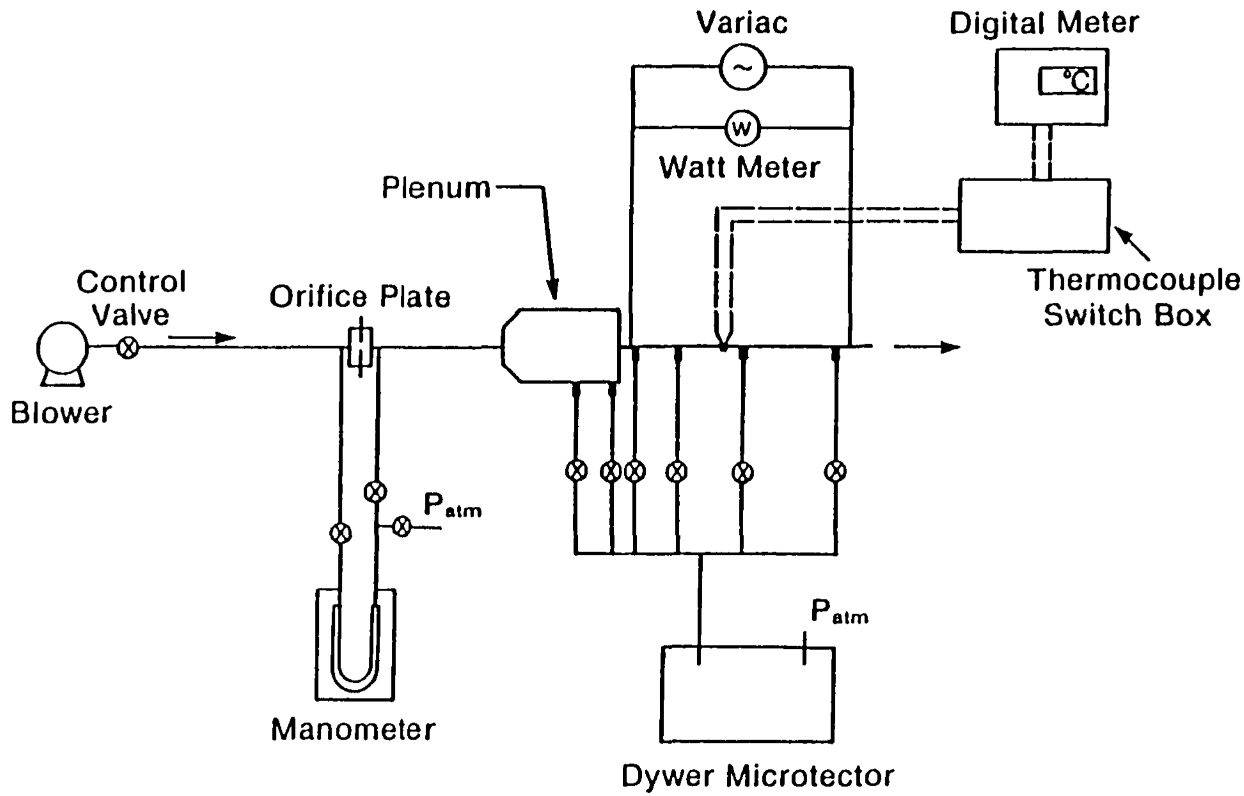



Figure 47. Flow, pressure drop, heat input, and temperature measurement system

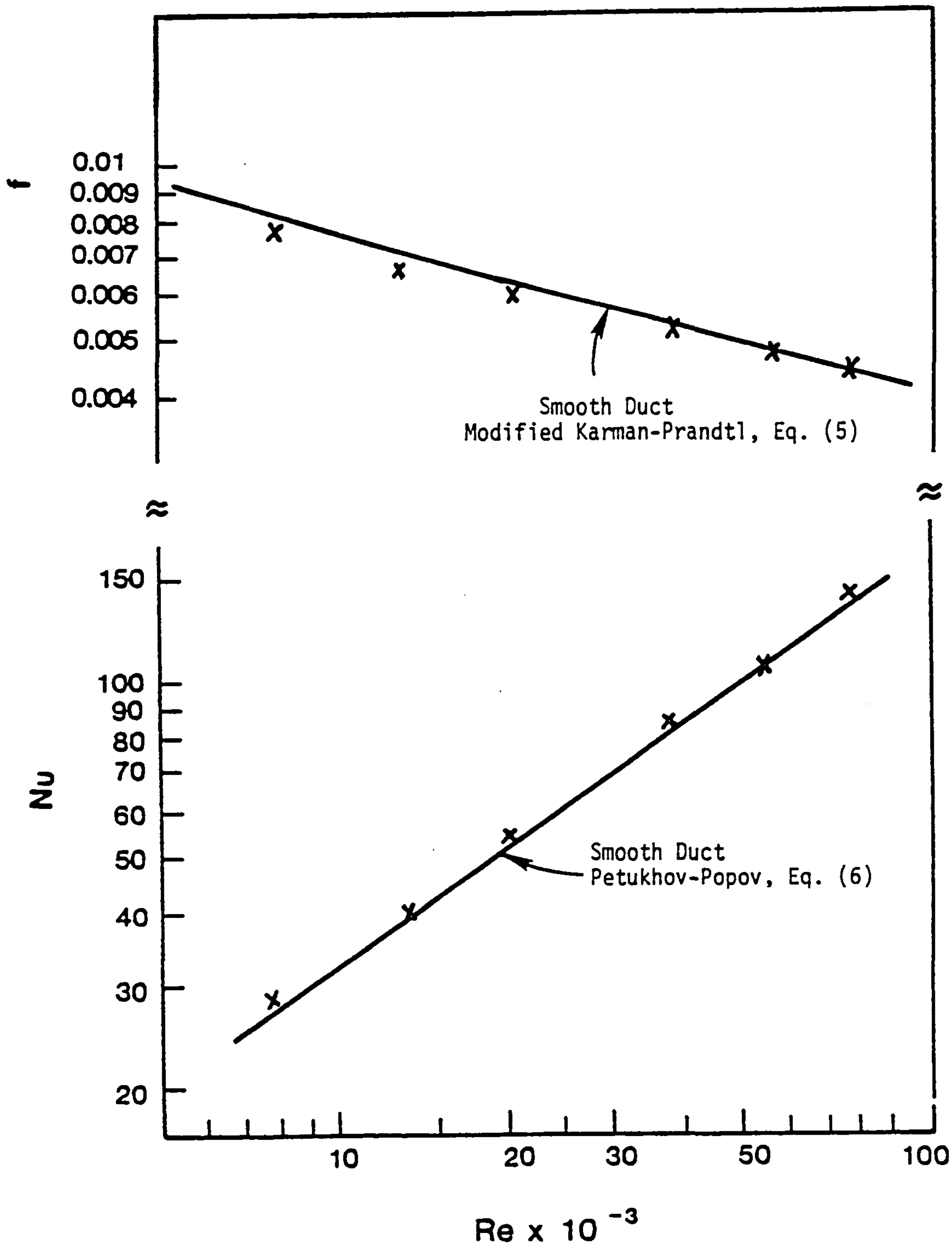



Figure 48. Friction and heat transfer for smooth duct (SCE)

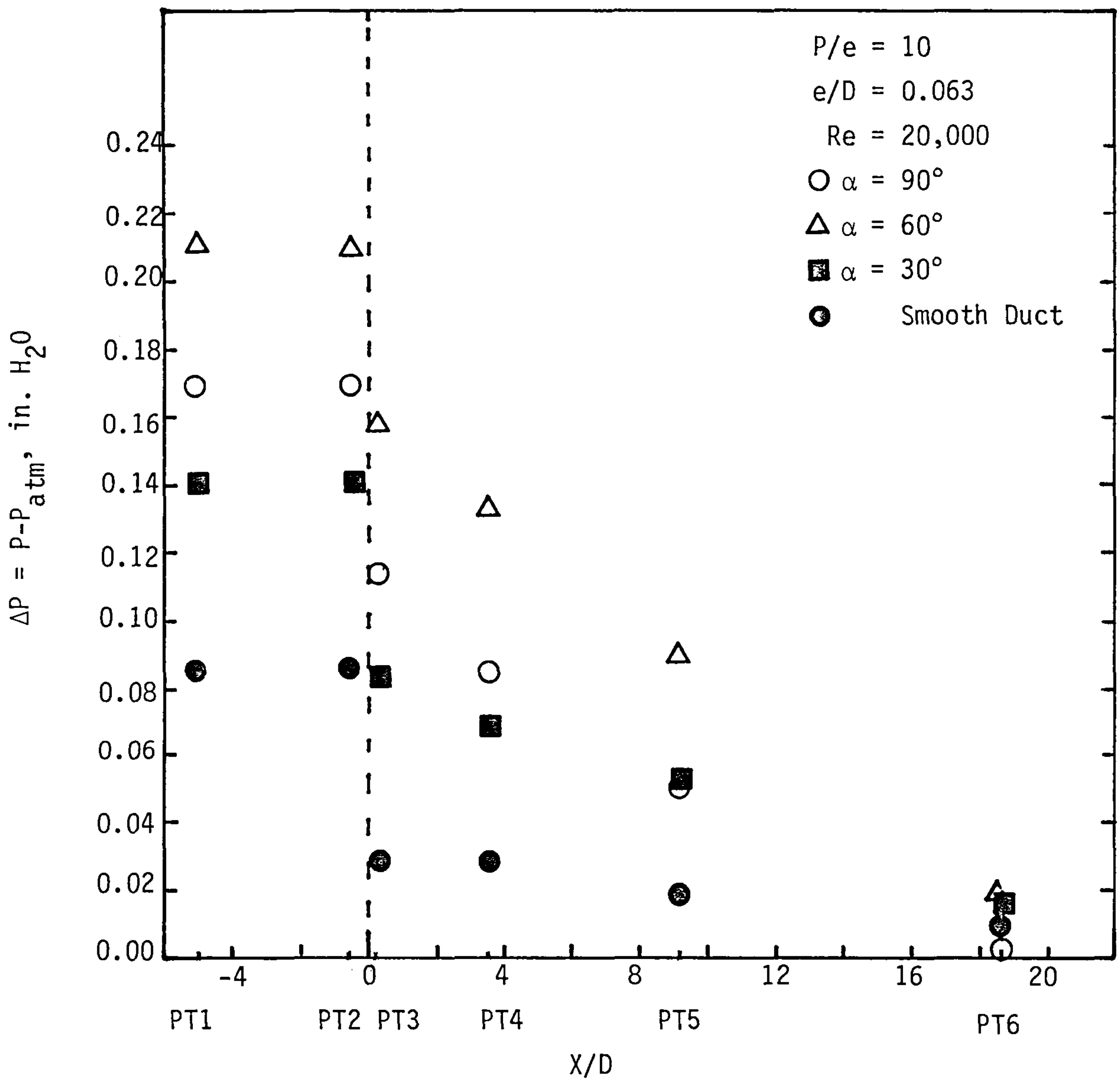



Figure 49. Pressure drop distributions for P/e = 10, Re = 20,000 (SCE)

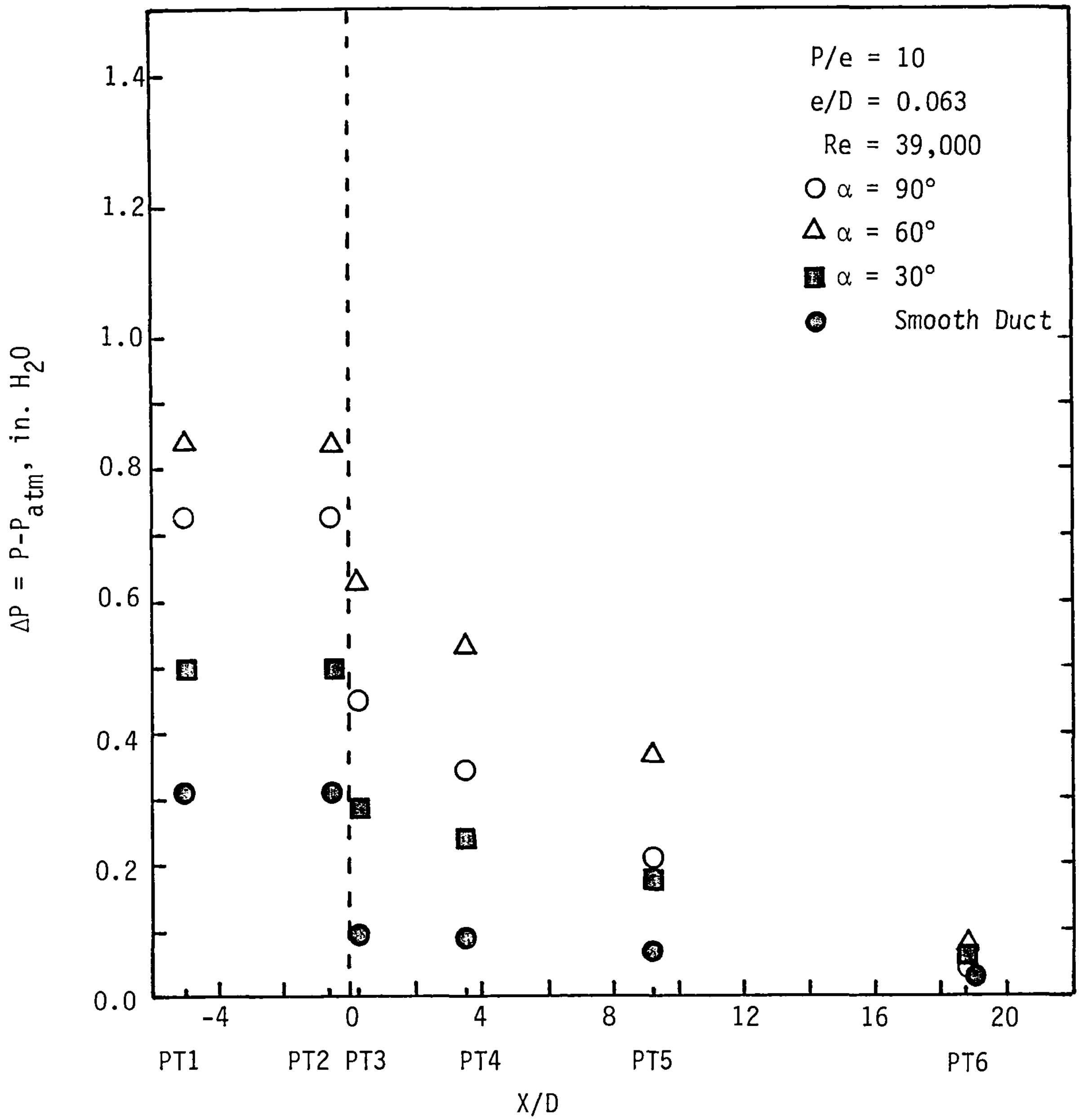



Figure 50. Pressure drop distributions for P/e = 10, Re = 39,000 (SCE)

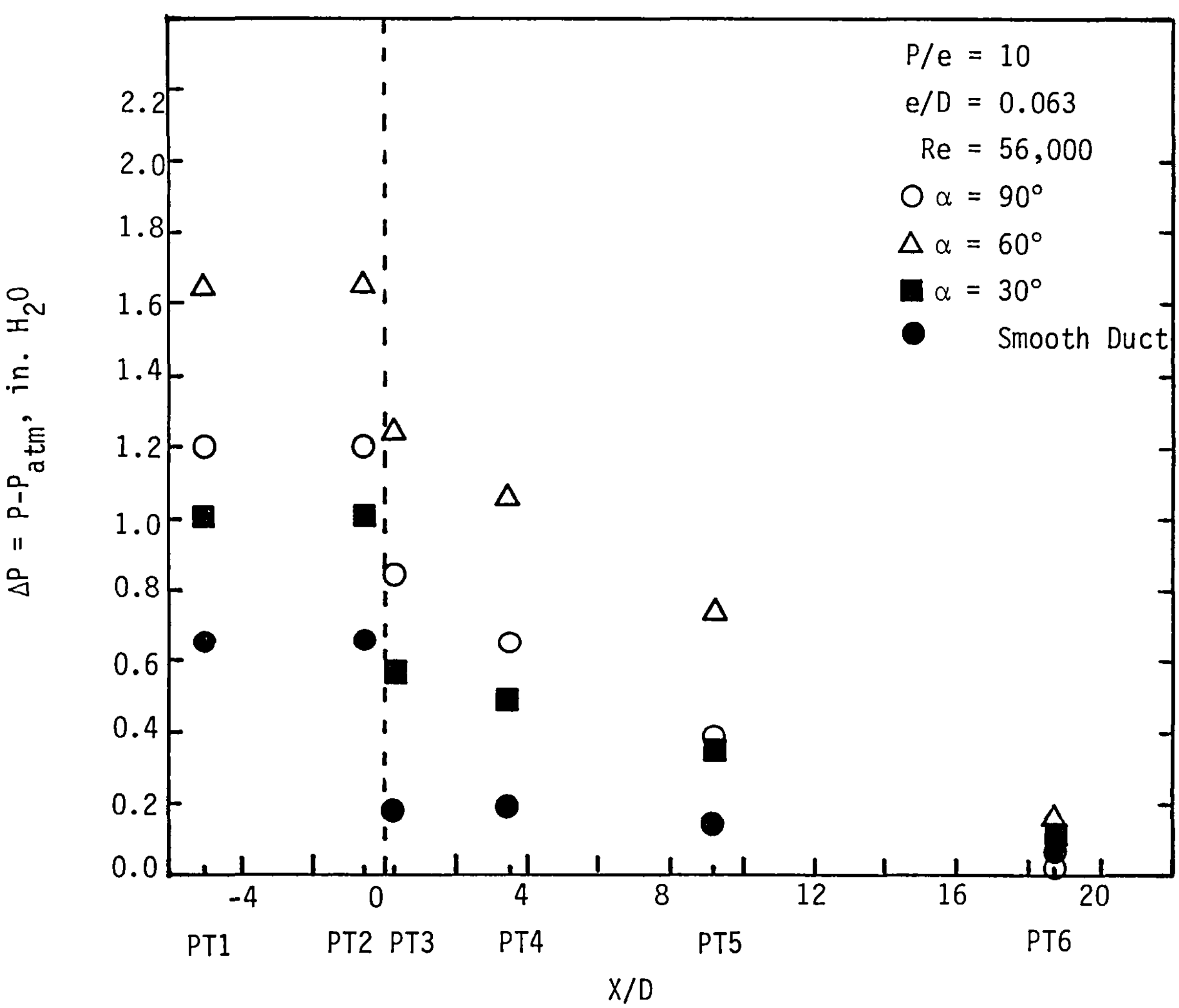



Figure 51. Pressure drop distributions for P/e = 10, Re = 56,000 (SCE)

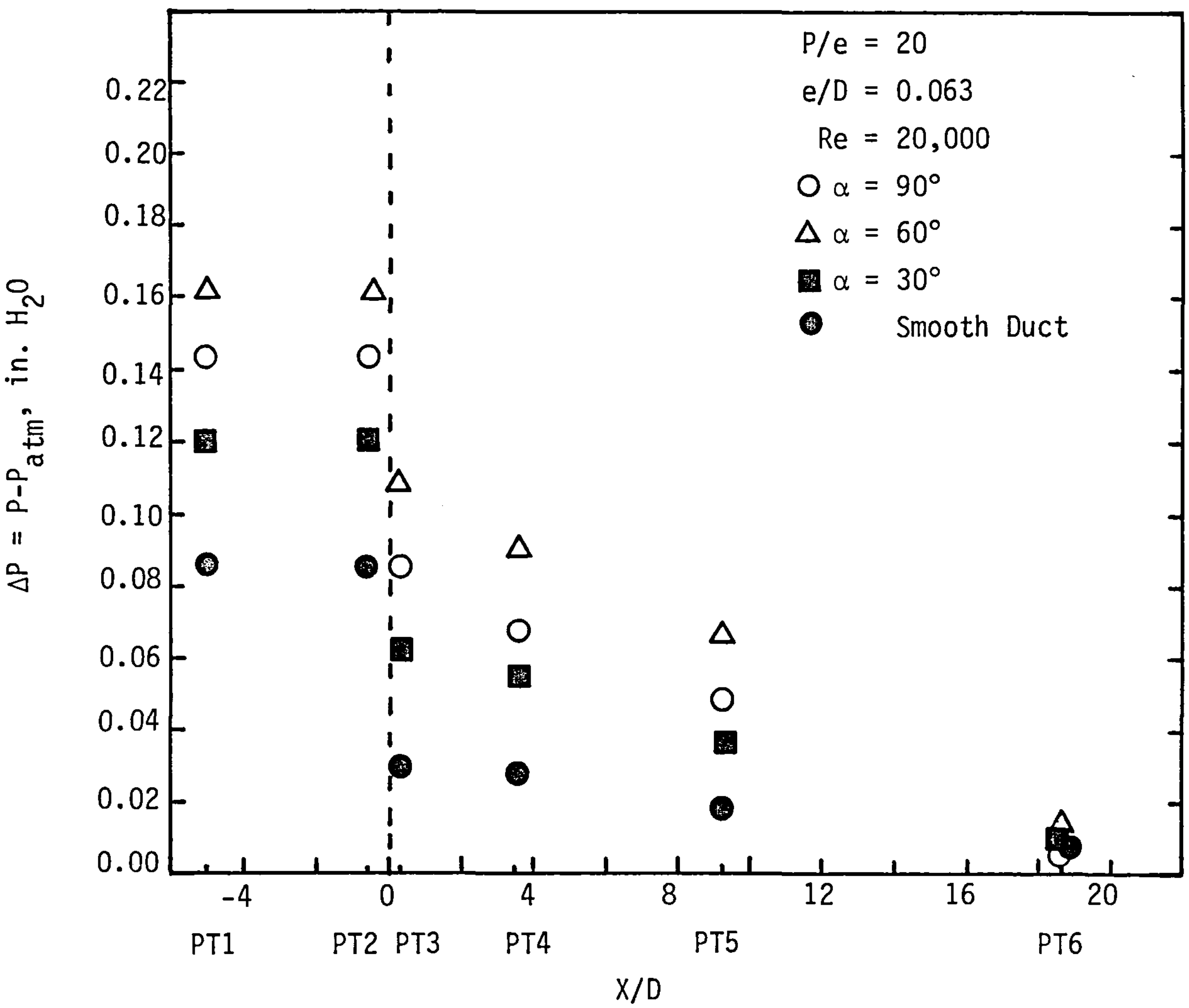



Figure 52. Pressure drop distributions for P/e = 20, Re = 20,000 (SCE)

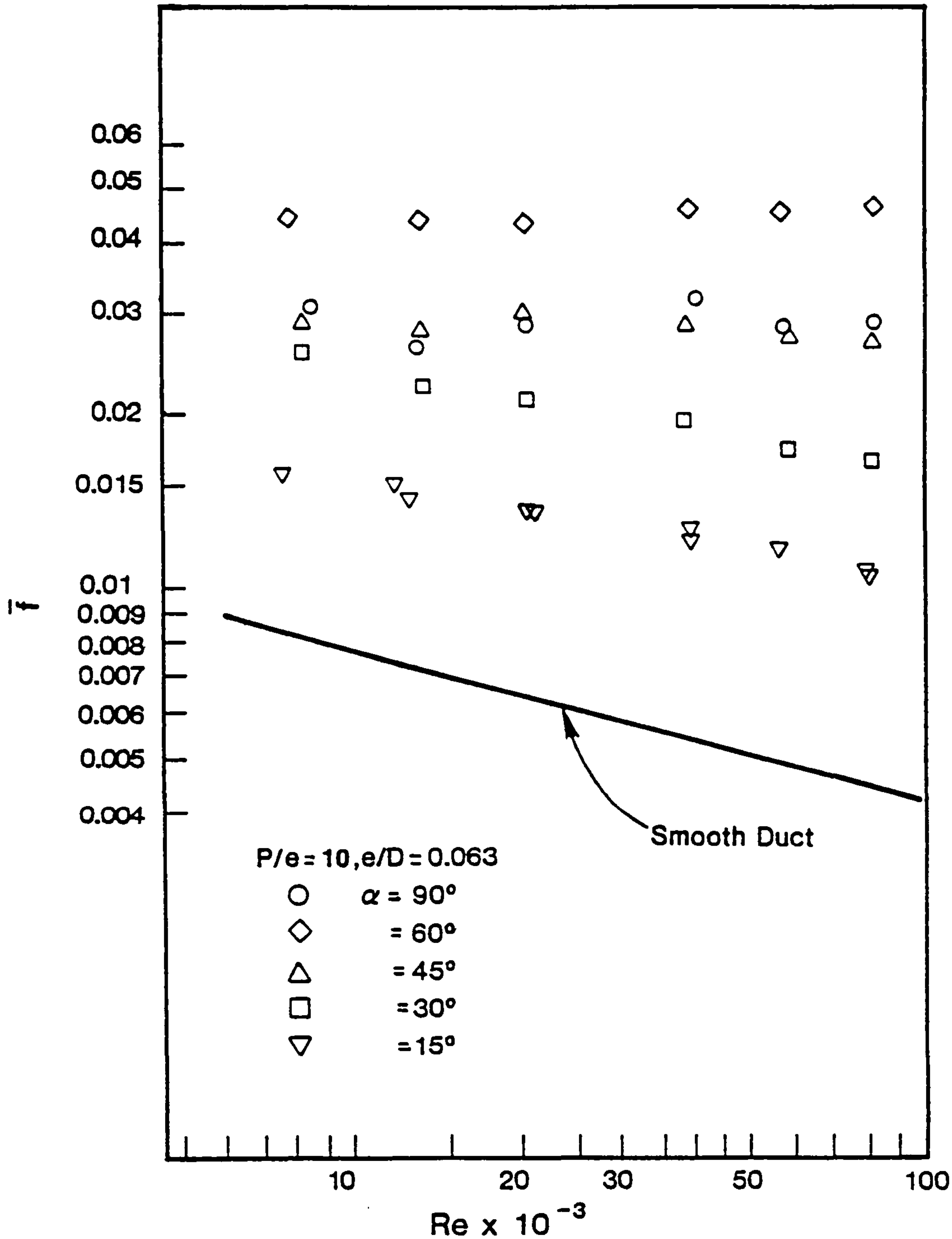



Figure 53. Average friction factor with different α for P/e = 10 (SCE)

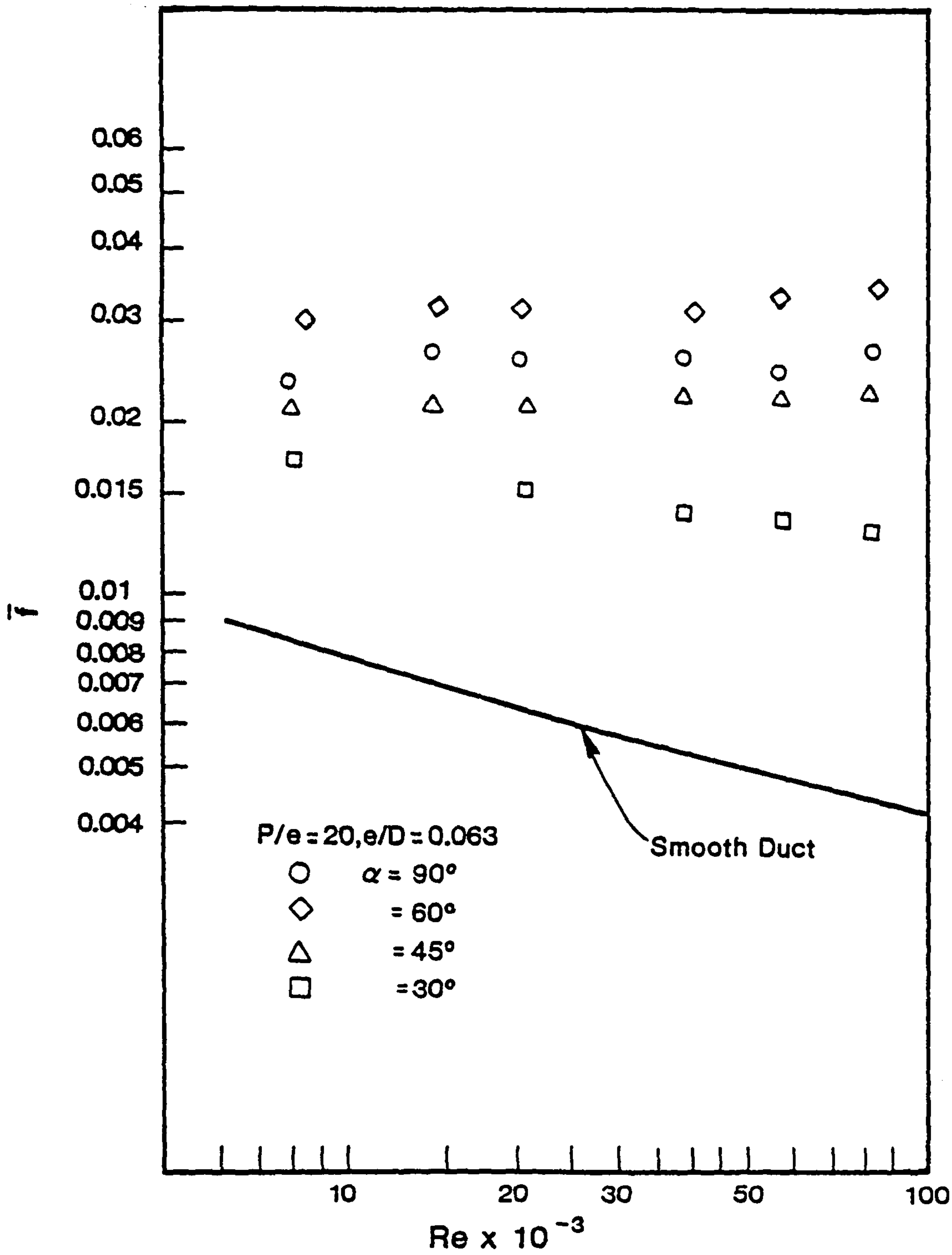



Figure 54. Average friction factor with different α for P/e = 20 (SCE)

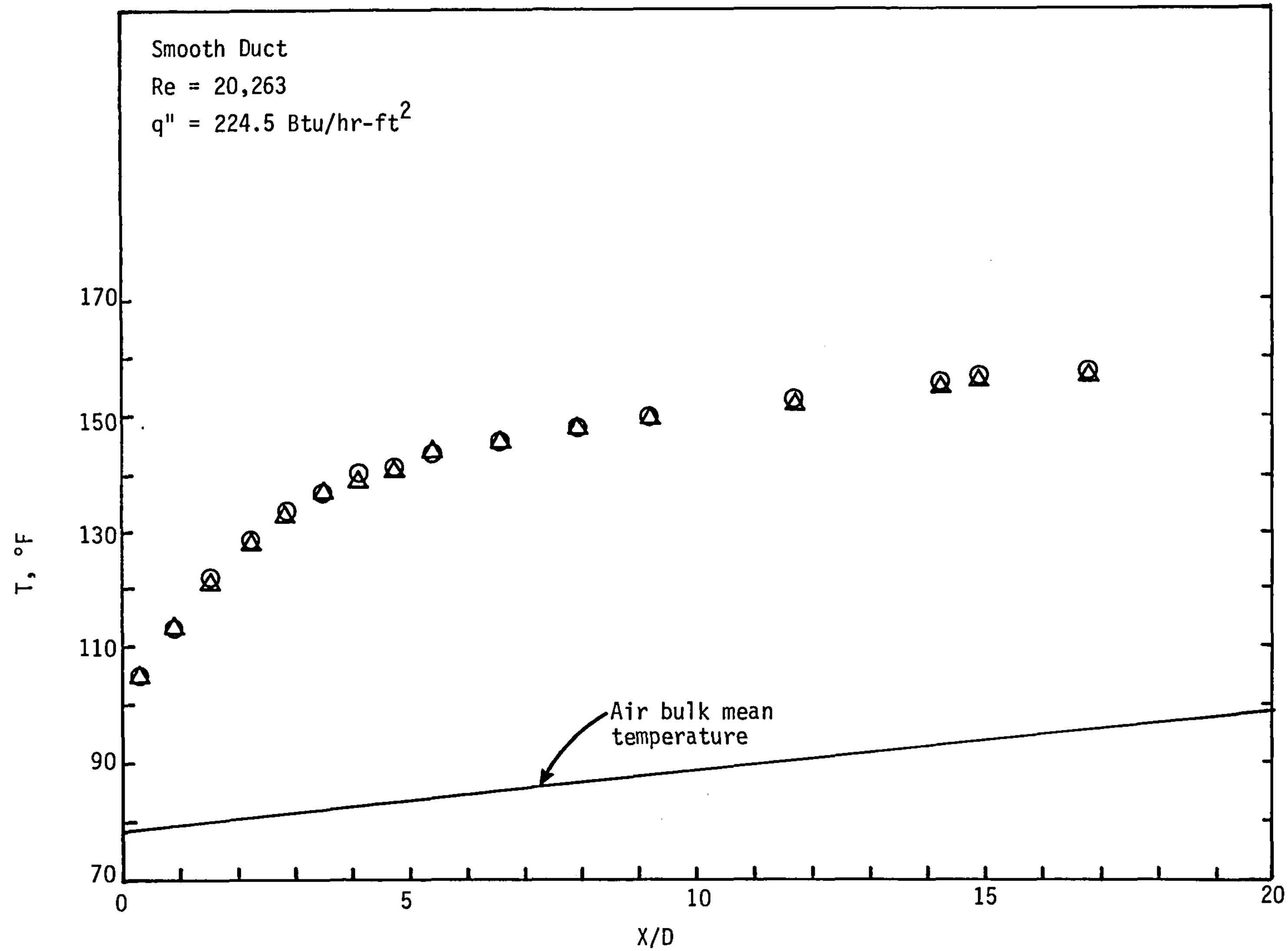



Figure 55. Temperature distributions for smooth duct (SCE)

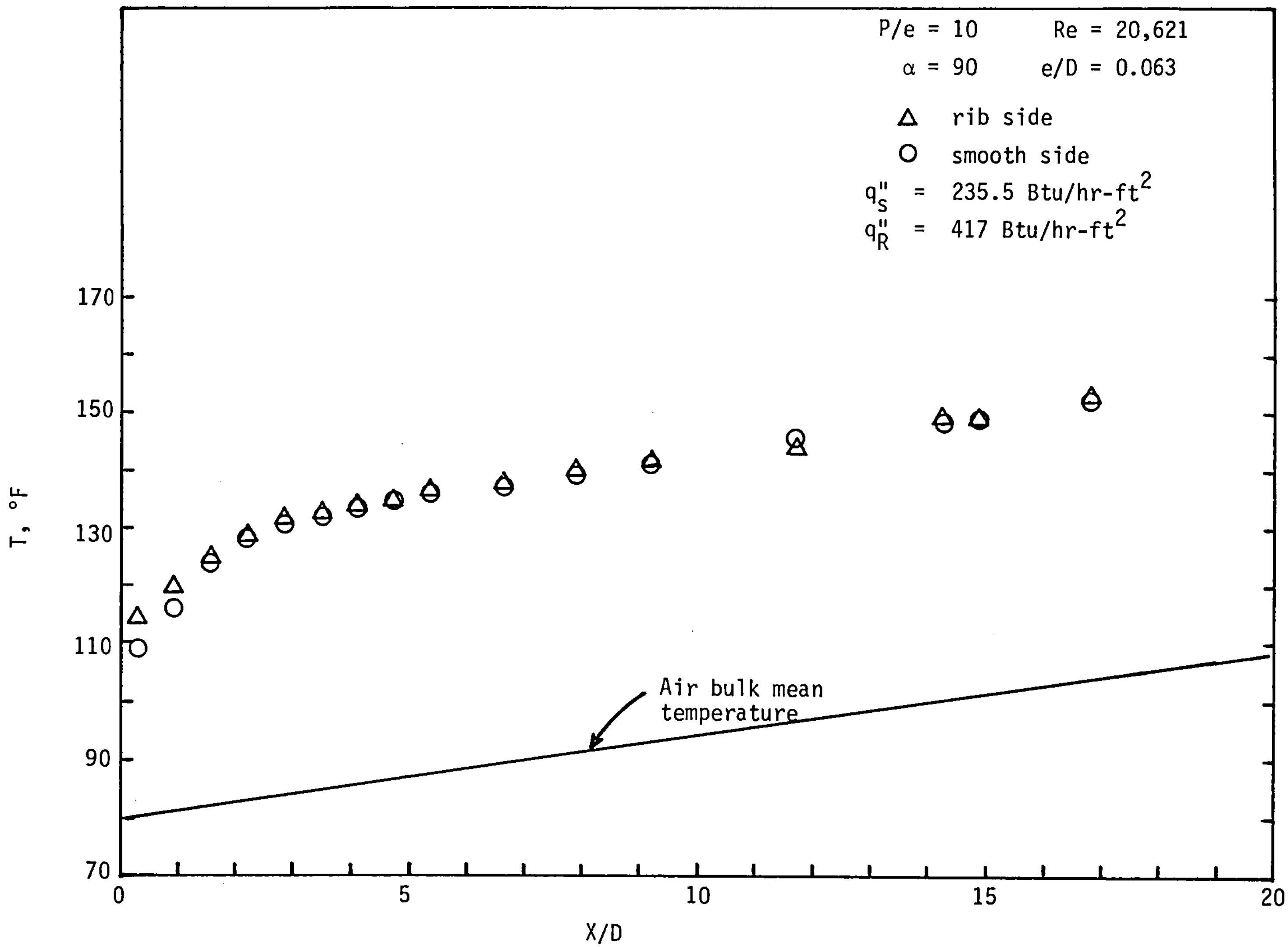



Figure 56. Temperature distributions for $\alpha$ = 90° (SCE)

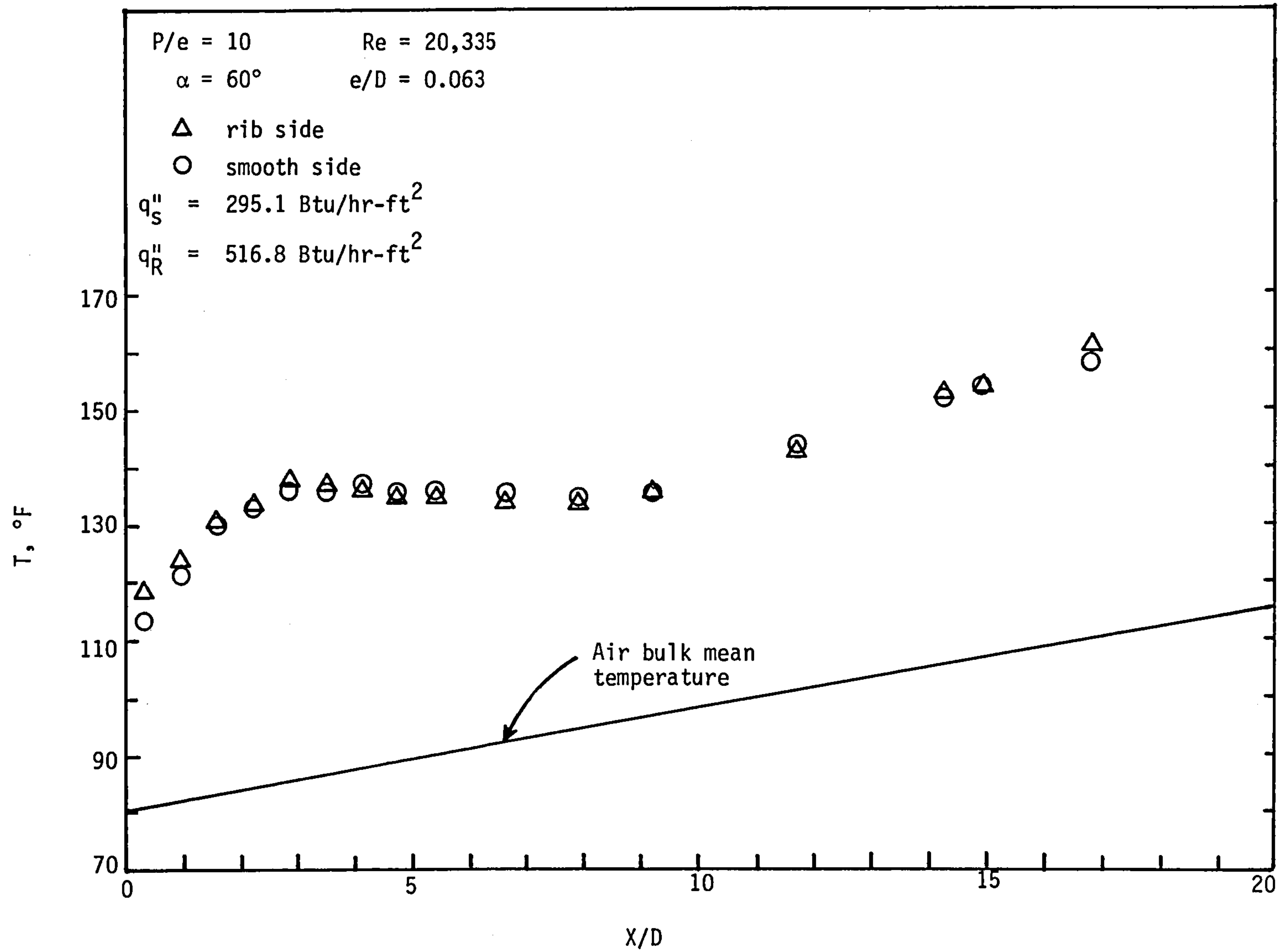



Figure 57. Temperature distributions for α = 60° (SCE)

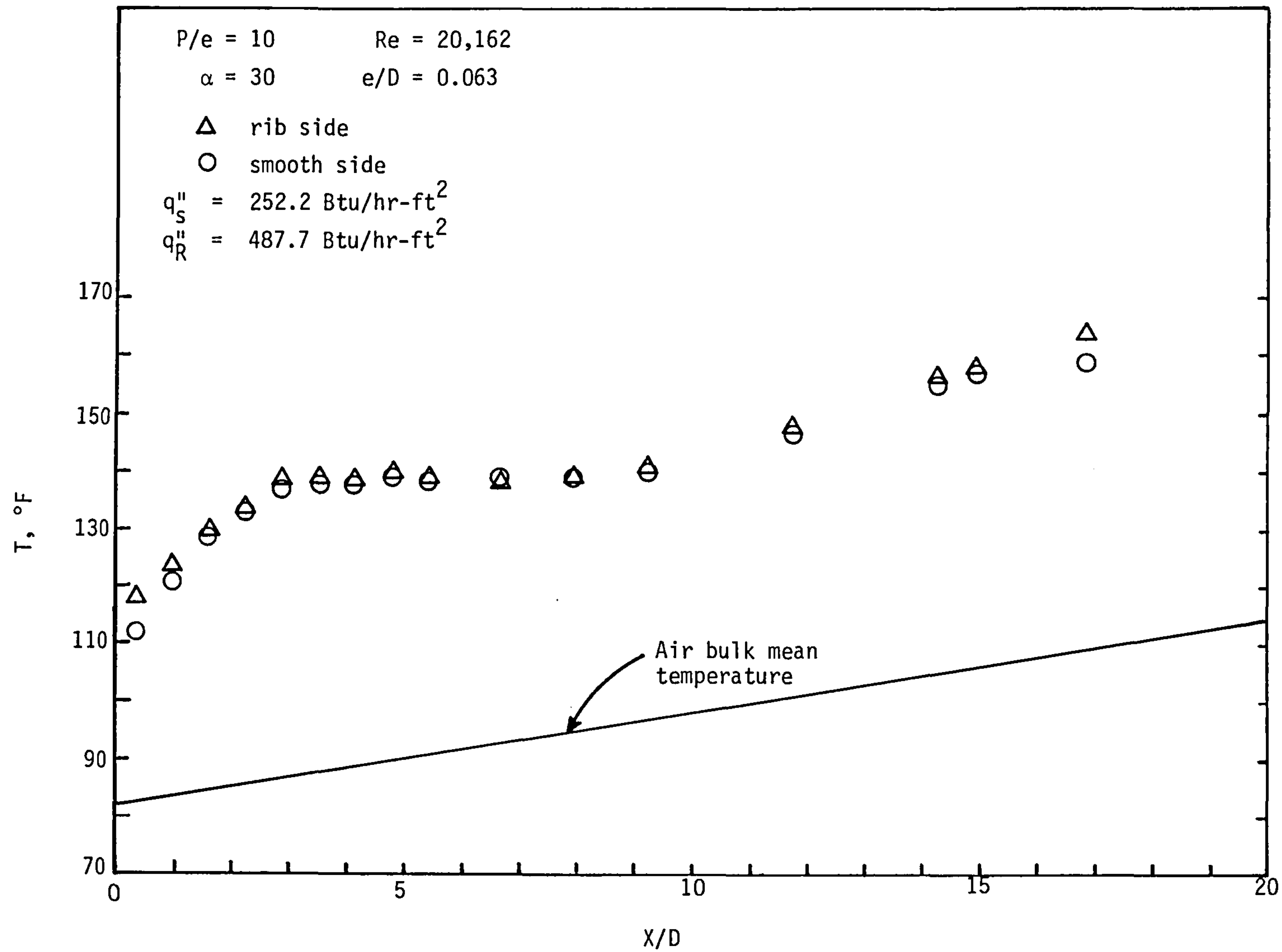



Figure 58. Temperature distributions for $\alpha = 30°$ (SCE)

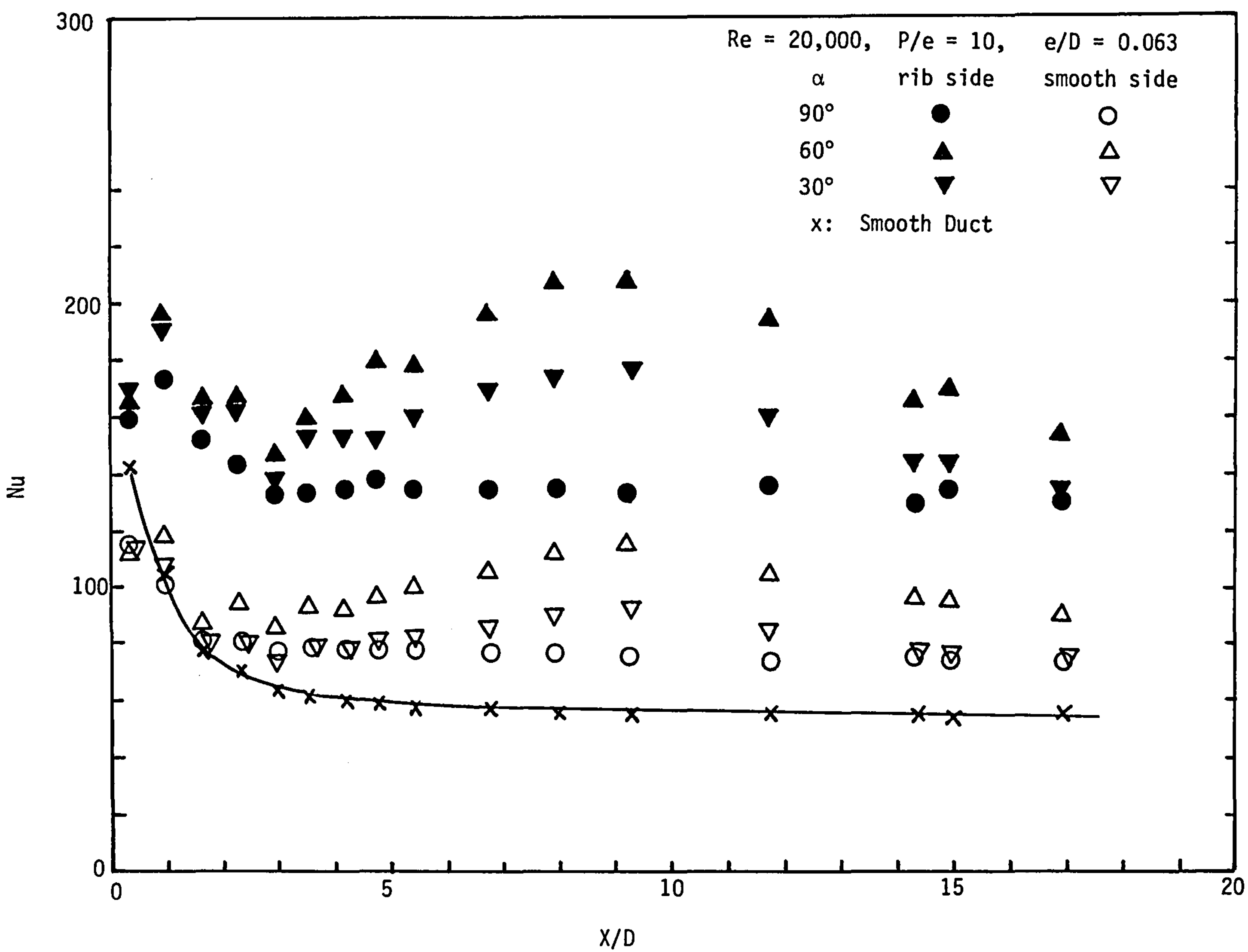



Figure 59. Nusselt number distributions for P/e = 10, Re = 20,000 (SCE)

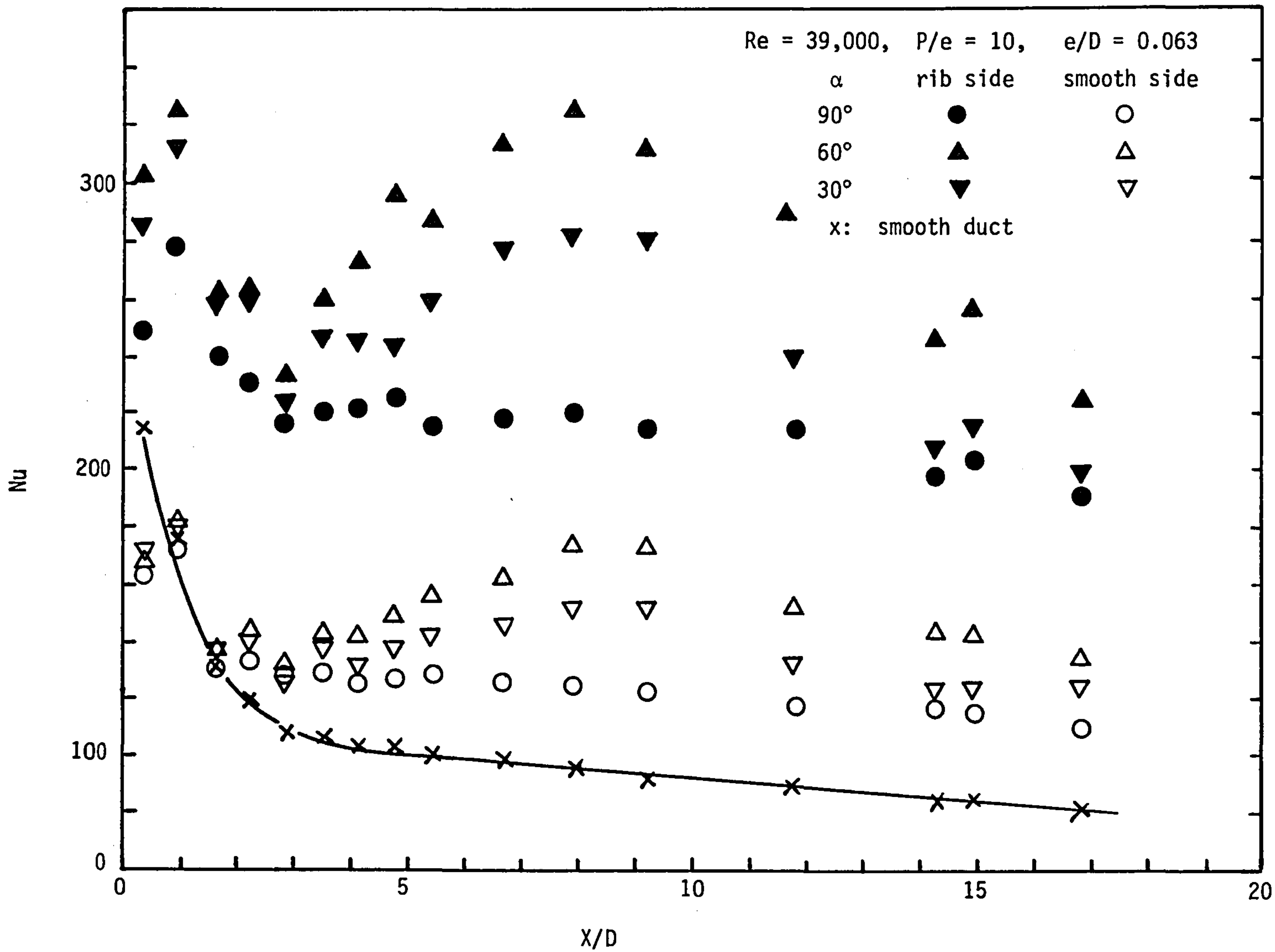



Figure 60. Nusselt number distributions for P/e = 10, Re = 39,000 (SCE)

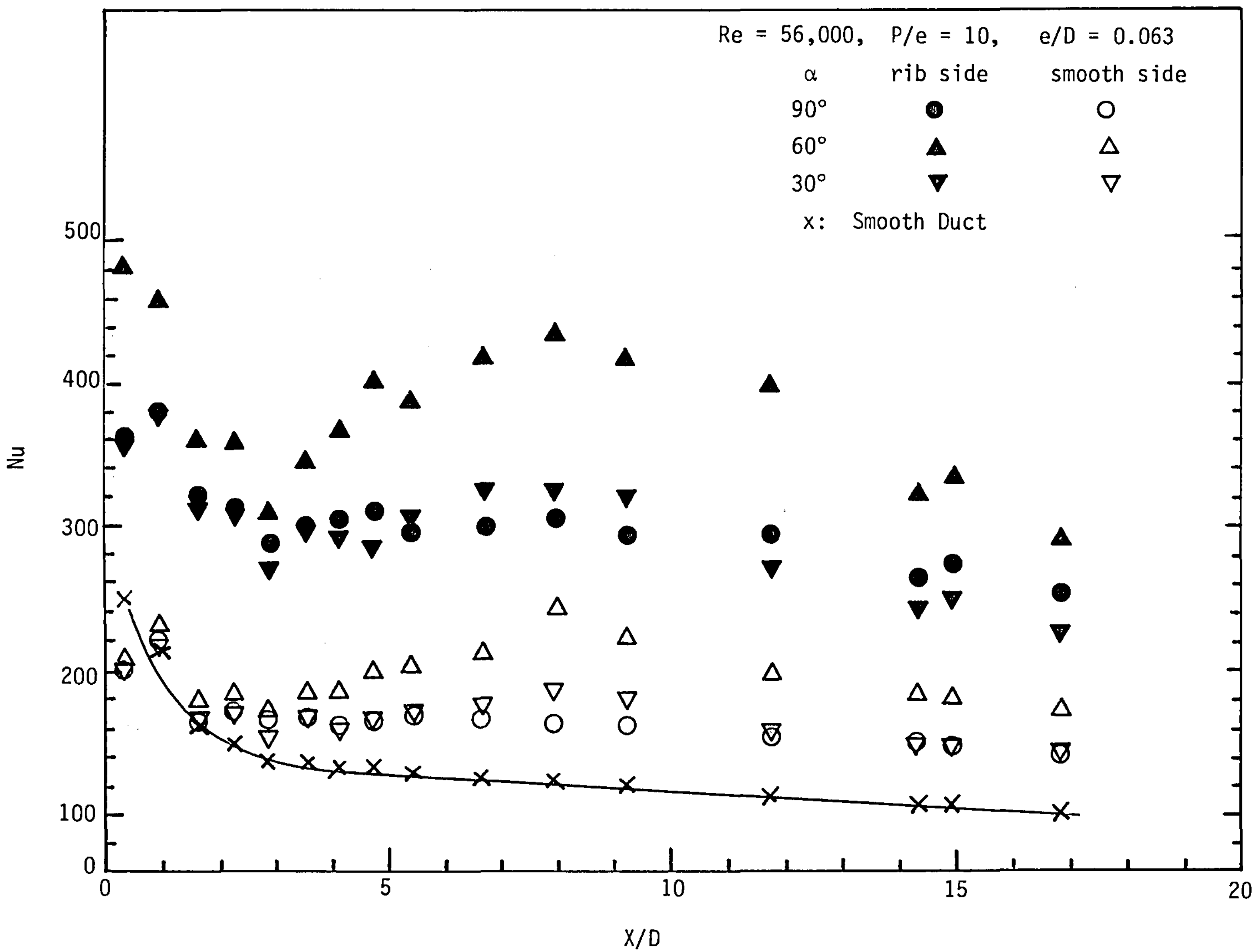



Figure 61. Nusselt number distributions for P/e = 10, Re = 56,000 (SCE)

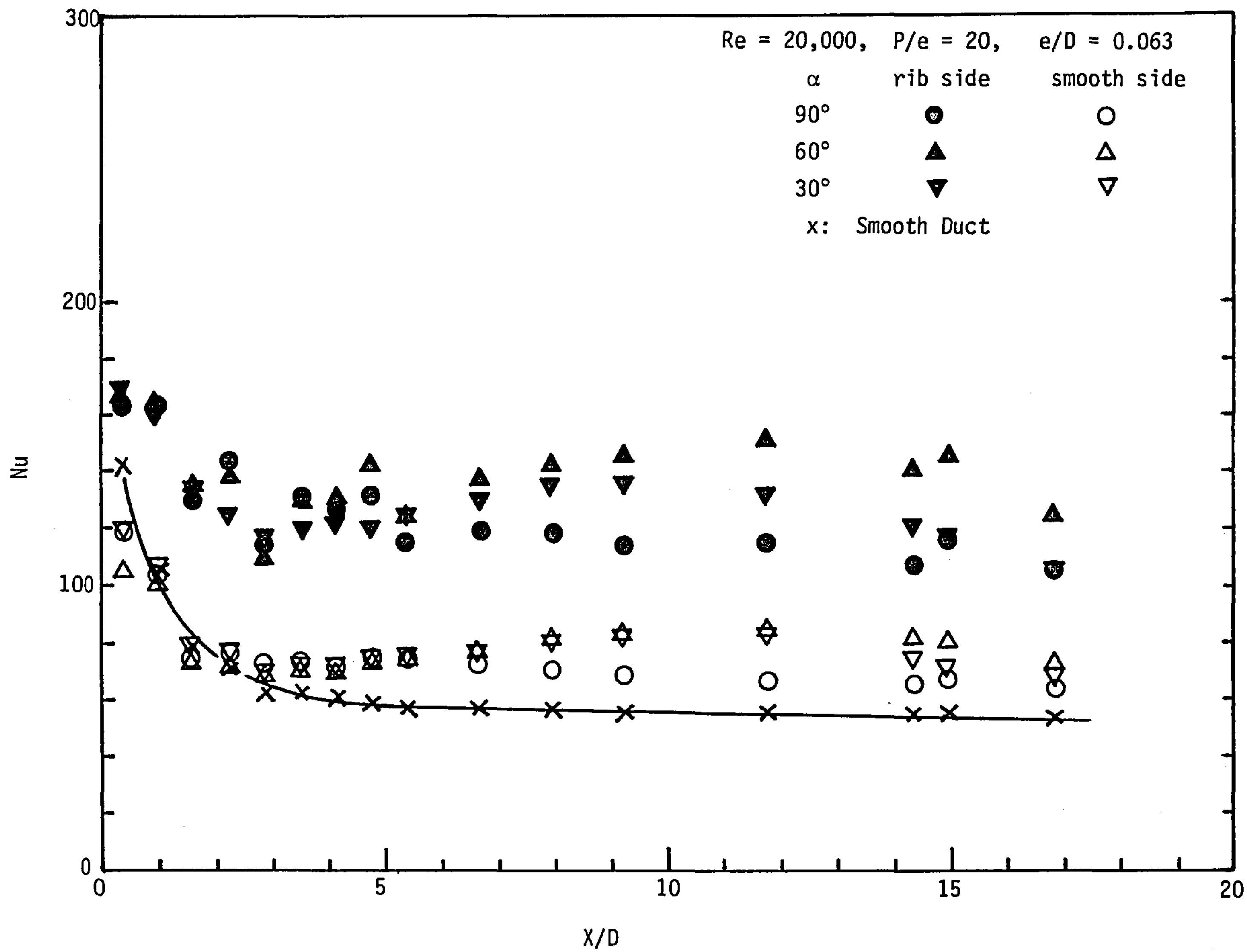



Figure 62. Nusselt number distributions for P/e = 20, Re = 20,000 (SCE)

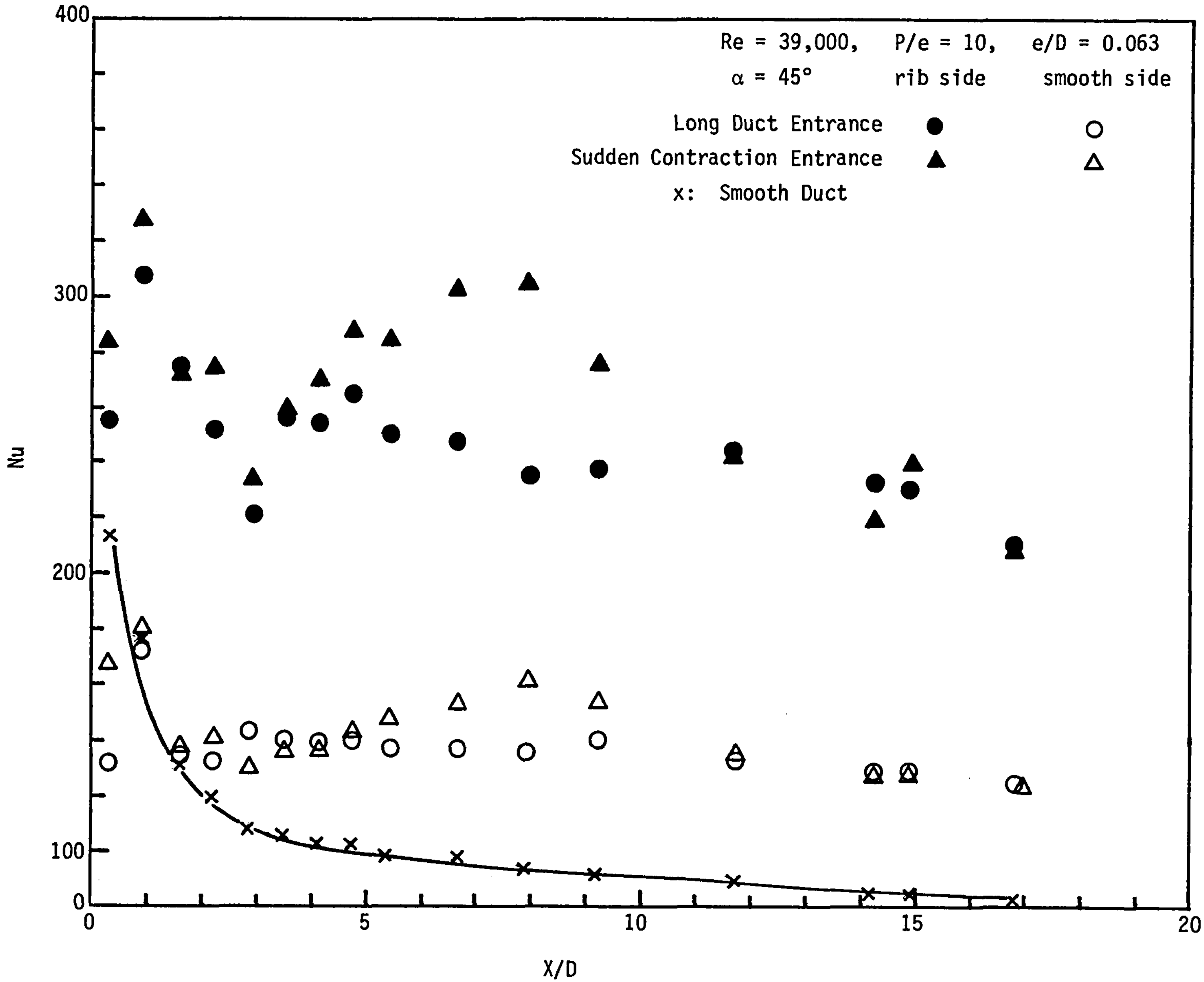



Figure 63. Nusselt number distributions for $\alpha = 45°$ with different entrance geometry

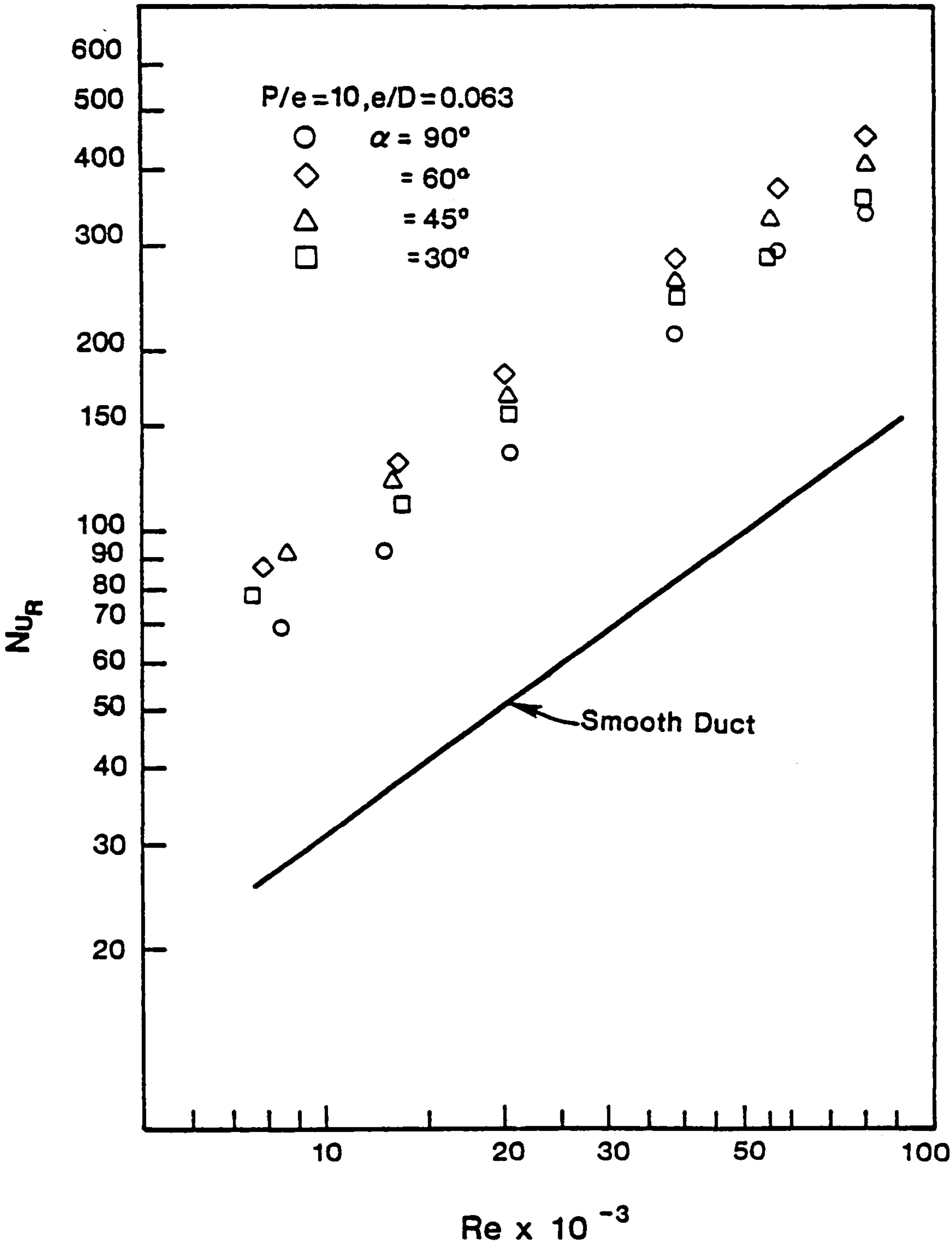



Figure 64. The ribbed side Nusselt number with different α for P/e = 10 (SCE)

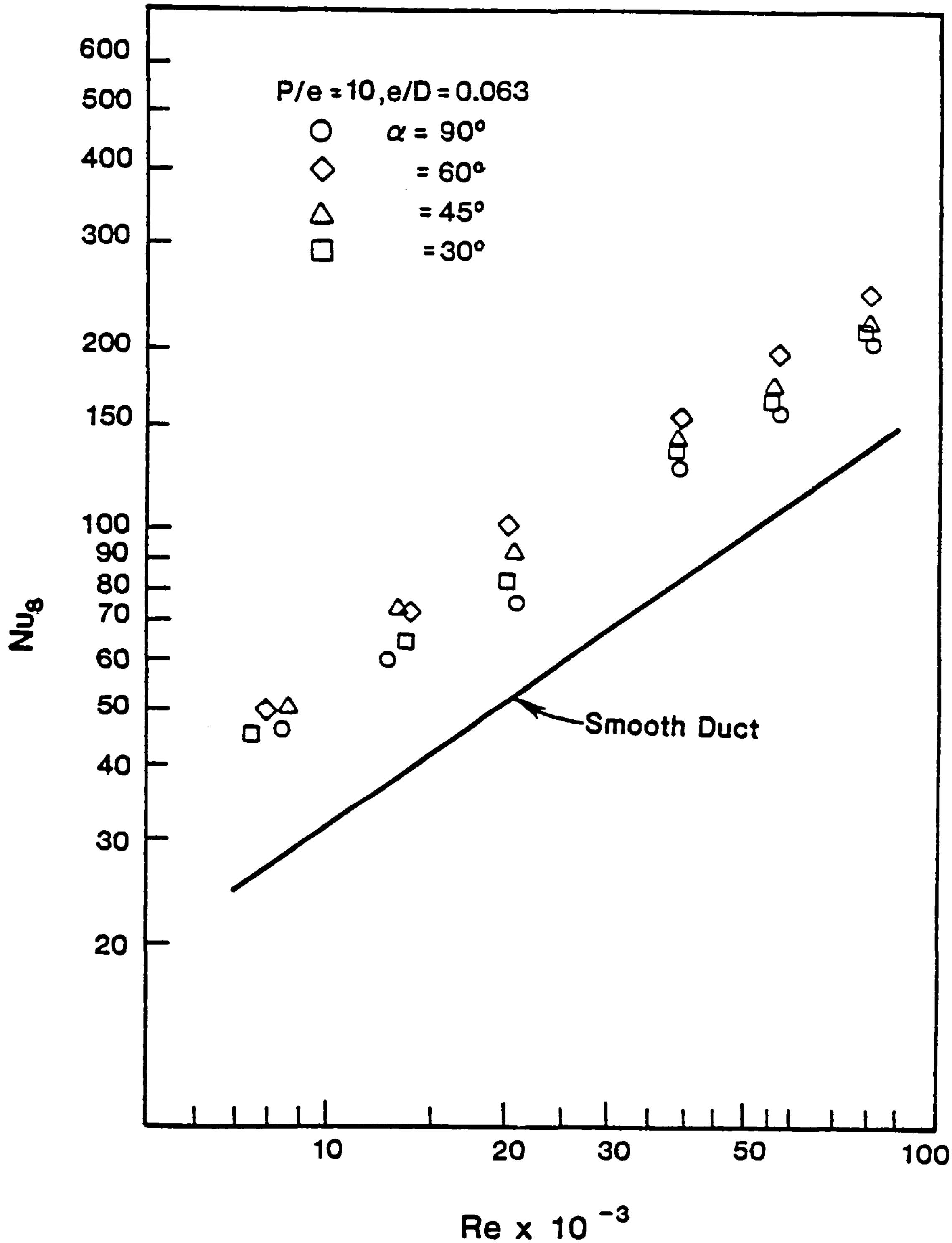



Figure 65. The smooth side Nusselt number with different α for P/e = 10 (SCE)

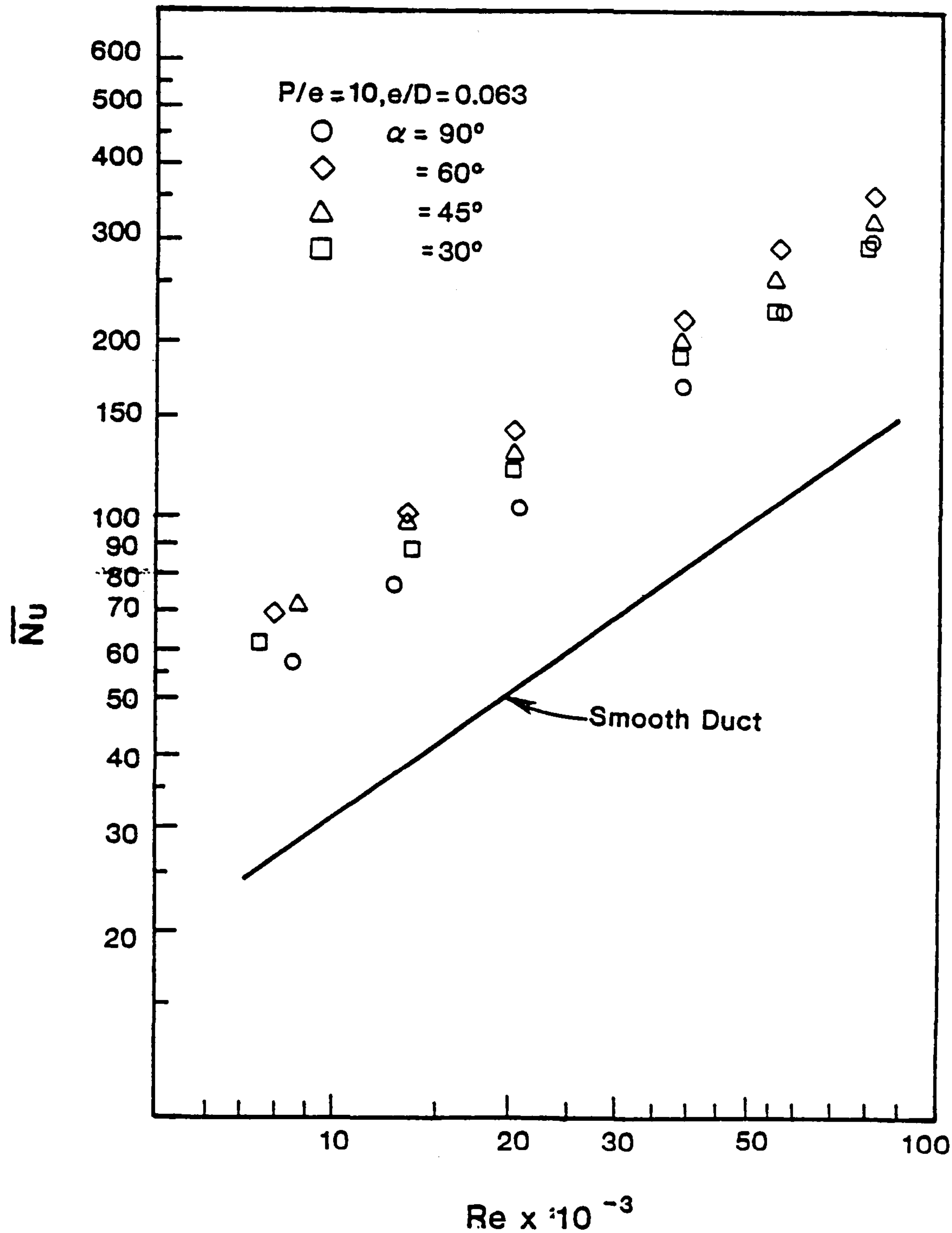



Figure 66. The average Nusselt number with different α for P/e = 10 (SCE)

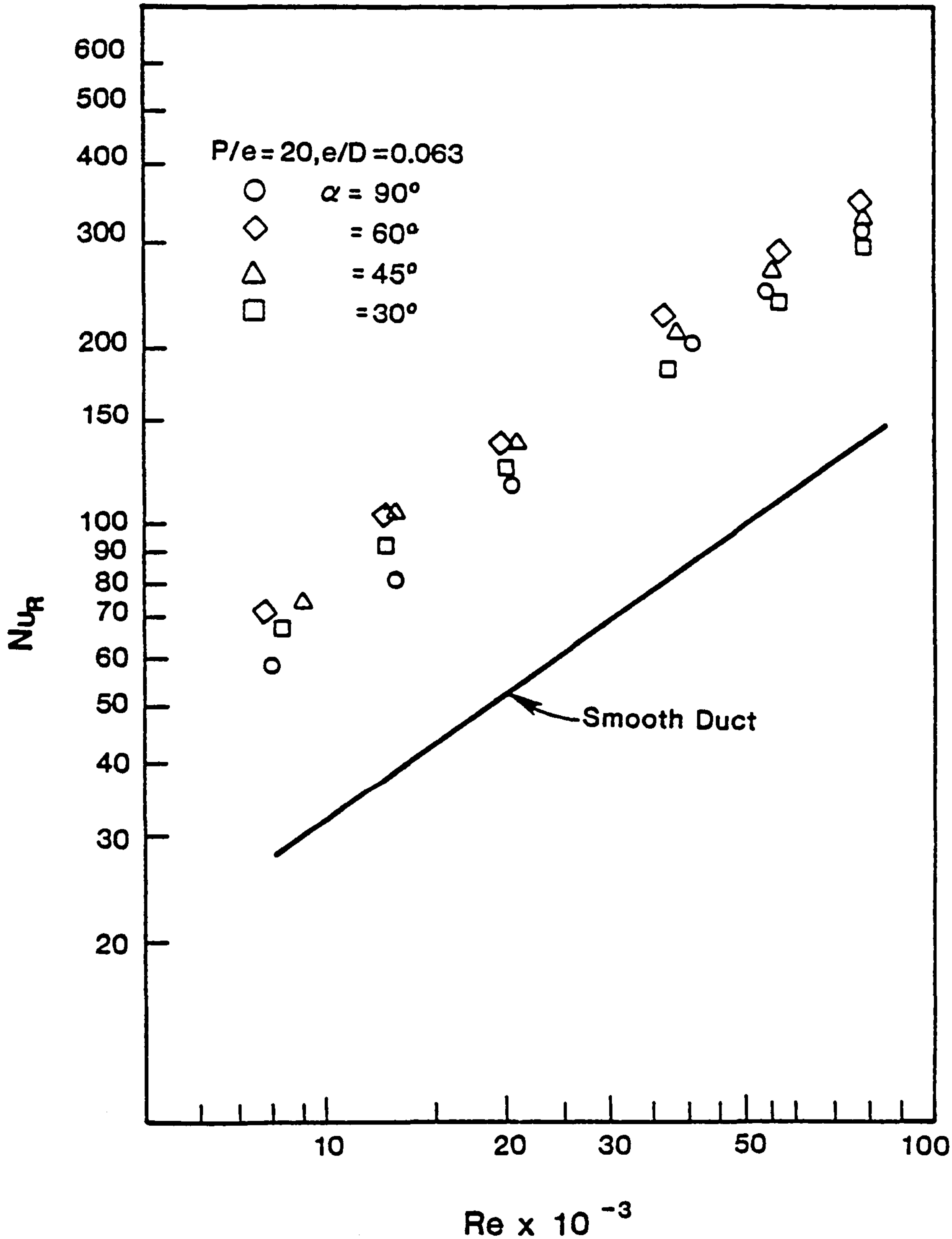



Figure 67. The ribbed side Nusselt number with different α for P/e = 20 (SCE)

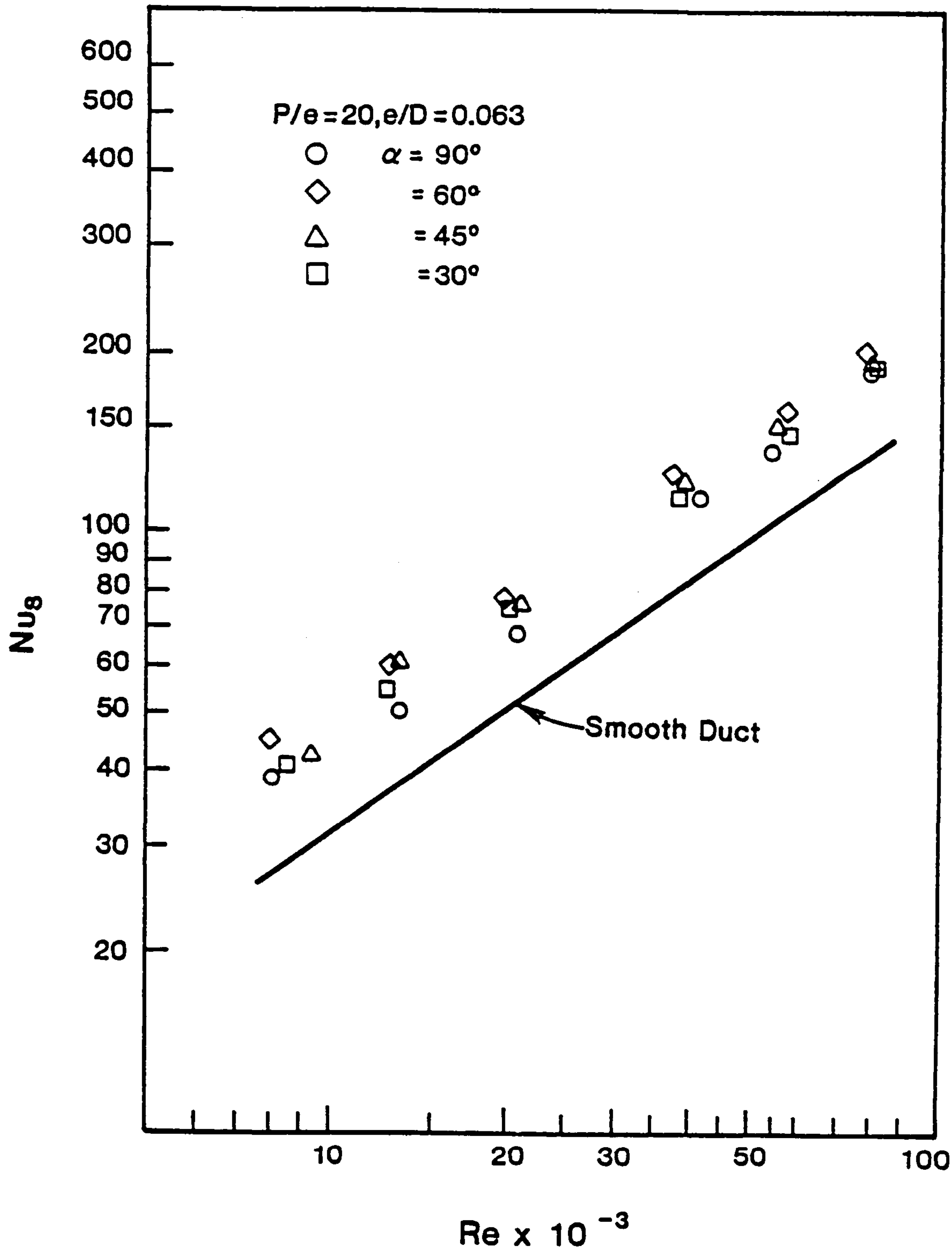



Figure 68. The smooth side Nusselt number with different α for P/e = 20 (SCE)

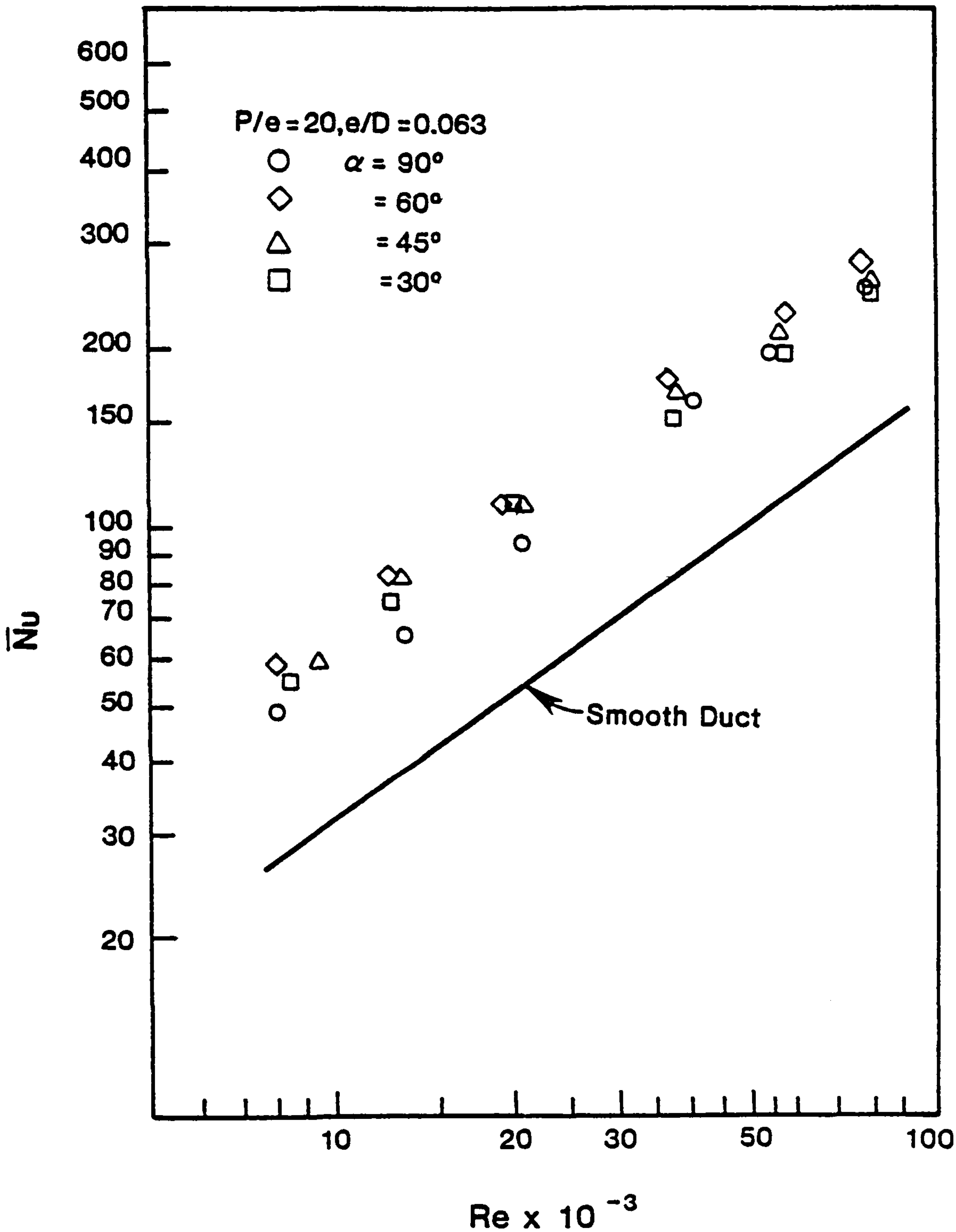



Figure 69. The average Nusselt number with different α for P/e = 20 (SCE)

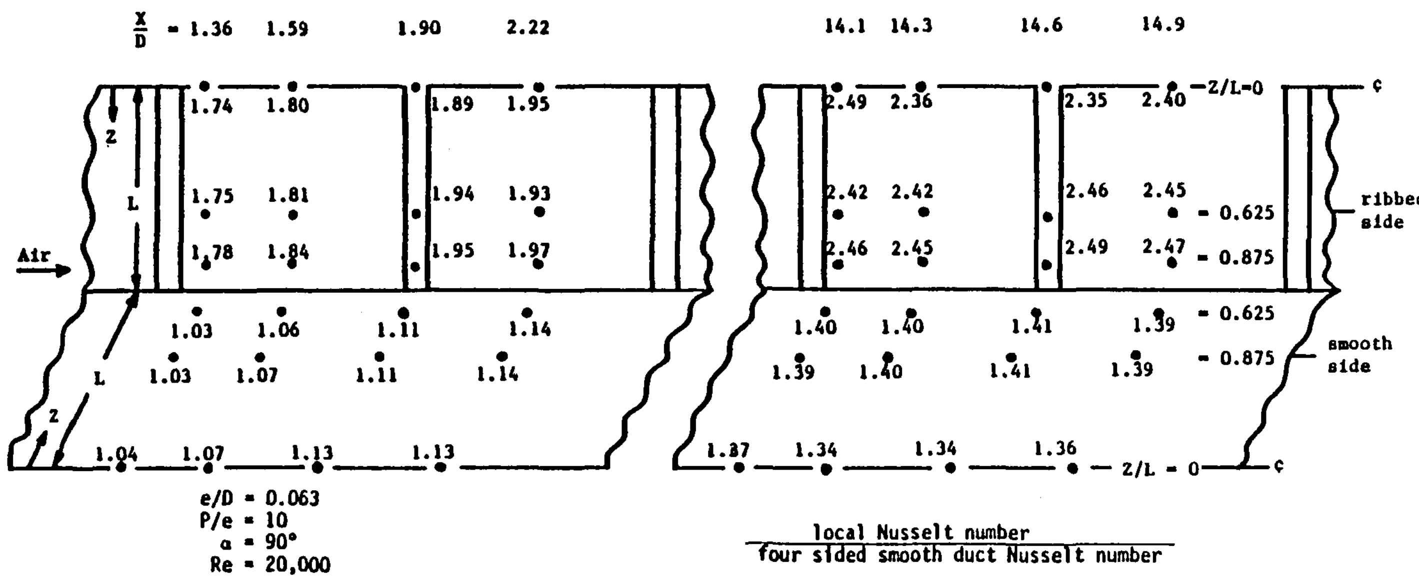



Figure 70. Local Nusselt number enhancement for $\alpha$ = 90°

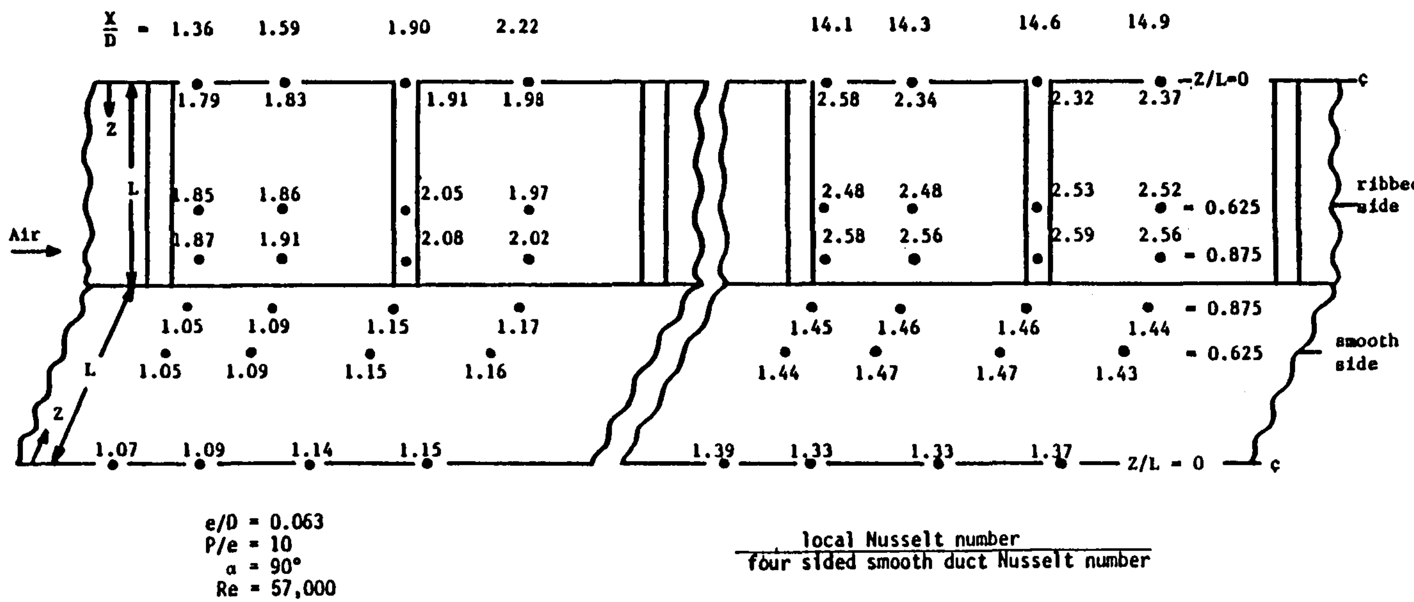



Figure 71. Local Nusselt number enhancement for P/e = 10

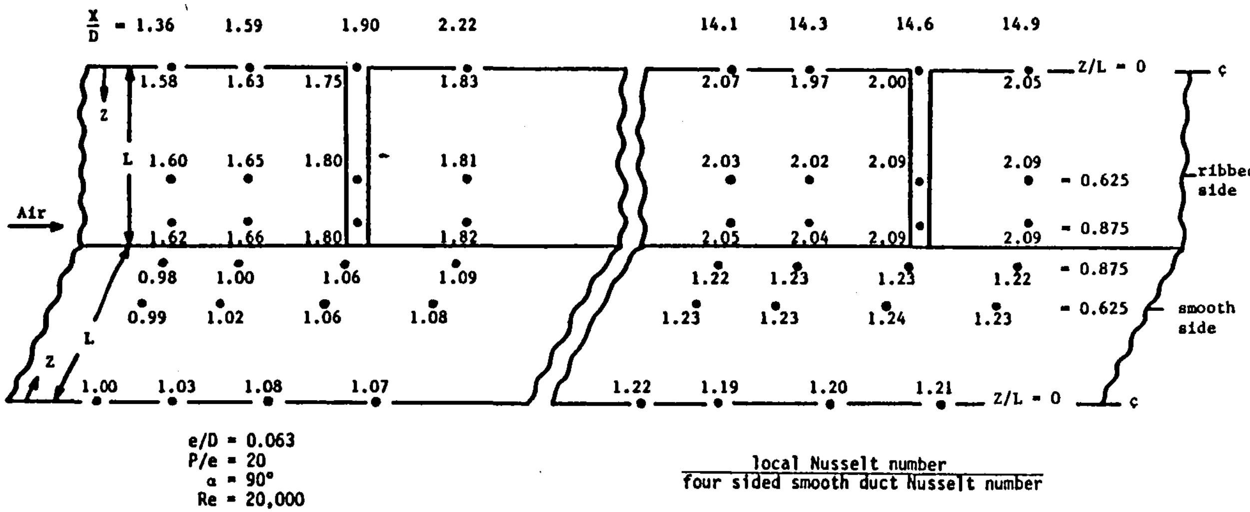



Figure 72. Local Nusselt number enhancement for P/e = 20

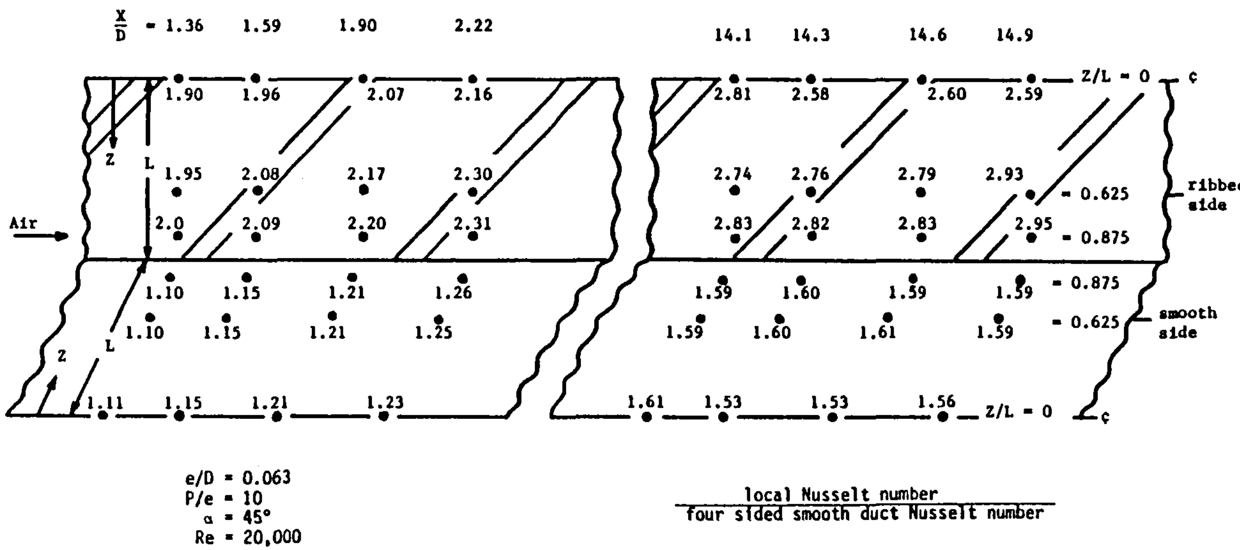



Figure 73. Local Nusselt number enhancement for α = 45°

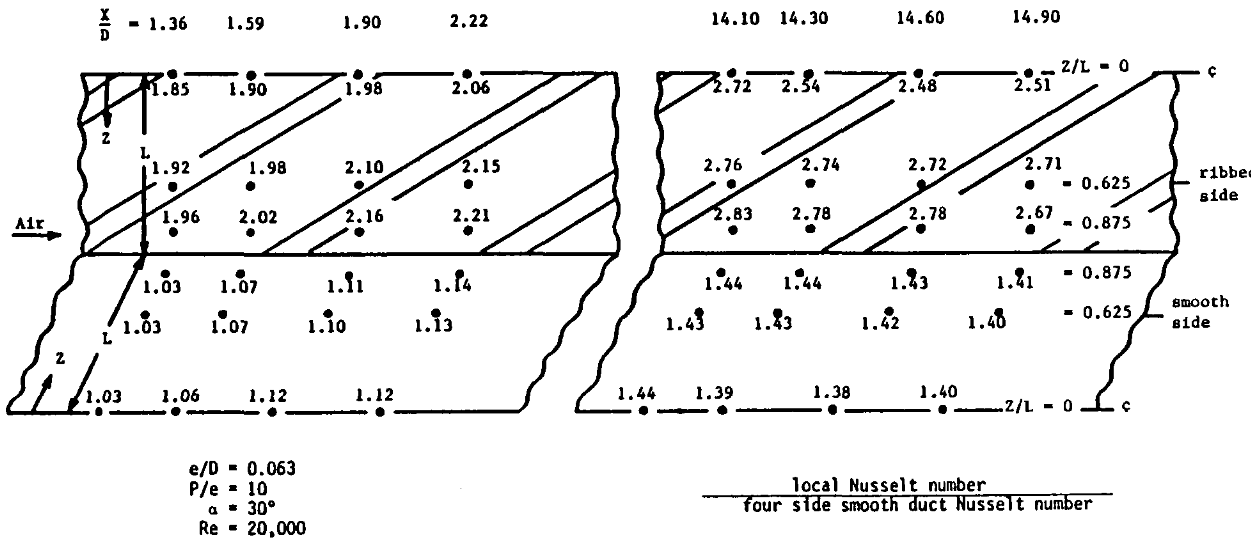



Figure 74. Local Nusselt number enhancement for α = 30°

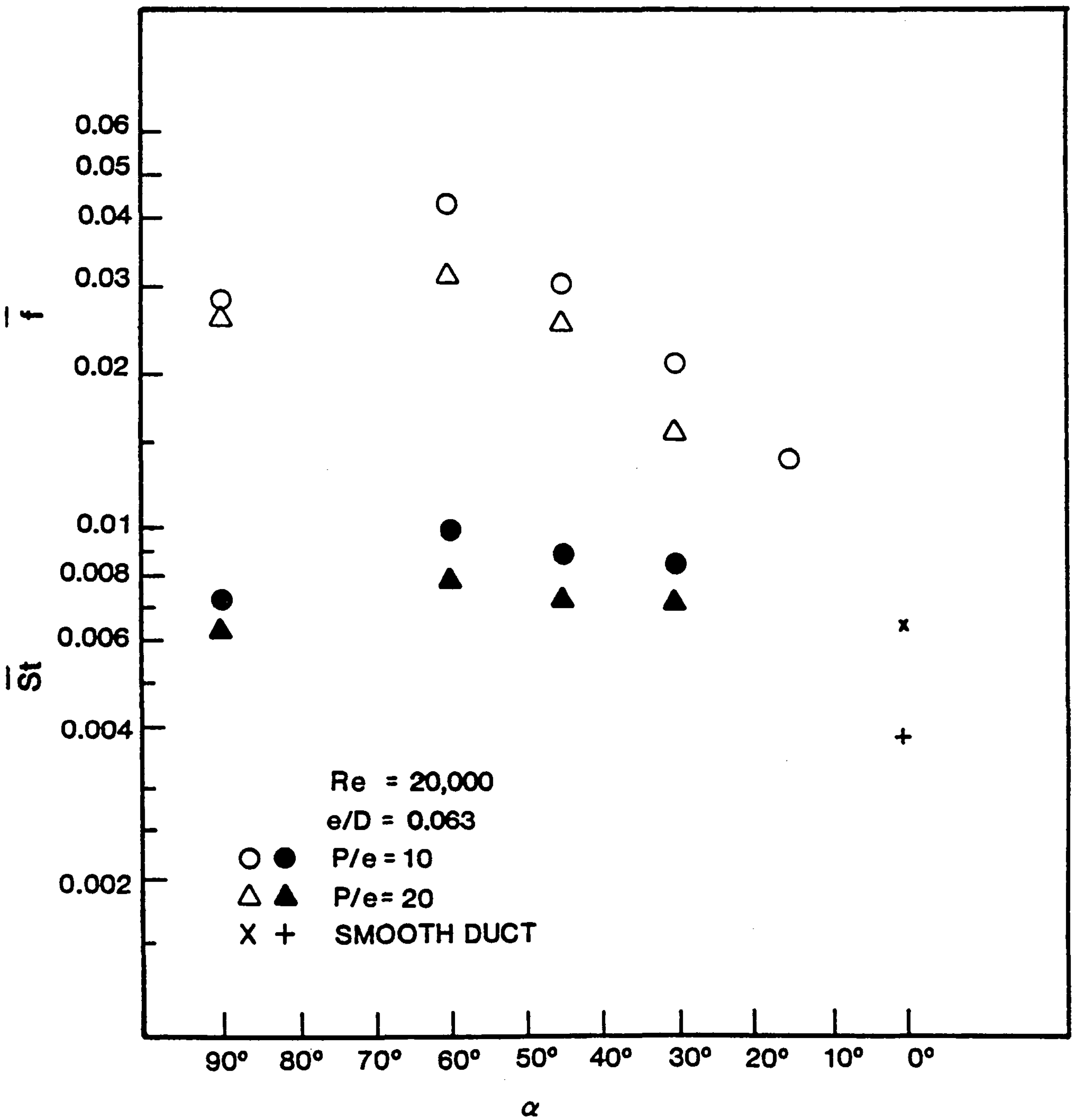



Figure 75. Friction and Stanton number vs α for Re = 20,000 (SCE)

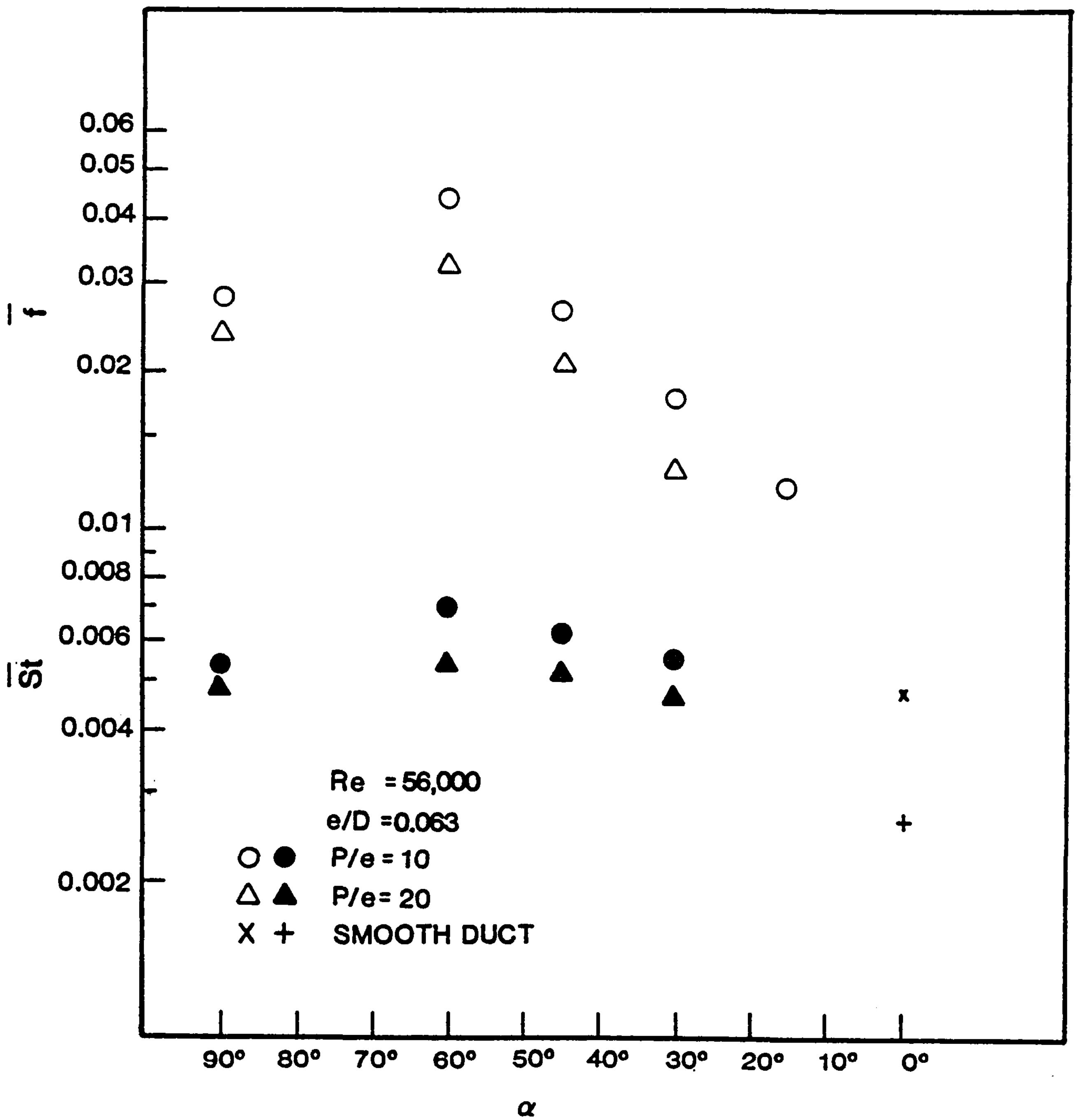



Figure 76. Friction and Stanton number vs α for Re = 56,000 (SCE)

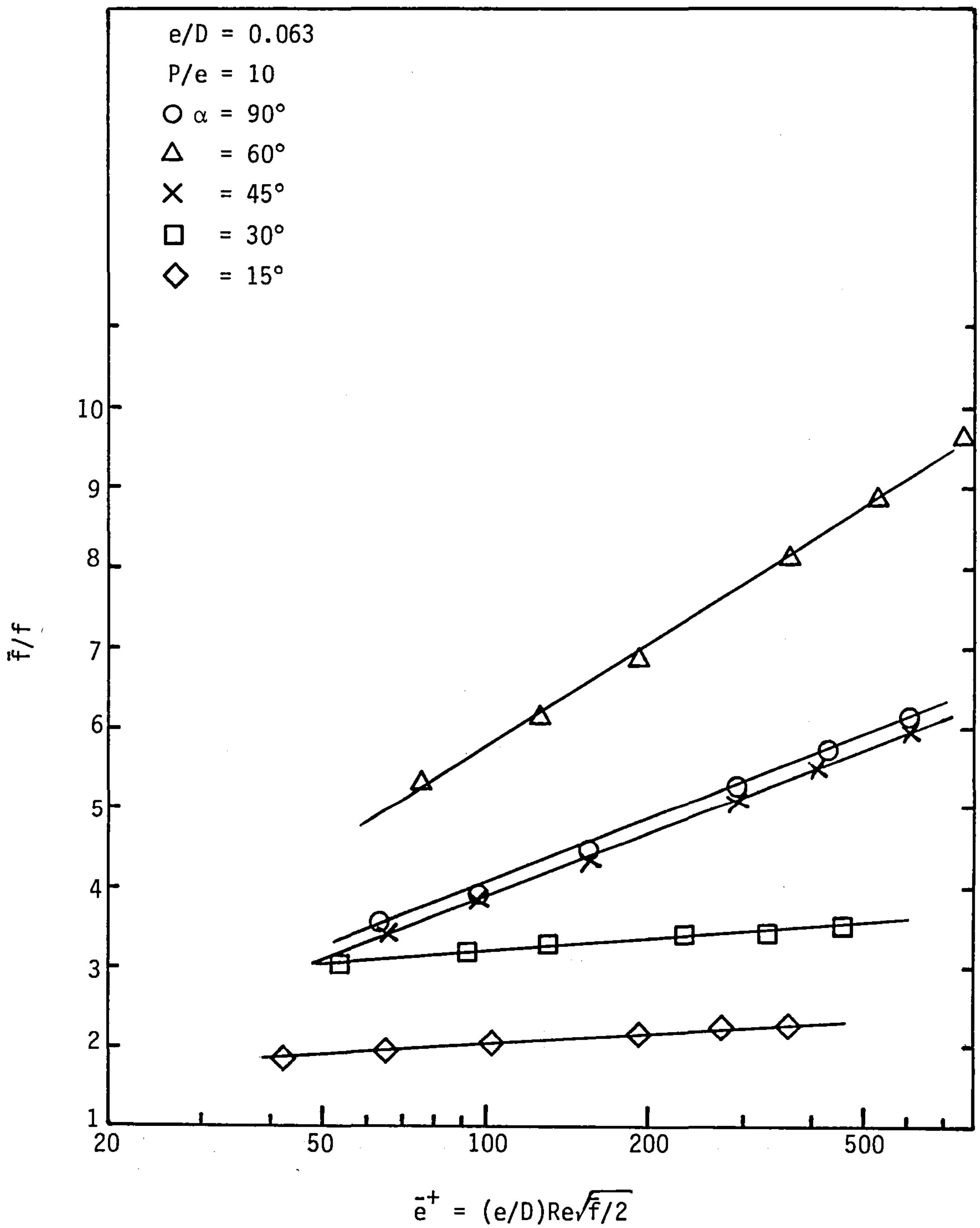



Figure 77. Increased friction factor with different α for P/e = 10 (SCE)

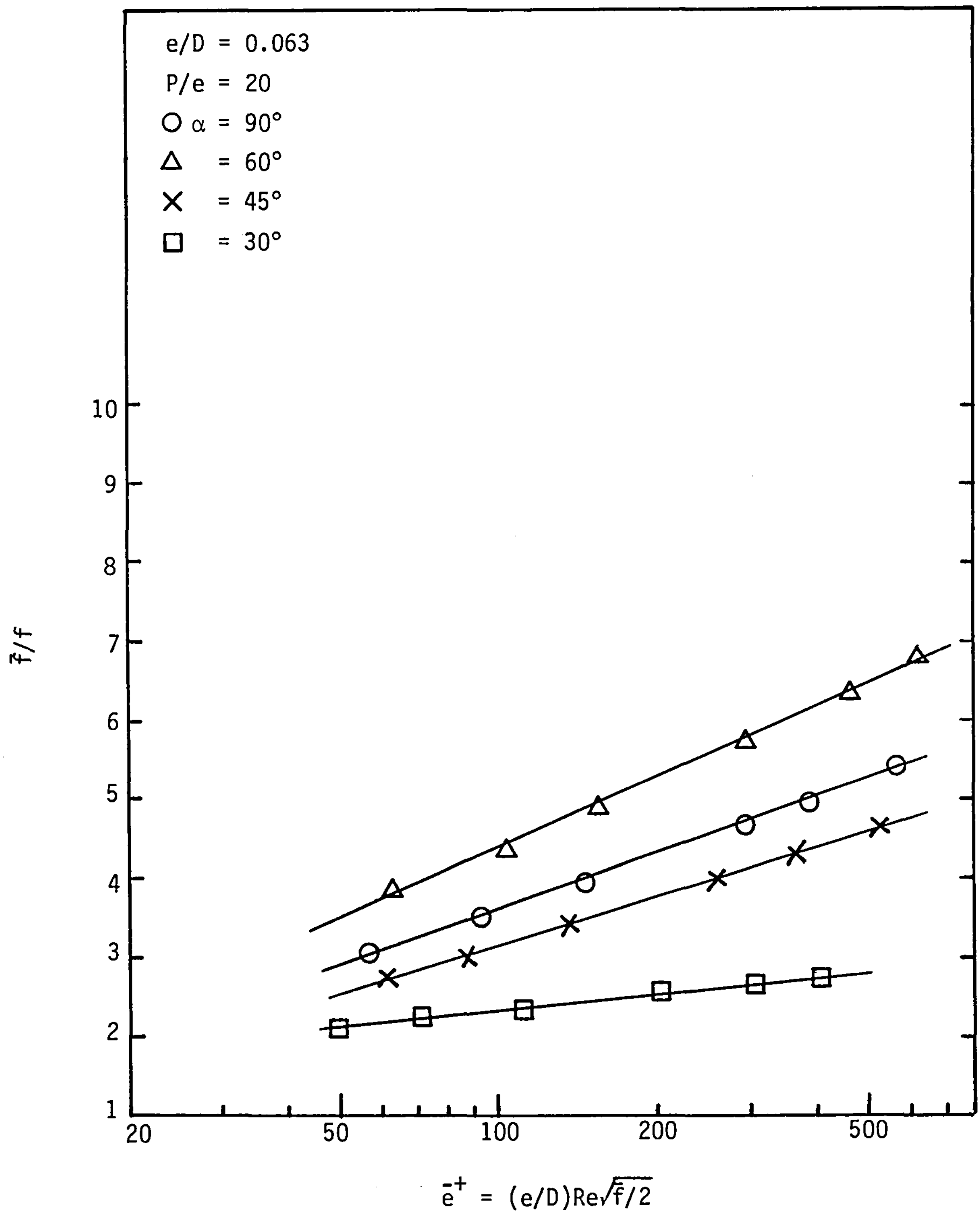



Figure 78. Increased friction factor with different α for P/e = 20 (SCE)

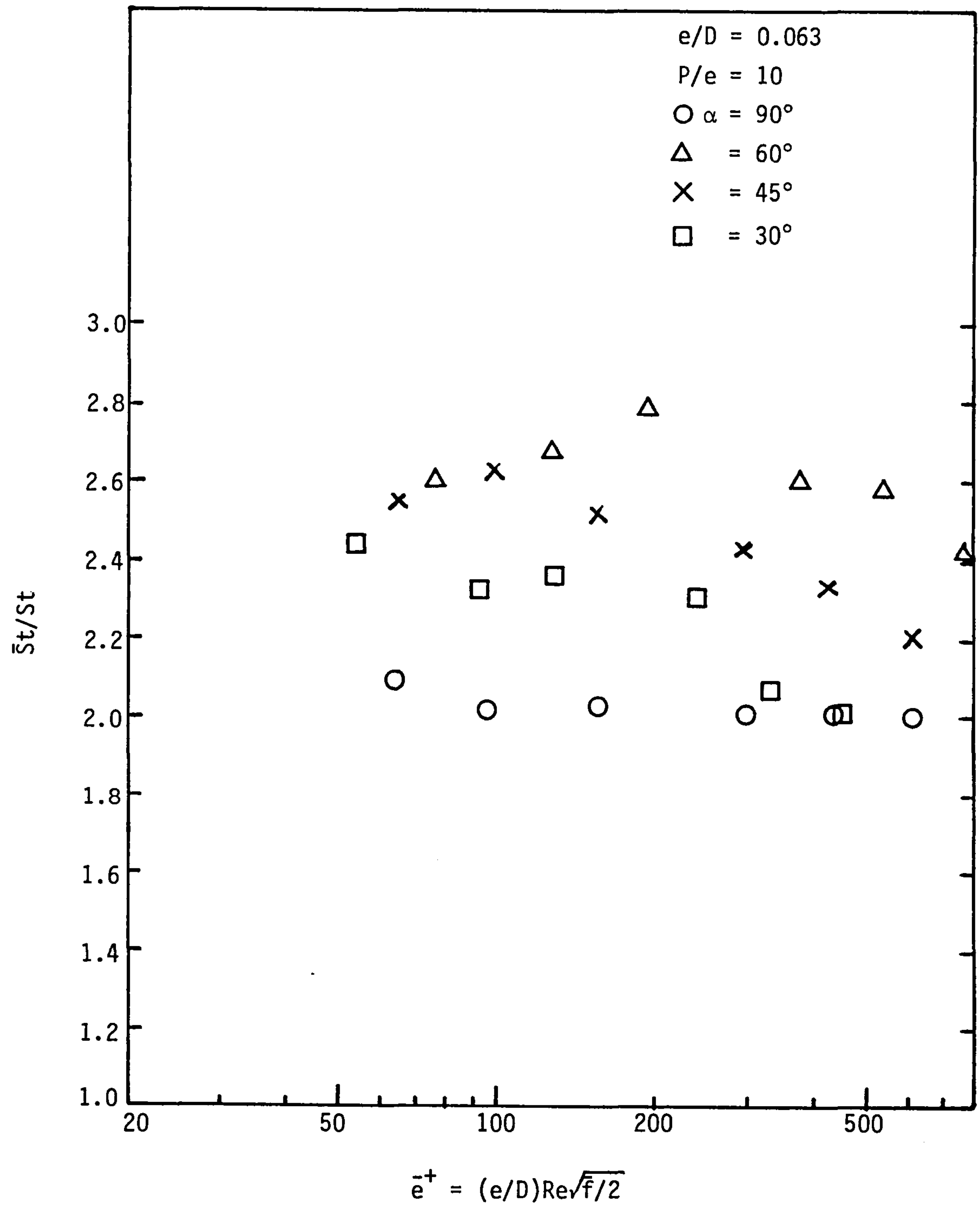



Figure 79. Increased Stanton number with different α for P/e = 10 (SCE)

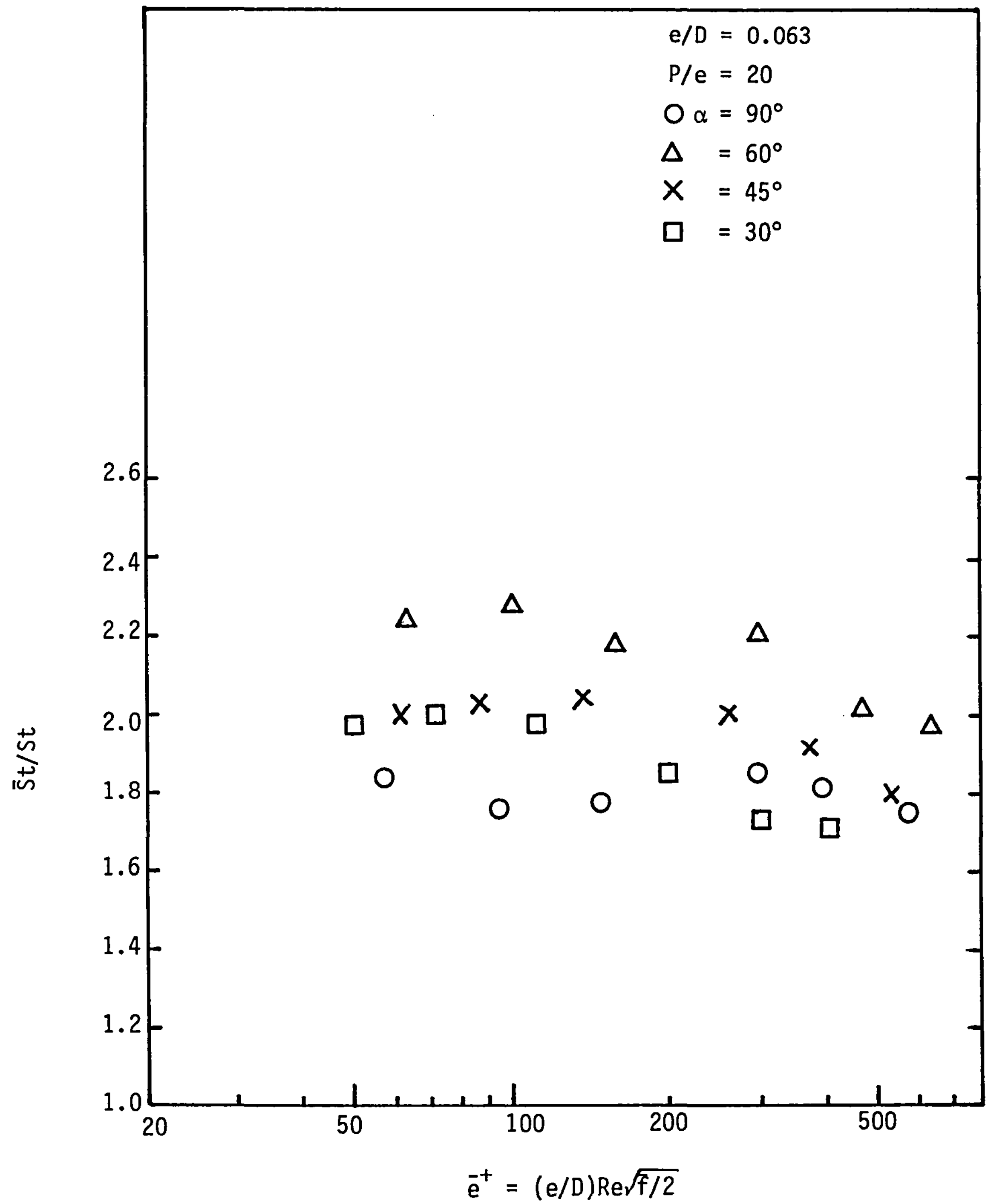



Figure 80. Increased Stanton number with different α for P/e = 20 (SCE)

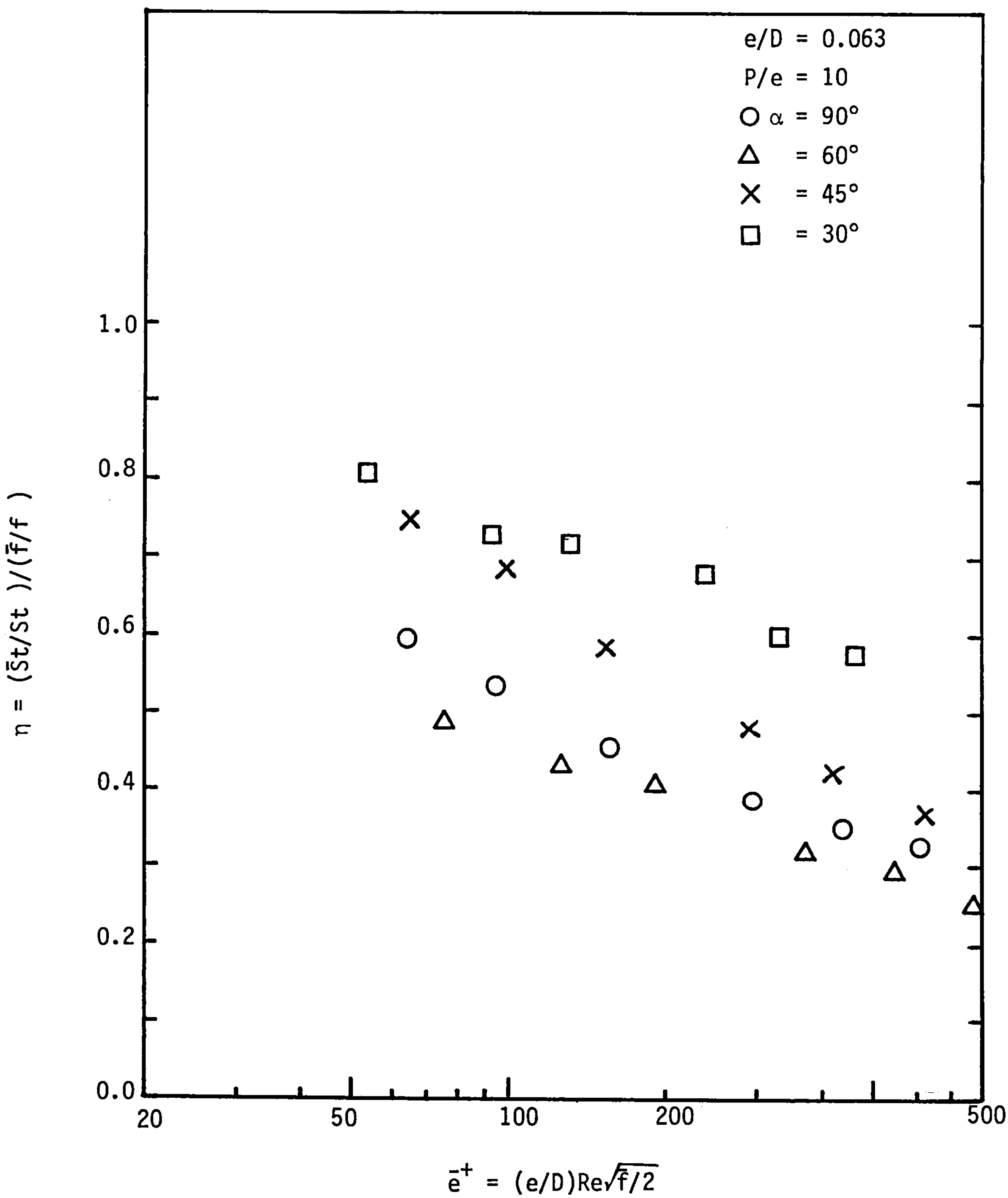



Figure 81. Efficiency index with different α for P/e = 10 (SCE)

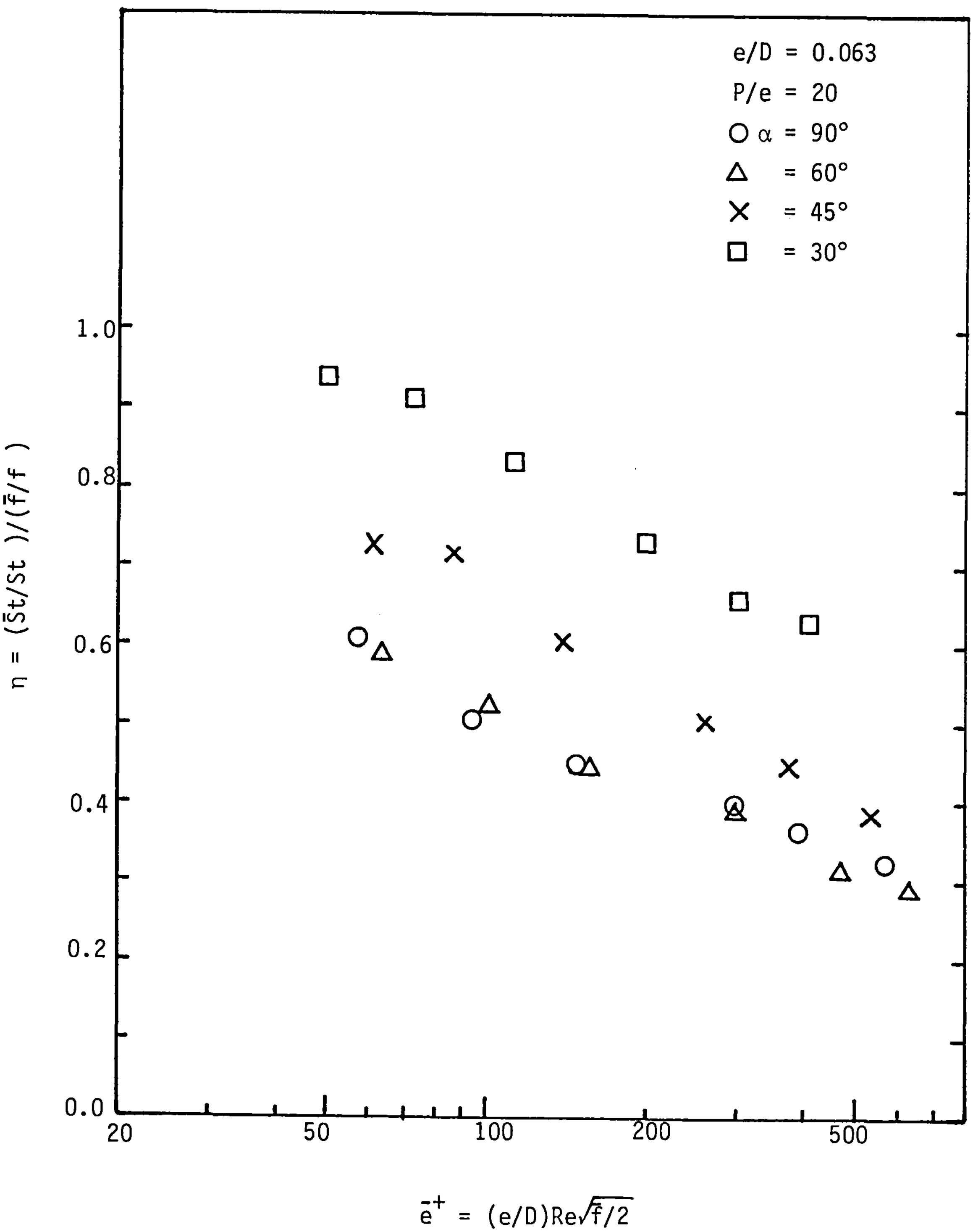



Figure 82. Efficiency index with different α for P/e = 20 (SCE)

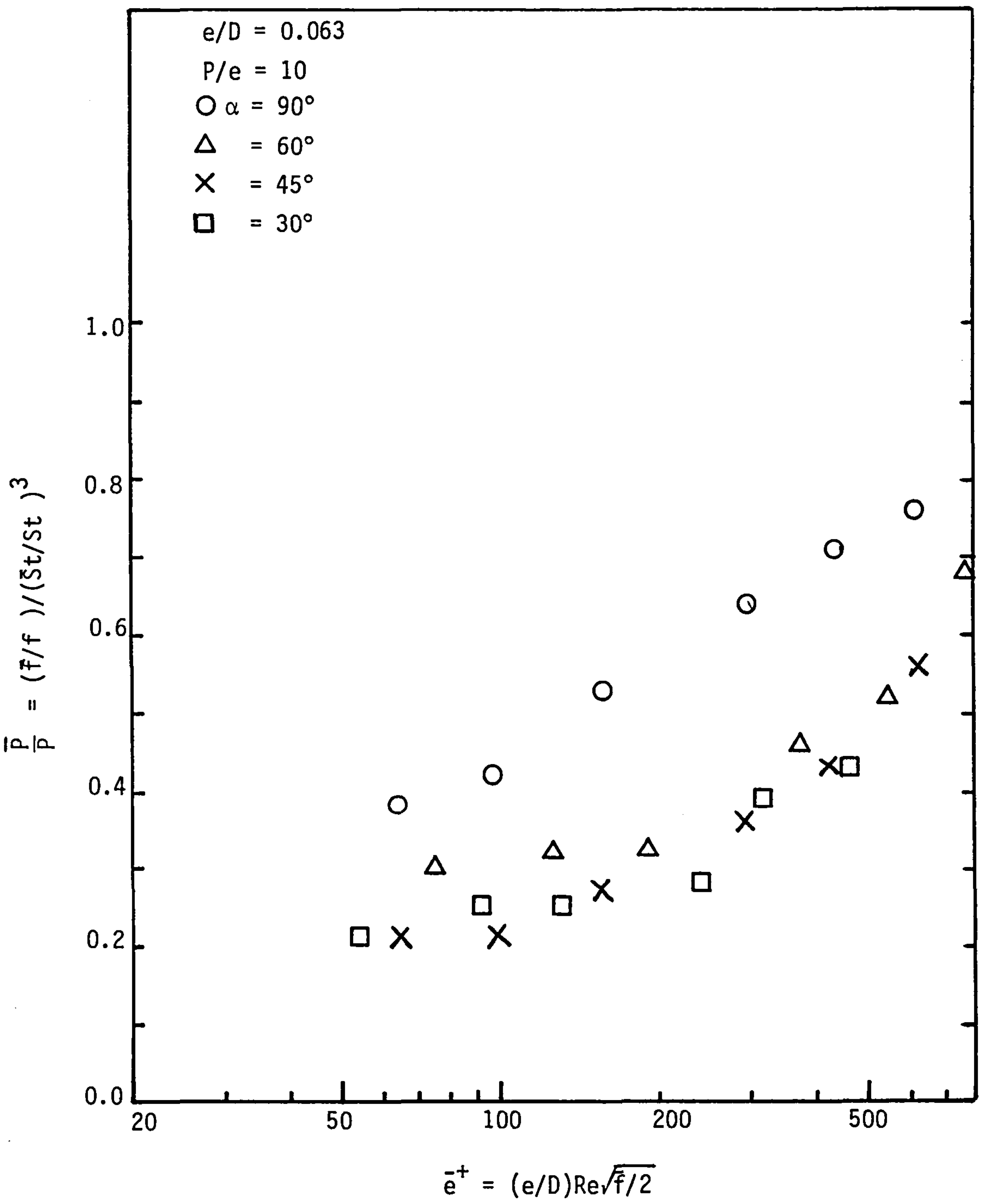



Figure 83. Reduced pumping power with different α for P/e = 10 (SCE)

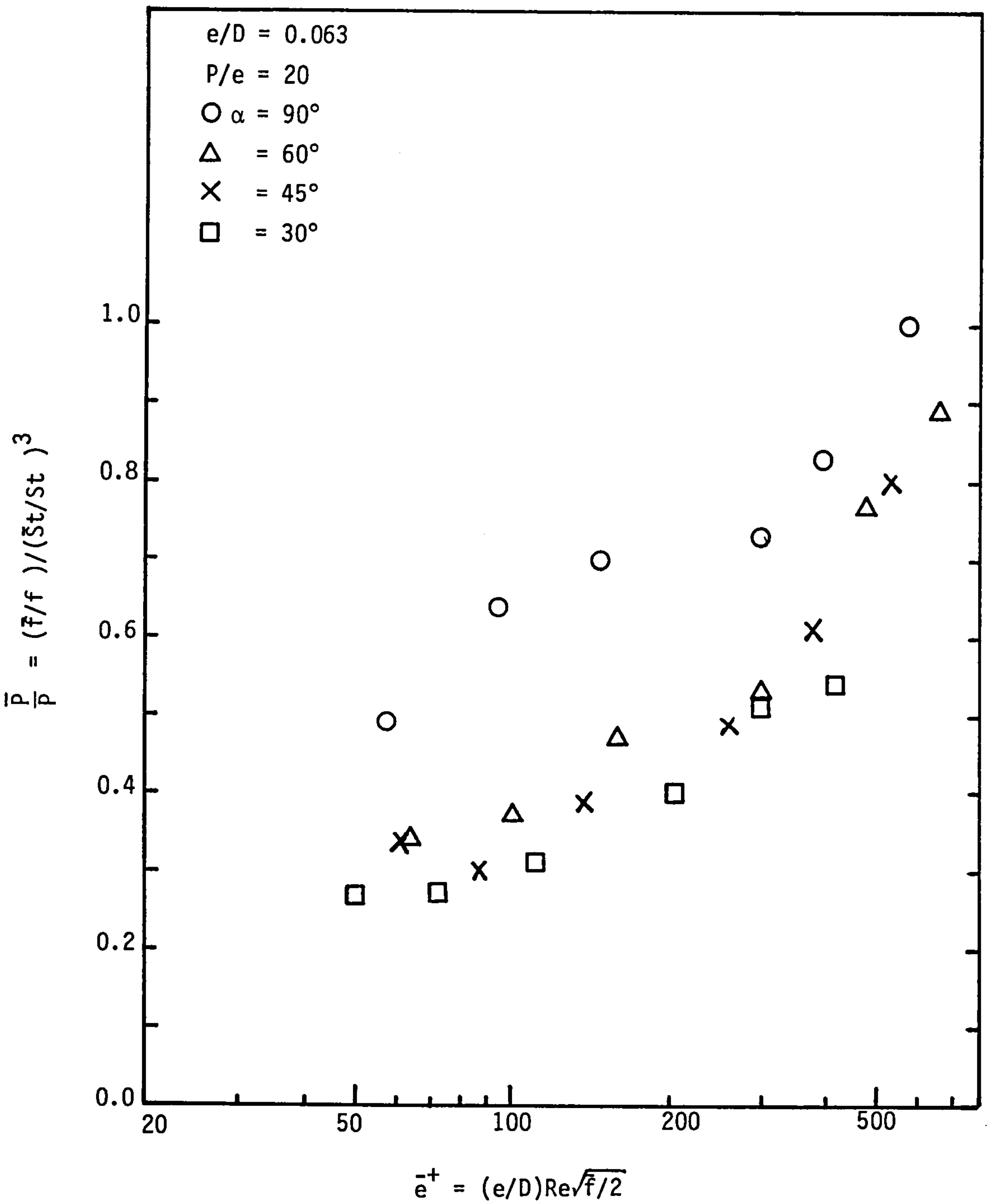



Figure 84. Reduced pumping power with different α for P/e = 20 (SCE)

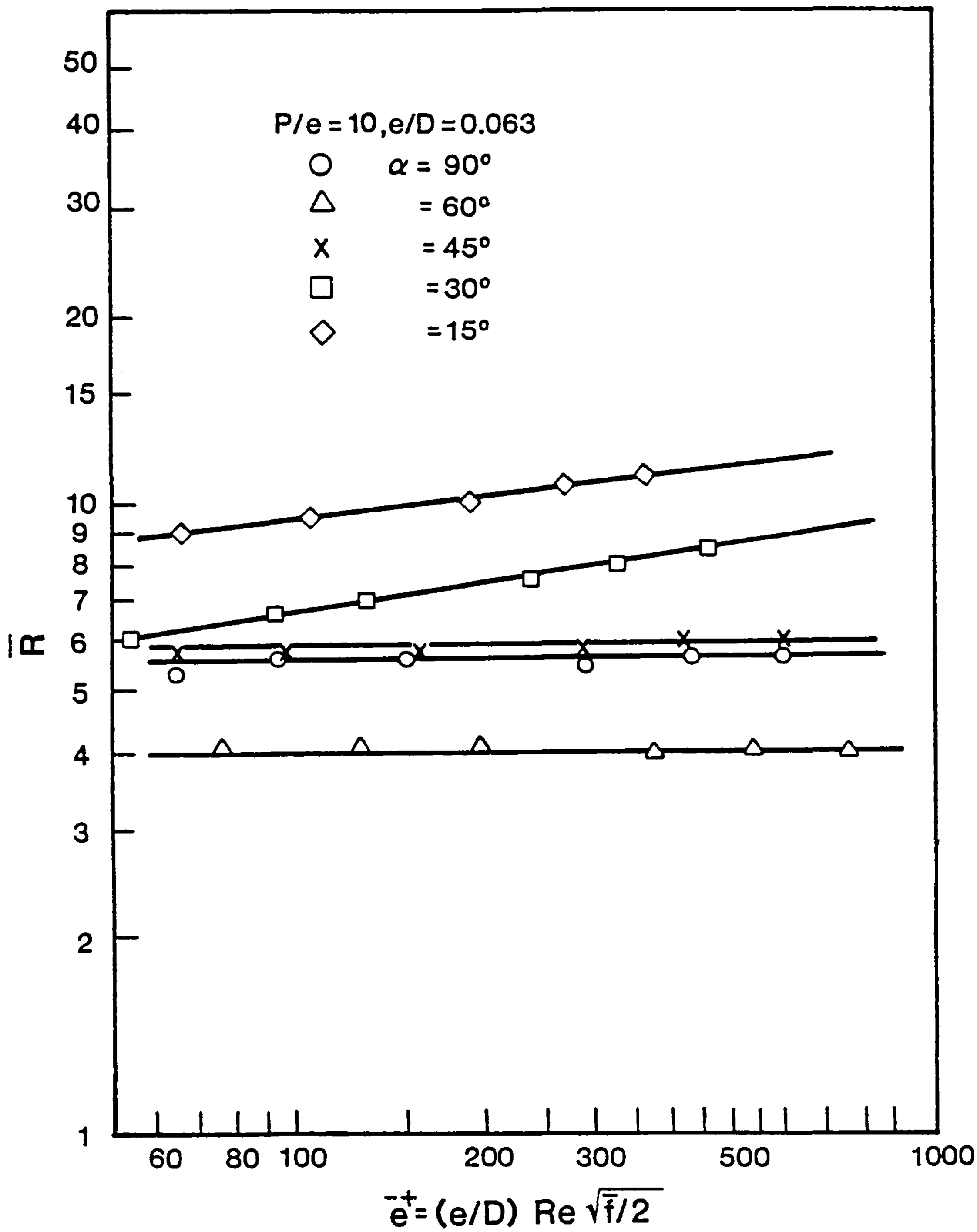



Figure 85. Momentum roughness function for P/e = 10 (SCE)

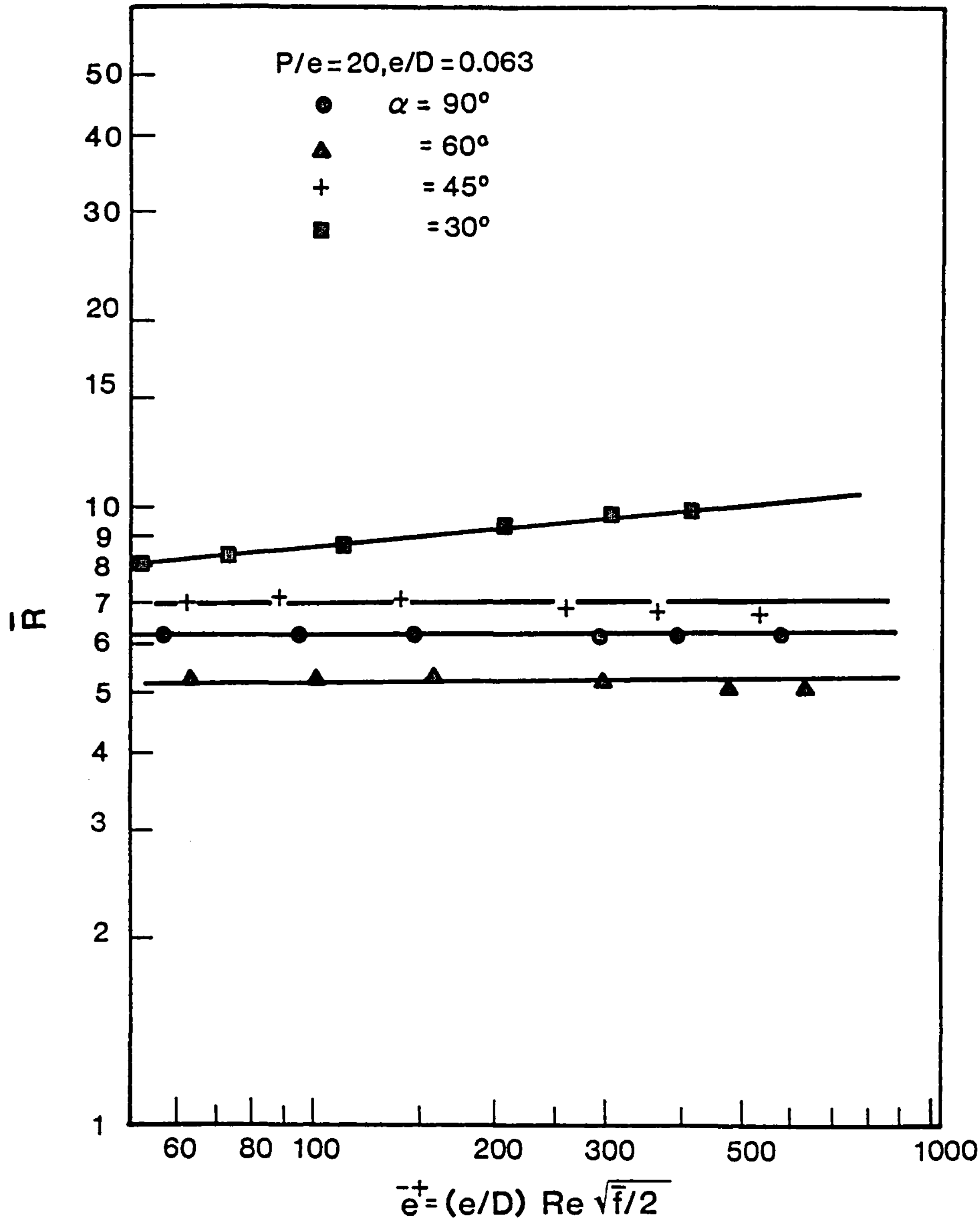



Figure 86. Momentum roughness function for P/e = 20 (SCE)

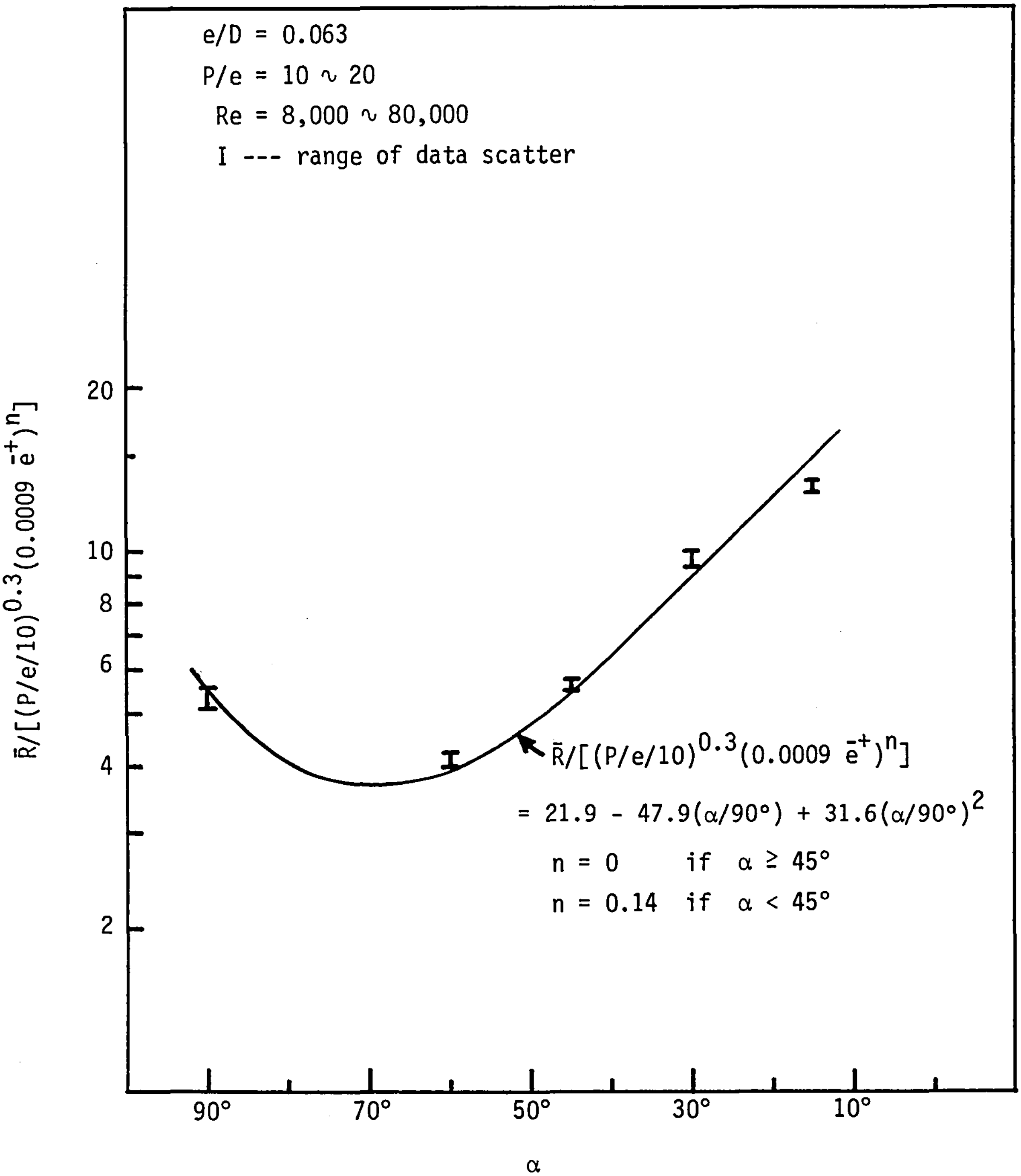



Figure 87. Average friction factor correlation (SCE)

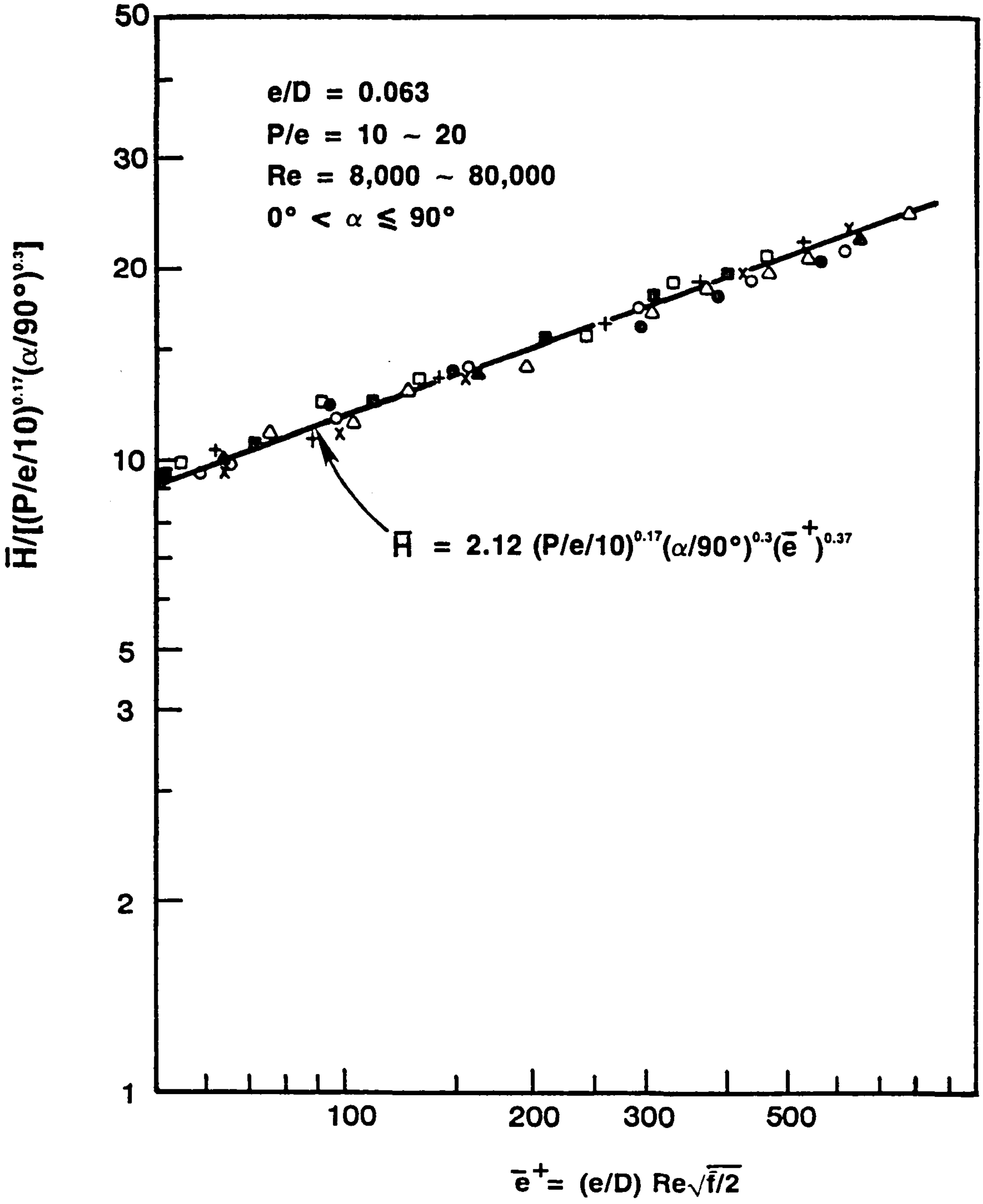



Figure 88. Heat transfer coefficients correlation (SCE)

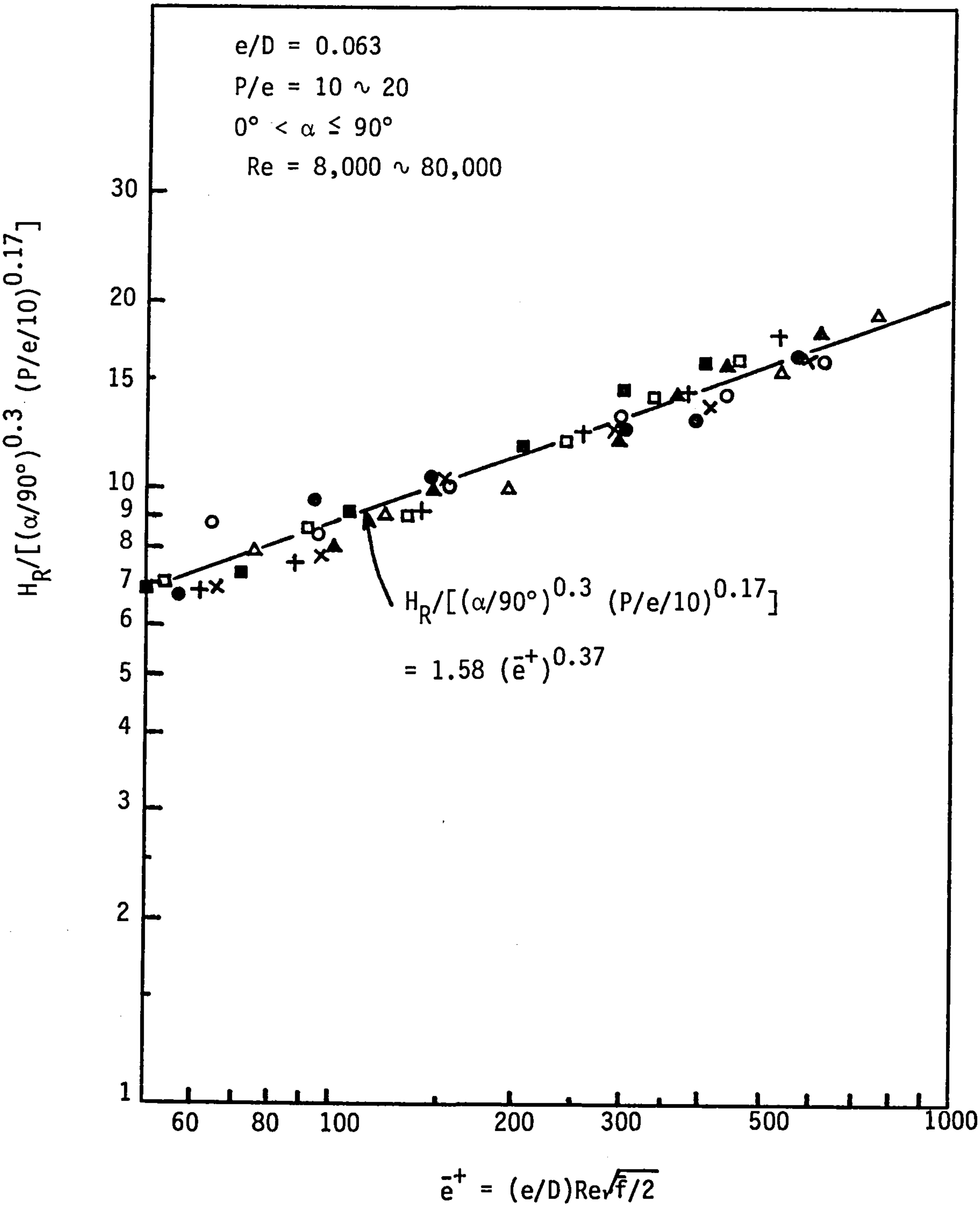



Figure 89. Ribbed side wall heat transfer correlation (SCE)

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

An experimental study of turbulent air flow in a square duct with two opposite rib-roughened walls has been performed. Two types of entrance conditions have been examined. The effect of rib angle-of-attack on the heat transfer coefficients and friction factor have been investigated. The following conclusions can be drawn:

1. Long duct entrance: For P/e = 10, the average Nusselt number of $\alpha = 90°$ is about 2 times higher than that the four sided smooth duct whereas the average friction factor is about 3 to 10 times higher. The average Nusselt number of $\alpha = 30°$ is about 5% higher than $\alpha = 90°$ while the average friction factor is about 20-45% lower. At $\alpha = 45°$ the average heat transfer is 25% greater than at $\alpha = 90°$, and the average friction factor remains the same. The results for P/e = 20 has the similar trends as those of P/e = 10, however, the friction and heat transfer enhancement are relatively reduced.
2. Sudden contraction entrance: For P/e = 10, the average Nusselt number of $\alpha = 90°$ is about 2 times higher than that the four sided smooth duct while the average friction factor is about 4-6 times higher. The average Nusselt number of $\alpha = 30°$ is about 20% higher than $\alpha = 90°$ while the average friction factor is about 20-45% lower. The ribs with an oblique angle to the flow ($\alpha = 30°$, $45°$, or $60°$) has a relatively higher heat transfer coefficients distribution (over shoot distribution) along the duct (after $X/D \geq 3$) than the ribs with a transverse angle to the

flow ($\alpha$ = 90°). The over shoot distribution is diminished when P/e = 20 or when the test section with a long duct entrance.

3. For both types of entrance conditions: The efficiency index for the $\alpha$ = 45° - 30° is about 30-50% higher than that the $\alpha$ = 90°, whereas the pumping power requirement (based on the same heat transfer duty and surface area) for the $\alpha$ = 45° - 30° is about 20-50% lower than that the $\alpha$ = 90°. The pumping power requirement for the P/e = 10 is about 20-30% lower than that the P/e = 20 for the same rib angle-of-attack. The conclusion is that the best thermal performance is achieved at angles-of-attack of 30° and 45° for both P/e ratios.
4. The thermal performance of this study is based on the average data of X/D = 2.85 to 16.81. The efficiency index (or the reduced pumping power) for sudden contraction entrance is higher than that for long duct entrance under the same flow rate and rib geometry. The sudden contraction entrance from the plenum causes a relatively higher heat transfer in the duct ($X/D \geq 3$), simultaneously it also creates a higher pressure drop at the entrance region ($X/D \approx 0$) which was not taken into account for comparison in this study.
5. Correlations for the average friction factor, the average heat transfer, and the ribbed-side-wall heat transfer have been obtained to account for P/e, $\alpha$, and $\bar{e}^+$ for both types of entrance conditions. The correlations can be used for turbine blade internal cooling design.

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# 7.0 APPENDIX

## 7.1 Tabulated Data for Long Entrance Duct

| | Re | $\dot{m}$ (kg/sec) | $\Delta P$ (cm $H_2O$) | $\bar{f} \times 10^3$ |
|---|---|---|---|---|
| Four sided smooth | 83,000 | 0.1155 | 0.6802 | 4.773 |
| | 81,000 | 0.1120 | 0.6436 | 4.842 |
| | 74,000 | 0.1029 | 0.5532 | 4.912 |
| | 71,000 | 0.0991 | 0.5177 | 4.923 |
| | 62,000 | 0.0860 | 0.4059 | 5.121 |
| | 55,000 | 0.0758 | 0.3272 | 5.382 |
| | 50,000 | 0.0690 | 0.2764 | 5.459 |
| | 42,000 | 0.0587 | 0.2144 | 5.743 |
| | 32,000 | 0.0440 | 0.1255 | 5.959 |
| | 21,000 | 0.0287 | 0.0569 | 6.353 |
| | 15,000 | 0.0208 | 0.0325 | 6.971 |
| | 15,000 | 0.0206 | 0.0305 | 6.472 |
| | 11,000 | 0.0160 | 0.0193 | 6.683 |
| | 8,500 | 0.01202 | 0.0117 | 7.286 |
| | 7,200 | 0.0100 | 0.0071 | 6.790 |
| | 5,800 | 0.0082 | 0.0051 | 6.815 |

| | Re | $\dot{m}$ (kg/sec) | $\Delta P$ (cm $H_2O$) | $\bar{f} \times 10^3$ |
|---|---|---|---|---|
| P/e = 10, α = 90°, e/D = 0.063 | 76,000 | 0.1070 | 3.5865 | 31.10 |
| | 69,000 | 0.0982 | 2.9413 | 30.94 |
| | 62,000 | 0.0877 | 2.3927 | 31.15 |
| | 58,000 | 0.0820 | 2.0853 | 31.51 |
| | 54,000 | 0.0758 | 1.7882 | 31.54 |
| | 49,000 | 0.0693 | 1.4732 | 31.24 |
| | 44,000 | 0.0620 | 1.1913 | 31.37 |
| | 38,000 | 0.0538 | 0.8865 | 30.98 |
| | 31,000 | 0.0440 | 0.6071 | 31.75 |
| | 22,000 | 0.0314 | 0.3150 | 32.22 |
| | 17,000 | 0.0239 | 0.1803 | 31.83 |
| | 15,000 | 0.0213 | 0.1463 | 32.33 |
| | 12,000 | 0.0164 | 0.0889 | 33.14 |
| | 8,900 | 0.0127 | 0.0559 | 34.61 |
| | 5,700 | 0.0081 | 0.0229 | 35.38 |

| | Re | $\dot{m}$ (kg/sec) | $\Delta P$ (cm $H_2O$) | $\bar{f} \times 10^3$ |
|---|---|---|---|---|
| P/e = 10, α = 75°, e/D = 0.063 | 76,000 | 0.1077 | 5.4966 | 47.67 |
| | 69,000 | 0.0981 | 4.5314 | 47.33 |
| | 62,000 | 0.0876 | 3.5966 | 47.11 |
| | 53,000 | 0.0758 | 2.6772 | 46.87 |
| | 43,000 | 0.0619 | 1.7719 | 46.40 |
| | 31,000 | 0.0438 | 0.8941 | 46.49 |
| | 21,000 | 0.0298 | 0.4115 | 45.99 |
| | 18,000 | 0.0253 | 0.2934 | 45.38 |
| | 16,000 | 0.0233 | 0.2438 | 44.69 |
| | 11,000 | 0.0161 | 0.1118 | 42.59 |
| | 6,900 | 0.0100 | 0.0356 | 34.88 |

| | Re | $\dot{m}$ (kg/sec) | $\Delta P$ (cm $H_2O$) | $\bar{f} \times 10^3$ |
|---|---|---|---|---|
| P/e = 10, α = 60°, e/D = 0.063 | 75,000 | 0.1066 | 5.2654 | 46.18 |
| | 68,000 | 0.0972 | 4.3104 | 45.49 |
| | 61,000 | 0.0868 | 3.3934 | 44.88 |
| | 52,000 | 0.0749 | 2.5248 | 44.59 |
| | 43,000 | 0.0612 | 1.6993 | 44.82 |
| | 30,000 | 0.0434 | 0.8585 | 44.71 |
| | 21,000 | 0.0298 | 0.4280 | 46.51 |
| | 17,000 | 0.0247 | 0.3048 | 47.58 |
| | 16,000 | 0.0230 | 0.2654 | 47.41 |
| | 11,000 | 0.0163 | 0.1422 | 48.30 |
| | 6,500 | 0.0094 | 0.0584 | 53.26 |

| | Re | $\dot{m}$ (kg/sec) | $\Delta P$ (cm $H_2O$) | $\bar{f} \times 10^3$ |
|---|---|---|---|---|
| P/e = 10, α = 45°, e/D = 0.063 | 86,000 | 0.1213 | 4.4196 | 30.79 |
| | 77,000 | 0.1080 | 3.5230 | 30.82 |
| | 70,000 | 0.0985 | 2.9134 | 30.69 |
| | 54,000 | 0.0760 | 1.7678 | 31.18 |
| | 44,000 | 0.0621 | 1.1608 | 30.63 |
| | 38,000 | 0.0538 | 0.8890 | 30.81 |
| | 31,000 | 0.0441 | 0.6071 | 31.78 |
| | 22,000 | 0.0313 | 0.2850 | 31.49 |
| | 19,000 | 0.0272 | 0.2464 | 33.68 |
| | 16,000 | 0.0233 | 0.1854 | 34.54 |
| | 12,000 | 0.0168 | 0.0991 | 35.14 |
| | 7,700 | 0.0109 | 0.0419 | 35.48 |

| | Re | $\dot{m}$ (kg/sec) | $\Delta P$ (cm $H_2O$) | $\bar{f} \times 10^3$ |
|---|---|---|---|---|
| P/e = 10, α = 30°, e/D = 0.063 | 89,000 | 0.1249 | 2.5502 | 16.67 |
| | 76,000 | 0.1077 | 1.9482 | 17.09 |
| | 69,000 | 0.0982 | 1.6510 | 17.41 |
| | 62,000 | 0.0877 | 1.3320 | 17.61 |
| | 54,000 | 0.0759 | 1.0363 | 18.27 |
| | 44,000 | 0.0620 | 0.7112 | 18.74 |
| | 31,000 | 0.0440 | 0.3937 | 20.50 |
| | 22,000 | 0.0313 | 0.2184 | 22.32 |
| | 19,000 | 0.0274 | 0.1676 | 22.26 |
| | 13,000 | 0.0186 | 0.0864 | 24.52 |
| | 7,500 | 0.0107 | 0.0356 | 29.26 |

| | Re | $\dot{m}$ (kg/sec) | $\Delta P$ (cm $H_2O$) | $\bar{f} \times 10^3$ |
|---|---|---|---|---|
| P/e = 10, α = 15°, e/D = 0.063 | 88,000 | 0.1245 | 1.6281 | 10.61 |
| | 76,000 | 0.1075 | 1.2395 | 10.83 |
| | 69,000 | 0.0980 | 1.0770 | 11.32 |
| | 62,000 | 0.0875 | 0.8661 | 11.41 |
| | 53,000 | 0.0757 | 0.6223 | 10.84 |
| | 44,000 | 0.0618 | 0.4674 | 12.29 |
| | 31,000 | 0.0438 | 0.2565 | 13.37 |
| | 21,000 | 0.0297 | 0.1270 | 14.31 |
| | 17,000 | 0.0250 | 0.0965 | 15.30 |
| | 12,000 | 0.0178 | 0.0546 | 17.00 |
| | 8,600 | 0.0124 | 0.0318 | 19.36 |
| | 6,900 | 0.0100 | 0.0216 | 21.21 |

| | Re | $\dot{m}$ (kg/sec) | $\Delta P$ (cm $H_2O$) | $\bar{f} \times 10^3$ |
|---|---|---|---|---|
| P/e = 20 | 83,000 | 0.1164 | 3.2080 | 23.26 |
| α = 90° | 73,000 | 0.1029 | 2.5248 | 23.38 |
| e/D = 0.063 | 62,000 | 0.0875 | 1.8161 | 23.24 |
| | 49,000 | 0.0691 | 1.1354 | 23.36 |
| | 44,000 | 0.0619 | 0.9017 | 23.12 |
| | 31,000 | 0.0439 | 0.4648 | 23.71 |
| | 16,000 | 0.0233 | 0.1245 | 23.38 |
| | 7,900 | 0.0112 | 0.0305 | 23.22 |
| P/e = 20 | 76,000 | 0.1075 | 3.65 | 31.73 |
| α = 75° | 69,000 | 0.0981 | 3.0315 | 31.71 |
| e/D = 0.063 | 53,000 | 0.0757 | 1.8059 | 31.65 |
| | 43,000 | 0.0618 | 1.1836 | 31.01 |
| | 31,000 | 0.0438 | 0.6007 | 31.23 |
| | 21,000 | 0.0302 | 0.2883 | 31.54 |
| | 17,000 | 0.0250 | 0.1994 | 31.54 |
| | 16,000 | 0.0235 | 0.1727 | 31.07 |
| | 11,000 | 0.0158 | 0.0787 | 31.17 |
| | 7,100 | 0.0103 | 0.0368 | 34.38 |
| P/e = 20 | 85,000 | 0.1207 | 3.2614 | 22.61 |
| α = 45° | 76,000 | 0.1076 | 2.6060 | 22.69 |
| e/D = 0.063 | 69,000 | 0.0981 | 2.1590 | 22.62 |
| | 62,000 | 0.0877 | 1.6967 | 22.28 |
| | 54,000 | 0.0758 | 1.2802 | 22.45 |
| | 44,000 | 0.0620 | 0.8331 | 21.86 |
| | 31,000 | 0.0440 | 0.4343 | 22.60 |
| | 19,000 | 0.0269 | 0.1702 | 23.41 |
| | 14,000 | 0.0198 | 0.0927 | 23.69 |
| | 7,200 | 0.0126 | 0.0267 | 24.94 |
| P/e = 20 | 86,000 | 0.1207 | 1.8618 | 12.92 |
| α = 30° | 83,000 | 0.1165 | 1.7348 | 12.93 |
| e/D = 0.063 | 77,000 | 0.1077 | 1.4986 | 13.07 |
| | 70,000 | 0.0981 | 1.2598 | 13.27 |
| | 62,000 | 0.0877 | 1.0135 | 13.37 |
| | 54,000 | 0.0758 | 0.7849 | 13.88 |
| | 44,000 | 0.0620 | 0.5359 | 14.18 |
| | 31,000 | 0.0440 | 0.2870 | 15.32 |
| | 22,000 | 0.0313 | 0.1600 | 16.55 |
| | 14,000 | 0.0192 | 0.0660 | 18.03 |
| | 7,500 | 0.0107 | 0.0254 | 22.52 |
| P/e = 20 | 87,000 | 0.1239 | 1.3159 | 8.59 |
| α = 15° | 81,000 | 0.1159 | 1.1582 | 8.67 |
| e/D = 0.063 | 75,000 | 0.1070 | 1.0033 | 8.78 |
| | 68,000 | 0.0975 | 0.8585 | 9.04 |
| | 61,000 | 0.0871 | 0.6477 | 8.54 |
| | 53,000 | 0.0754 | 0.5385 | 9.44 |
| | 43,000 | 0.0616 | 0.3785 | 9.96 |
| | 31,000 | 0.0437 | 0.0232 | 10.34 |
| | 21,000 | 0.0297 | 0.1016 | 11.44 |
| | 15,000 | 0.0210 | 0.0559 | 12.60 |
| | 9,600 | 0.0138 | 0.0254 | 13.21 |
| | 7,400 | 0.0107 | 0.0178 | 15.56 |

## At X/D = 11.5

P/e = 10, α = 90° e/D = 0.063

| Re | $\dot{m}$ (kg/sec) | $\bar{T}_w(R)$ (°C) | $\bar{T}_w(S)$ (°C) | $T_b$ (°C) | $\dot{q}''(R)$ ($W/m^2$) | $\dot{q}''(S)$ ($W/m^2$) | Nu(R) | Nu(S) | Nu(AV) | St(AV) x $10^5$ | $\bar{e}^+$ | $\bar{St}/St$ | $\bar{f}/f$ | η | $\bar{P}/P$ | $\bar{R}$ | $\bar{H}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 71,390 | 0.1021 | 57.2 | 57.0 | 33.1 | 2873 | 1853 | 339.6 | 221.1 | 280.4 | 552 | 555.5 | 2.2 | 6.7 | 0.33 | 0.63 | 5.35 | 19.87 |
| 61,405 | 0.0879 | 55.6 | 55.2 | 32.8 | 2335 | 1426 | 292.9 | 182.0 | 237.5 | 548 | 481.6 | 2.1 | 6.5 | 0.32 | 0.70 | 5.35 | 20.04 |
| 30,771 | 0.0440 | 51.0 | 50.2 | 32.9 | 1141 | 599 | 180.3 | 99.0 | 139.7 | 643 | 242.5 | 2.02 | 5.7 | 0.35 | 0.69 | 5.35 | 16.68 |
| 21,452 | 0.0308 | 53.0 | 52.3 | 34.1 | 888 | 475 | 133.6 | 73.9 | 103.8 | 686 | 170.9 | 1.93 | 5.16 | 0.37 | 0.72 | 5.23 | 15.76 |
| 16,544 | 0.0239 | 54.6 | 54.2 | 35.6 | 737 | 418 | 109.3 | 63.5 | 86.4 | 740 | | | | | | 5.23 | 14.42 |
| 10,173 | 0.0148 | 56.8 | 56.2 | 38.1 | 535 | 268 | 80.1 | 41.6 | 60.9 | 847 | 82.7 | 1.93 | 4.42 | 0.44 | 0.61 | 4.99 | 12.71 |
| 8,314 | 0.0121 | 54.6 | 54.2 | 38.3 | 365 | 185 | 62.6 | 32.6 | 47.6 | 813 | 67.8 | 1.75 | 4.32 | 0.41 | 0.78 | 4.88 | 13.59 |

P/e = 10, α = 75°, e/D = 0.063

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 75,534 | 0.1081 | 52.6 | 54.6 | 32.8 | 2873 | 1968 | 415.3 | 258.2 | 336.8 | 632 | 723.7 | 2.58 | 10.44 | 0.25 | 0.61 | 3.84 | 21.57 |
| 61,301 | 0.088 | 53.3 | 55.3 | 33.9 | 2464 | 1632 | 360.8 | 216.8 | 288.8 | 667 | 587.3 | 2.55 | 9.89 | 0.26 | 0.60 | 3.84 | 20.30 |
| 43,245 | 0.0622 | 54.4 | 56.1 | 34.8 | 1968 | 1233 | 284.4 | 164.2 | 224.3 | 735 | 412.1 | 2.53 | 8.85 | 0.29 | 0.53 | 3.84 | 18.17 |
| 20,982 | 0.0305 | 59.5 | 61.2 | 39.1 | 1233 | 811 | 168.7 | 102.5 | 135.6 | 916 | 196.9 | 2.58 | 7.42 | 0.35 | 0.43 | 3.92 | 13.88 |
| 10,235 | 0.015 | 60.6 | 61.5 | 42.4 | 666 | 418 | 101.8 | 60.7 | 81.3 | 1125 | 94.4 | 2.59 | 5.58 | 0.46 | 0.32 | 3.99 | 9.97 |
| 6,281 | 0.0092 | 60.0 | 60.1 | 43.4 | 418 | 225 | 69.7 | 37.3 | 53.5 | 1206 | 57.2 | 2.39 | 4.61 | 0.52 | 0.34 | 4.88 | 8.29 |

P/e = 10, α = 60°, e/D = 0.063

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 74,689 | 0.1072 | 55.4 | 55.9 | 34.2 | 2873 | 1968 | 383.9 | 256.9 | 320.4 | 608 | 711.8 | 2.48 | 10.15 | 0.24 | 0.67 | 3.92 | 22.27 |
| 60,703 | 0.0873 | 55.6 | 56.1 | 34.7 | 2464 | 1632 | 333. | 216.0 | 274.5 | 641 | 570.4 | 2.45 | 9.79 | 0.25 | 0.67 | 3.99 | 20.72 |
| 42,694 | 0.0616 | 56.9 | 57.0 | 35.8 | 1968 | 1233 | 263.6 | 164.3 | 214.0 | 710 | 405.6 | 2.45 | 8.94 | 0.27 | 0.61 | 3.99 | 18.45 |
| 20,569 | 0.0300 | 62.9 | 62.7 | 40.5 | 1328 | 811 | 165.5 | 102.0 | 133.8 | 922 | 198.1 | 2.60 | 7.58 | 0.34 | 0.43 | 3.92 | 13.77 |
| 10,567 | 0.0156 | 64.1 | 63.4 | 43.4 | 811 | 418 | 108.6 | 57.9 | 83.3 | 1113 | 102.8 | 2.56 | 6.45 | 0.40 | 0.38 | 3.78 | 11.24 |
| 6,385 | 0.0094 | 65.9 | 64.6 | 45.4 | 599 | 268 | 80.5 | 38.4 | 59.5 | 1323 | 62.8 | 2.65 | 6.02 | 0.44 | 0.32 | 3.41 | 9.57 |

P/e = 10, α = 45°, e/D = 0.063

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 71,729 | 0.1025 | 53.9 | 53.8 | 32.5 | 2873 | 1853 | 383.6 | 248.5 | 316.1 | 625 | 550.9 | 2.5 | 6.74 | 0.37 | 0.43 | 5.35 | 17.24 |
| 61,653 | 0.088 | 52.6 | 52.0 | 32.0 | 2335 | 1426 | 323.5 | 204.0 | 263.8 | 607 | 475.8 | 2.33 | 6.53 | 0.36 | 0.52 | 5.35 | 17.83 |
| 52,457 | 0.0759 | 56.9 | 57.9 | 36.8 | 2087 | 1527 | 291.2 | 203.3 | 247.3 | 668 | 408.2 | 2.43 | 6.33 | 0.38 | 0.44 | 5.35 | 15.96 |
| 30,965 | 0.0442 | 48.1 | 47.2 | 32.1 | 1141 | 599 | 204.8 | 113.8 | 159.3 | 729 | 242.9 | 2.28 | 5.71 | 0.40 | 0.48 | 5.23 | 14.68 |
| 30,177 | 0.0440 | 61.3 | 62.4 | 40.0 | 1527 | 1054 | 195.9 | 128.8 | 162.4 | 763 | 238.9 | 2.38 | 5.61 | 0.42 | 0.42 | 5.23 | 13.90 |
| 21,150 | 0.0311 | 66.1 | 65.9 | 43.7 | 1328 | 811 | 164.0 | 100.7 | 132.4 | 886 | 170.1 | 2.50 | 5.16 | 0.48 | 0.33 | 5.23 | 11.60 |
| 6,571 | 0.0098 | 72.5 | 72.4 | 49.9 | 666 | 365 | 80.4 | 44.2 | 62.3 | 1342 | 55.1 | 2.68 | 4.09 | 0.66 | 0.21 | 4.88 | 10.87 |

P/e = 10, α = 30°, e/D = 0.063

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 83,719 | 0.1205 | 60.7 | 60.7 | 35.1 | 3016 | 2210 | 332.8 | 244.6 | 288.7 | 488 | 478.8 | 2.05 | 3.82 | 0.54 | 0.44 | 8.17 | 16.22 |
| 74,439 | 0.1073 | 60.5 | 60.6 | 35.5 | 2733 | 1968 | 309.4 | 221.6 | 265.5 | 506 | 432.1 | 2.07 | 3.8 | 0.54 | 0.43 | 8.01 | 15.81 |
| 52,257 | 0.0756 | 60.9 | 60.7 | 36.7 | 2087 | 1426 | 243.2 | 167.0 | 205.1 | 557 | 309.8 | 2.03 | 3.74 | 0.54 | 0.45 | 7.86 | 14.73 |
| 42,625 | 0.0617 | 59.7 | 59.5 | 37.2 | 1741 | 1141 | 217.1 | 144.0 | 180.6 | 601 | 261.4 | 2.15 | 3.65 | 0.59 | 0.37 | 7.58 | 13.88 |
| 17,027 | 0.0252 | 62.7 | 62.5 | 40.9 | 969 | 535 | 123.6 | 69.0 | 96.3 | 802 | 115.8 | 2.11 | 3.56 | 0.59 | 0.38 | 6.55 | 10.84 |
| 13,464 | 0.0200 | 59.5 | 59.0 | 40.8 | 737 | 365 | 108.5 | 52.3 | 80.4 | 861 | 93.5 | 2.13 | 3.5 | 0.61 | 0.36 | 6.36 | 10.18 |
| 9,637 | 0.0141 | 59.8 | 58.8 | 41.6 | 599 | 268 | 91.5 | 43.4 | 67.5 | 989 | 69.6 | 2.22 | 3.46 | 0.64 | 0.32 | 5.93 | 9.07 |

At X/D = 11.5

P/e = 20, α = 90°, e/D = 0.063

| Re | $\dot{m}$ (kg/sec) | $\bar{T}_w(R)$ (°C) | $\bar{T}_w(S)$ (°C) | $T_b$ (°C) | $\dot{q}''(R)$ ($W/m^2$) | $\dot{q}''(S)$ ($W/m^2$) | Nu(R) | Nu(S) | Nu(AV) | St(AV) x $10^5$ | $\bar{e}^+$ | $St/St$ | $\bar{f}/f$ | n | $\bar{P}/P$ | $\bar{R}$ | $\bar{H}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 81,775 | 0.1169 | 55.0 | 56.0 | 32.5 | 2464 | 1853 | 312 | 225.3 | 268.7 | 466 | 551.6 | 1.94 | 5.34 | 0.36 | 0.73 | 6.55 | 20.59 |
| 72,552 | 0.1034 | 51.4 | 52.0 | 31.3 | 1968 | 1426 | 281.6 | 197.5 | 240.0 | 471 | 489.4 | 1.90 | 5.20 | 0.37 | 0.76 | 6.55 | 20.34 |
| 61,679 | 0.088 | 54.0 | 54.6 | 31.9 | 1968 | 1426 | 255.6 | 180.5 | 218.1 | 501 | 416.1 | 1.93 | 5.0 | 0.39 | 0.70 | 6.55 | 18.96 |
| 48,828 | 0.0696 | 53.2 | 53.7 | 31.3 | 1632 | 1141 | 213.9 | 146.6 | 180.3 | 523 | 329.4 | 1.87 | 4.7 | 0.40 | 0.72 | 6.55 | 18.05 |
| 30,929 | 0.0442 | 53.9 | 54.0 | 32.5 | 1141 | 737 | 152.4 | 97.6 | 125.0 | 572 | 208.6 | 1.79 | 4.16 | 0.42 | 0.73 | 6.55 | 16.28 |
| 20,570 | 0.0295 | 56.3 | 55.9 | 34.3 | 888 | 535 | 114.6 | 70.3 | 92.5 | 637 | 138.8 | 1.78 | 3.65 | 0.49 | 0.65 | 6.55 | 14.34 |
| 15,471 | 0.0223 | 56.4 | 56.3 | 35.3 | 666 | 418 | 89.6 | 56.6 | 73.1 | 669 | 104.4 | 1.72 | 3.38 | 0.51 | 0.66 | 6.55 | 13.53 |
| 11,342 | 0.0164 | 56.5 | 56.1 | 36.4 | 535 | 315 | 74.7 | 44.9 | 59.8 | 747 | 76.5 | 1.74 | 3.07 | 0.57 | 0.58 | 6.55 | 11.84 |
| 6,587 | 0.0096 | 56.2 | 55.7 | 38.3 | 315 | 149 | 49.1 | 24. | 36.6 | 788 | 44.4 | 1.58 | 2.70 | 0.59 | 0.68 | 6.55 | 11.08 |

P/e = 20, α = 75°, e/D = 0.063

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 73,962 | 0.1073 | 59.9 | 63.3 | 37.7 | 2597 | 2087 | 328.2 | 228.9 | 278.6 | 534 | 582.9 | 2.16 | 7.0 | 0.31 | 0.69 | 5.29 | 20.82 |
| 42,358 | 0.0617 | 62.0 | 64.7 | 39.4 | 1741 | 1328 | 214.9 | 146.2 | 180.6 | 604 | 333.8 | 2.08 | 5.96 | 0.35 | 0.66 | 5.29 | 18.10 |
| 20,540 | 0.0301 | 67.0 | 68.8 | 42.6 | 1141 | 811 | 129.5 | 85.7 | 107.6 | 742 | 162.1 | 2.07 | 4.92 | 0.42 | 0.55 | 5.29 | 14.24 |
| 10,793 | 0.0159 | 66.5 | 67.4 | 44.4 | 599 | 418 | 74.7 | 50.0 | 62.4 | 819 | 85.3 | 1.90 | 4.13 | 0.46 | 0.60 | 5.29 | 12.65 |
| 6,769 | 0.0100 | 64.8 | 65.3 | 45.3 | 365 | 225 | 51.5 | 30.9 | 41.2 | 864 | 53.5 | 1.76 | 3.95 | 0.45 | 0.72 | 4.99 | 12.70 |

P/e = 20, α = 45°, e/D = 0.063

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 83,534 | 0.1204 | 60.6 | 60.3 | 35.5 | 2873 | 2087 | 323.4 | 237.9 | 280.7 | 478 | 553.8 | 1.99 | 5.11 | 0.39 | 0.65 | 6.75 | 19.51 |
| 67,750 | 0.0979 | 62.8 | 62.8 | 36.6 | 2597 | 1853 | 278.8 | 198.5 | 238.7 | 499 | 450.1 | 1.96 | 4.89 | 0.40 | 0.65 | 6.75 | 18.58 |
| 52,213 | 0.0756 | 62.9 | 63.0 | 37.3 | 2087 | 1426 | 229.6 | 155.9 | 192.8 | 523 | 348.4 | 1.90 | 4.59 | 0.41 | 0.67 | 6.75 | 17.60 |
| 30,238 | 0.0439 | 65.1 | 65.3 | 39.8 | 1426 | 969 | 157 | 106.1 | 131.6 | 617 | 203.5 | 1.93 | 3.95 | 0.49 | 0.55 | 6.75 | 14.51 |
| 18,230 | 0.0268 | 68.2 | 68.1 | 42.5 | 1054 | 666 | 113.9 | 72.1 | 93.0 | 724 | 123.8 | 1.96 | 3.67 | 0.53 | 0.49 | 6.55 | 12.30 |
| 12,182 | 0.0179 | 66.7 | 66.6 | 43.6 | 737 | 418 | 88.3 | 50.3 | 69.3 | 808 | 83.6 | 1.92 | 3.29 | 0.58 | 0.46 | 6.45 | 11.11 |
| 6,755 | 0.0100 | 68.0 | 67.3 | 45.2 | 535 | 268 | 64.7 | 33.4 | 49.1 | 1031 | 46.7 | 2.10 | 2.91 | 0.72 | 0.31 | 6.27 | 8.17 |

P/e = 20, α = 30°, e/D = 0.063

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 83,115 | 0.1197 | 65.9 | 65.9 | 35.4 | 3016 | 2335 | 279.7 | 216.5 | 248.1 | 423 | 418.8 | 1.76 | 2.95 | 0.60 | 0.54 | 9.72 | 16.38 |
| 73,656 | 0.1066 | 67.4 | 67.4 | 37.2 | 2733 | 2087 | 253.7 | 193.7 | 223.7 | 430 | 375.4 | 1.72 | 2.96 | 0.58 | 0.58 | 9.72 | 16.07 |
| 59,841 | 0.0869 | 67.6 | 67.4 | 38.2 | 2335 | 1741 | 222.5 | 166.8 | 194.7 | 461 | 310.7 | 1.74 | 2.84 | 0.61 | 0.54 | 9.49 | 15.10 |
| 51,617 | 0.075 | 66.1 | 65.8 | 38.6 | 1968 | 1426 | 199.9 | 146.5 | 173.2 | 475 | 272.8 | 1.73 | 2.83 | 0.61 | 0.55 | 9.27 | 14.93 |
| 42,092 | 0.0613 | 66.8 | 66.5 | 39.3 | 1741 | 1233 | 176.7 | 126.4 | 151.6 | 511 | 227.8 | 1.76 | 2.79 | 0.63 | 0.51 | 9.07 | 13.99 |
| 29,746 | 0.0435 | 67.9 | 67.6 | 40.5 | 1426 | 969 | 144.9 | 99.7 | 122.3 | 582 | 164.7 | 1.82 | 2.72 | 0.67 | 0.45 | 8.68 | 12.45 |
| 17,223 | 0.0253 | 68.2 | 67.9 | 42.9 | 969 | 599 | 106.1 | 66.3 | 86.2 | 709 | 101.3 | 1.87 | 2.65 | 0.71 | 0.41 | 8.01 | 10.51 |
| 8,757 | 0.0132 | 70.3 | 69.7 | 45.9 | 666 | 365 | 75. | 42.1 | 58.6 | 946 | 55.0 | 2.06 | 2.63 | 0.78 | 0.30 | 7.08 | 8.15 |

7.2 Tabulated Data for Sudden Contraction Duct

| | Re | $\dot{m}$ (lbm/sec) | $\Delta P_{2-3}$ (in $H_2O$) | $\Delta P_{4-6}$ (in $H_2O$) | $\bar{f}_{4-6}$ |
|---|---|---|---|---|---|
| Four sided smooth | 7,600 | 0.0237 | 0.007 | 0.003 | 0.0084 |
| | 12,800 | 0.0397 | 0.020 | 0.006 | 0.00674 |
| | 19,800 | 0.0624 | 0.057 | 0.019 | 0.00608 |
| | 39,200 | 0.122 | 0.203 | 0.062 | 0.00525 |
| | 58,400 | 0.181 | 0.481 | 0.124 | 0.00496 |
| | 80,800 | 0.251 | 0.732 | 0.219 | 0.00481 |
| P/e = 10, α = 90°, e/D = 0.063 | 8,500 | 0.0263 | 0.008 | 0.015 | 0.031 |
| | 13,800 | 0.0429 | 0.026 | 0.038 | 0.0272 |
| | 20,200 | 0.0626 | 0.056 | 0.083 | 0.0279 |
| | 40,200 | 0.125 | 0.246 | 0.316 | 0.0287 |
| | 56,900 | 0.1765 | 0.36 | 0.64 | 0.0285 |
| | 82,300 | 0.256 | 0.90 | 1.33 | 0.0288 |
| P/e = 10, α = 60°, e/D = 0.063 | 7,800 | 0.0243 | 0.006 | 0.017 | 0.0445 |
| | 13,200 | 0.0411 | 0.022 | 0.049 | 0.0438 |
| | 20,400 | 0.0634 | 0.052 | 0.115 | 0.0432 |
| | 39,200 | 0.122 | 0.21 | 0.459 | 0.0462 |
| | 56,600 | 0.1758 | 0.41 | 0.904 | 0.045 |
| | 82,000 | 0.255 | 0.9 | 1.874 | 0.0466 |
| P/e = 10, α = 45°, e/D = 0.063 | 8,200 | 0.0255 | 0.008 | 0.015 | 0.0294 |
| | 13,200 | 0.0411 | 0.024 | 0.035 | 0.0282 |
| | 19,900 | 0.0619 | 0.056 | 0.080 | 0.0303 |
| | 39,300 | 0.122 | 0.241 | 0.283 | 0.0287 |
| | 58,400 | 0.181 | 0.408 | 0.578 | 0.027 |
| | 81,200 | 0.252 | 0.90 | 1.11 | 0.0265 |
| P/e = 10, α = 30°, e/D = 0.063 | 8,200 | 0.0255 | 0.008 | 0.009 | 0.0259 |
| | 13,300 | 0.0414 | 0.022 | 0.026 | 0.0224 |
| | 20,200 | 0.0626 | 0.056 | 0.052 | 0.0211 |
| | 39,100 | 0.121 | 0.214 | 0.187 | 0.0194 |
| | 57,700 | 0.179 | 0.437 | 0.376 | 0.0174 |
| | 80,600 | 0.250 | 0.875 | 0.692 | 0.0165 |
| P/e = 20, α = 90°, e/D = 0.063 | 7,960 | 0.0247 | 0.009 | 0.009 | 0.0235 |
| | 14,000 | 0.0435 | 0.025 | 0.029 | 0.0265 |
| | 20,100 | 0.0625 | 0.057 | 0.063 | 0.0256 |
| | 39,300 | 0.122 | 0.245 | 0.218 | 0.0261 |
| | 56,800 | 0.176 | 0.44 | 0.49 | 0.0246 |
| | 81,000 | 0.251 | 1.0 | 0.96 | 0.0268 |
| P/e = 20, α = 60°, e/D = 0.063 | 8,400 | 0.0261 | 0.009 | 0.012 | 0.030 |
| | 14,300 | 0.0442 | 0.027 | 0.038 | 0.0317 |
| | 20,200 | 0.0627 | 0.054 | 0.077 | 0.0316 |
| | 40,200 | 0.125 | 0.23 | 0.309 | 0.0312 |
| | 56,900 | 0.177 | 0.57 | 0.638 | 0.0332 |
| | 82,500 | 0.256 | 0.84 | 1.40 | 0.0341 |
| P/e = 20, α = 45°, e/D = 0.063 | 7,900 | 0.0244 | 0.009 | 0.008 | 0.0211 |
| | 14,000 | 0.0435 | 0.025 | 0.029 | 0.0215 |
| | 20,800 | 0.0645 | 0.05 | 0.06 | 0.0212 |
| | 39,300 | 0.122 | 0.21 | 0.215 | 0.0224 |
| | 57,900 | 0.180 | 0.36 | 0.444 | 0.0222 |
| | 80,900 | 0.251 | 1.85 | 0.864 | 0.0226 |
| P/e = 20, α = 30°, e/D = 0.063 | 8,000 | 0.0250 | 0.011 | 0.008 | 0.0173 |
| | | | | | |
| | 20,500 | 0.0635 | 0.06 | 0.045 | 0.0154 |
| | 39,300 | 0.122 | 0.22 | 0.146 | 0.0139 |
| | 57,800 | 0.180 | 0.45 | 0.29 | 0.0134 |
| | 80,900 | 0.251 | 0.85 | 0.534 | 0.0129 |

RUN NUMBER=210HS08-00/00 E/D=0.000 P/E= 0.00 ALPA= 0 D= 2.956 IN
PR=.71 MDOT= .0238 LBM/SEC RE= 7668. QGE(R)= 109.5 BTU/HR-SQ FT
QGE(S)= 109.5 INLET TEMP= 79.1 F TATM= 73.3 F PATM=14.64 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 111.9 | 112.0 | 79.5 | 129.9 | 112.9 | 65.2 | 56.5 | 60.9 | .01101 |
| .95 | 118.4 | 118.4 | 80.3 | 104.5 | 104.5 | 44.6 | 44.6 | 44.6 | .00807 |
| 1.59 | 124.9 | 124.8 | 81.1 | 99.5 | 98.3 | 36.9 | 36.6 | 36.7 | .00666 |
| 2.22 | 130.9 | 130.5 | 82.0 | 95.6 | 97.0 | 31.7 | 32.4 | 32.1 | .00582 |
| 2.85 | 135.9 | 135.4 | 82.8 | 91.9 | 89.6 | 28.0 | 27.6 | 27.8 | .00504 |
| 3.49 | 139.6 | 138.7 | 83.6 | 91.4 | 95.8 | 26.4 | 28.1 | 27.2 | .00495 |
| 4.12 | 142.0 | 141.2 | 84.4 | 101.9 | 97.2 | 28.6 | 27.6 | 28.1 | .00512 |
| 4.76 | 144.3 | 143.1 | 85.2 | 98.0 | 101.8 | 26.8 | 28.4 | 27.6 | .00502 |
| 5.39 | 146.2 | 145.0 | 86.1 | 98.0 | 97.3 | 26.2 | 26.6 | 26.4 | .00482 |
| 6.66 | 148.7 | 147.2 | 87.7 | 100.0 | 101.3 | 26.3 | 27.3 | 26.8 | .00491 |
| 7.93 | 150.6 | 149.4 | 89.3 | 99.7 | 99.9 | 26.1 | 26.6 | 26.4 | .00483 |
| 9.20 | 151.9 | 151.0 | 91.0 | 100.1 | 100.1 | 26.2 | 26.6 | 26.4 | .00486 |
| 11.73 | 153.4 | 153.0 | 94.3 | 100.8 | 100.5 | 27.1 | 27.2 | 27.1 | .00501 |
| 14.27 | 155.1 | 154.7 | 97.5 | 99.2 | 100.0 | 27.2 | 27.6 | 27.4 | .00508 |
| 14.91 | 155.2 | 155.0 | 98.4 | 101.2 | 99.2 | 28.1 | 27.7 | 27.9 | .00517 |
| 16.81 | 155.8 | 154.8 | 100.8 | 95.5 | 95.8 | 27.3 | 27.9 | 27.6 | .00514 |

FULLY DEVELOPED REGION : NU(R):RFD= 27.42 NU(S):SFD= 27.60 NU(AV):AFD= 27.51

RUN NUMBER=211HS12-00/00 E/D=0.000 P/E= 0.00 ALPA= 0 D= 2.956 IN
PR=.71 MDOT= .0421 LBM/SEC RE= 13578. QGE(R)= 185.7 BTU/HR-SQ FT
QGE(S)= 182.9 INLET TEMP= 78.9 F TATM= 71.8 F PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 107.8 | 107.2 | 79.3 | 202.6 | 188.1 | 115.7 | 109.7 | 112.7 | .01151 |
| .95 | 115.9 | 115.6 | 80.1 | 180.8 | 178.1 | 82.1 | 81.4 | 81.8 | .00836 |
| 1.59 | 124.0 | 124.0 | 80.8 | 170.7 | 165.3 | 64.3 | 62.1 | 63.2 | .00647 |
| 2.22 | 130.9 | 131.0 | 81.6 | 170.1 | 166.0 | 56.0 | 54.6 | 55.3 | .00566 |
| 2.85 | 136.7 | 136.6 | 82.4 | 166.5 | 162.7 | 49.7 | 48.6 | 49.1 | .00504 |
| 3.49 | 141.0 | 140.6 | 83.2 | 167.6 | 169.7 | 46.9 | 47.8 | 47.4 | .00486 |
| 4.12 | 144.0 | 143.9 | 84.0 | 177.7 | 168.9 | 47.8 | 45.5 | 46.7 | .00480 |
| 4.76 | 147.0 | 146.5 | 84.7 | 175.0 | 174.7 | 45.3 | 45.7 | 45.5 | .00469 |
| 5.39 | 149.7 | 149.0 | 85.5 | 172.5 | 169.8 | 43.3 | 43.1 | 43.2 | .00445 |
| 6.66 | 153.4 | 152.4 | 87.1 | 175.1 | 174.0 | 42.4 | 42.8 | 42.6 | .00440 |
| 7.93 | 156.3 | 155.8 | 88.6 | 175.8 | 172.0 | 41.6 | 41.1 | 41.4 | .00428 |
| 9.20 | 158.9 | 158.4 | 90.2 | 174.7 | 172.6 | 40.7 | 40.5 | 40.6 | .00421 |
| 11.73 | 162.1 | 162.5 | 93.3 | 176.1 | 172.8 | 40.7 | 39.7 | 40.2 | .00419 |
| 14.27 | 166.0 | 166.3 | 96.4 | 172.9 | 171.1 | 39.3 | 38.8 | 39.0 | .00408 |
| 14.91 | 166.3 | 166.9 | 97.2 | 176.6 | 171.9 | 40.5 | 39.0 | 39.7 | .00416 |
| 16.81 | 168.0 | 168.1 | 99.6 | 170.0 | 167.2 | 39.1 | 38.4 | 38.8 | .00407 |

FULLY DEVELOPED REGION : NU(R):RFD= 39.91 NU(S):SFD= 38.99 NU(AV):AFD= 39.45

RUN NUMBER=212HS20-00/00 E/D=0.000 P/E= 0.00 ALPA= 0 D= 2.956 IN
PR=.71 MDOT= .0626 LBM/SEC RE= 20263. QGE(R)= 224.5 BTU/HR-SQ FT
QGE(S)= 224.5 INLET TEMP= 78.3 F TATM= 71.2 F PATM=14.64 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 104.4 | 104.6 | 78.6 | 236.0 | 213.8 | 149.2 | 134.1 | 141.7 | .00972 |
| .95 | 112.8 | 113.3 | 79.3 | 219.9 | 219.8 | 106.7 | 105.2 | 105.9 | .00728 |
| 1.59 | 121.2 | 122.0 | 79.9 | 204.6 | 202.2 | 80.5 | 78.2 | 79.4 | .00546 |
| 2.22 | 127.8 | 128.6 | 80.5 | 208.6 | 208.0 | 71.7 | 70.4 | 71.0 | .00489 |
| 2.85 | 133.2 | 133.9 | 81.2 | 203.2 | 201.3 | 63.4 | 62.0 | 62.7 | .00432 |
| 3.49 | 136.8 | 137.2 | 81.8 | 206.8 | 213.2 | 61.0 | 62.4 | 61.7 | .00425 |
| 4.12 | 139.1 | 140.0 | 82.5 | 217.0 | 208.5 | 62.0 | 58.7 | 60.3 | .00416 |
| 4.76 | 141.4 | 141.8 | 83.1 | 214.3 | 216.7 | 59.5 | 59.8 | 59.6 | .00412 |
| 5.39 | 143.4 | 143.5 | 83.7 | 212.8 | 213.6 | 57.6 | 57.7 | 57.7 | .00399 |
| 6.66 | 146.0 | 145.9 | 85.0 | 214.6 | 216.2 | 56.7 | 57.3 | 57.0 | .00395 |
| 7.93 | 147.8 | 148.3 | 86.3 | 216.4 | 214.8 | 56.6 | 55.7 | 56.2 | .00390 |
| 9.20 | 149.8 | 150.1 | 87.6 | 214.6 | 215.5 | 55.4 | 55.3 | 55.4 | .00385 |
| 11.73 | 152.0 | 153.3 | 90.1 | 216.2 | 215.3 | 55.9 | 54.5 | 55.2 | .00385 |
| 14.27 | 155.4 | 156.2 | 92.7 | 212.8 | 214.8 | 54.0 | 53.8 | 53.9 | .00377 |
| 14.91 | 155.5 | 156.9 | 93.3 | 217.0 | 214.4 | 55.5 | 53.7 | 54.6 | .00382 |
| 16.81 | 157.2 | 158.3 | 95.2 | 210.3 | 210.2 | 53.8 | 52.9 | 53.3 | .00375 |

FULLY DEVELOPED REGION : NU(R):RFD= 54.80 NU(S):SFD= 53.71 NU(AV):AFD= 54.25

RUN NUMBER=213HS40-00/00 E/D=0.000 P/E= 0.00 ALPA= 0 D= 2.956 IN
PR=.71 MDOT= .1209 LBM/SEC RE= 39071. QGE(R)= 346.4 BTU/HR-SQ FT
QGE(S)= 346.4 INLET TEMP= 81.3 F TATM= 72.4 F PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 104.6 | 105.8 | 81.6 | 338.6 | 287.0 | 238.3 | 192.0 | 215.1 | .00768 |
| .95 | 113.0 | 114.2 | 82.1 | 341.9 | 341.8 | 179.3 | 172.2 | 175.7 | .00628 |
| 1.59 | 121.3 | 122.7 | 82.6 | 320.8 | 320.4 | 134.0 | 129.4 | 131.7 | .00471 |
| 2.22 | 127.2 | 128.5 | 83.1 | 329.9 | 328.2 | 121.1 | 116.8 | 119.0 | .00425 |
| 2.85 | 131.7 | 132.9 | 83.6 | 326.0 | 325.6 | 109.5 | 106.7 | 108.1 | .00387 |
| 3.49 | 134.5 | 135.5 | 84.1 | 330.7 | 337.8 | 106.0 | 106.2 | 106.1 | .00380 |
| 4.12 | 136.2 | 137.9 | 84.6 | 339.4 | 330.0 | 106.2 | 99.9 | 103.0 | .00369 |
| 4.76 | 137.9 | 139.2 | 85.1 | 341.6 | 339.0 | 104.4 | 101.2 | 102.8 | .00369 |
| 5.39 | 139.9 | 140.4 | 85.6 | 334.4 | 338.6 | 99.3 | 99.6 | 99.5 | .00357 |
| 6.66 | 142.2 | 142.8 | 86.7 | 338.1 | 338.6 | 97.9 | 97.0 | 97.5 | .00350 |
| 7.93 | 144.2 | 145.2 | 87.7 | 339.7 | 338.8 | 96.5 | 94.6 | 95.5 | .00344 |
| 9.20 | 146.8 | 147.8 | 88.7 | 337.3 | 337.6 | 93.1 | 91.6 | 92.3 | .00333 |
| 11.73 | 150.6 | 152.3 | 90.7 | 338.4 | 337.6 | 90.3 | 87.6 | 89.0 | .00322 |
| 14.27 | 155.7 | 156.8 | 92.8 | 333.6 | 336.5 | 84.4 | 83.8 | 84.1 | .00305 |
| 14.91 | 155.8 | 157.7 | 93.3 | 340.9 | 336.9 | 86.7 | 83.2 | 85.0 | .00308 |
| 16.81 | 159.0 | 160.4 | 94.3 | 332.1 | 332.5 | 82.1 | 80.5 | 81.3 | .00296 |

FULLY DEVELOPED REGION : NU(R):RFD= 85.90 NU(S):SFD= 83.77 NU(AV):AFD= 84.84

RUN NUMBER=214HS60-00/00 E/D=0.000 P/E= 0.00 ALPA= 0 D= 2.956 IN
PR=.71 MDOT= .1790 LBM/SEC RE= 57585. QGE(R)= 457.2 BTU/HR-SQ FT
QGE(S)= 457.2 INLET TEMP= 85.4 F TATM= 74.9 F PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 110.0 | 112.2 | 85.6 | 424.4 | 357.6 | 280.5 | 216.8 | 248.7 | .00603 |
| .95 | 118.8 | 121.1 | 86.1 | 452.4 | 452.1 | 222.9 | 207.8 | 215.3 | .00522 |
| 1.59 | 127.5 | 130.0 | 86.5 | 426.2 | 422.5 | 167.4 | 156.3 | 161.8 | .00393 |
| 2.22 | 133.1 | 135.3 | 87.0 | 438.6 | 439.1 | 153.0 | 146.0 | 149.5 | .00363 |
| 2.85 | 137.1 | 139.2 | 87.4 | 436.5 | 436.8 | 141.2 | 135.6 | 138.4 | .00336 |
| 3.49 | 139.4 | 141.4 | 87.9 | 442.9 | 449.1 | 138.0 | 134.7 | 136.4 | .00332 |
| 4.12 | 140.8 | 143.5 | 88.4 | 450.0 | 440.5 | 137.6 | 128.1 | 132.9 | .00323 |
| 4.76 | 142.2 | 144.5 | 88.8 | 456.2 | 449.6 | 137.0 | 129.5 | 133.2 | .00324 |
| 5.39 | 144.4 | 145.4 | 89.3 | 443.2 | 450.7 | 128.7 | 128.6 | 128.7 | .00313 |
| 6.66 | 146.4 | 147.8 | 90.2 | 449.6 | 449.2 | 127.9 | 124.8 | 126.3 | .00308 |
| 7.93 | 148.5 | 150.1 | 91.1 | 450.9 | 449.5 | 125.4 | 121.6 | 123.5 | .00302 |
| 9.20 | 151.5 | 152.7 | 92.0 | 447.1 | 448.4 | 119.8 | 117.8 | 118.8 | .00291 |
| 11.73 | 155.0 | 157.5 | 93.8 | 449.7 | 448.3 | 116.9 | 111.9 | 114.4 | .00280 |
| 14.27 | 161.1 | 162.7 | 95.6 | 442.5 | 447.0 | 107.2 | 105.7 | 106.4 | .00262 |
| 14.91 | 161.0 | 163.8 | 96.1 | 453.0 | 447.0 | 110.5 | 104.6 | 107.6 | .00265 |
| 16.81 | 164.6 | 166.7 | 97.5 | 442.0 | 442.7 | 104.0 | 101.1 | 102.6 | .00253 |

FULLY DEVELOPED REGION : NU(R):RFD=109.65 NU(S):SFD=105.82 NU(AV):AFD=107.74

RUN NUMBER=215HS80-00/00 E/D=0.000 P/E= 0.00 ALPA= 0 D= 2.956 IN
PR=.71 MDOT= .2500 LBM/SEC RE= 80872. QGE(R)= 599.2 BTU/HR-SQ FT
QGE(S)= 599.2 INLET TEMP= 81.8 F TATM= 72.0 F PATM=14.64 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 105.4 | 109.0 | 82.0 | 524.2 | 454.9 | 363.2 | 273.2 | 318.2 | .00550 |
| .95 | 114.2 | 117.8 | 82.4 | 594.6 | 594.2 | 303.5 | 272.0 | 287.8 | .00497 |
| 1.59 | 122.9 | 126.6 | 82.9 | 566.7 | 562.8 | 228.9 | 208.1 | 218.5 | .00378 |
| 2.22 | 128.3 | 131.6 | 83.3 | 582.1 | 583.3 | 209.2 | 195.3 | 202.2 | .00350 |
| 2.85 | 132.3 | 135.4 | 83.7 | 574.3 | 576.3 | 191.0 | 180.2 | 185.6 | .00321 |
| 3.49 | 134.0 | 137.2 | 84.1 | 590.0 | 594.5 | 191.1 | 181.0 | 186.0 | .00322 |
| 4.12 | 135.4 | 139.3 | 84.6 | 592.3 | 581.0 | 188.1 | 171.3 | 179.7 | .00311 |
| 4.76 | 136.8 | 140.1 | 85.0 | 599.3 | 591.8 | 186.6 | 173.4 | 180.0 | .00312 |
| 5.39 | 139.1 | 140.8 | 85.4 | 584.6 | 594.1 | 175.5 | 172.9 | 174.2 | .00302 |
| 6.66 | 141.0 | 143.2 | 86.3 | 592.2 | 591.4 | 174.2 | 167.2 | 170.7 | .00297 |
| 7.93 | 143.2 | 145.6 | 87.1 | 593.0 | 592.1 | 170.0 | 162.8 | 166.4 | .00289 |
| 9.20 | 146.2 | 148.5 | 88.0 | 589.4 | 590.4 | 162.5 | 156.6 | 159.5 | .00278 |
| 11.73 | 149.7 | 153.6 | 89.7 | 592.2 | 590.1 | 157.9 | 147.8 | 152.9 | .00267 |
| 14.27 | 156.1 | 158.5 | 91.4 | 584.6 | 590.1 | 144.2 | 140.4 | 142.3 | .00249 |
| 14.91 | 156.1 | 159.8 | 91.8 | 595.6 | 588.8 | 147.9 | 138.2 | 143.0 | .00250 |
| 16.81 | 160.1 | 163.2 | 93.1 | 583.6 | 584.4 | 138.7 | 132.7 | 135.7 | .00238 |

FULLY DEVELOPED REGION : NU(R):RFD=147.17 NU(S):SFD=139.78 NU(AV):AFD=143.47

RUN NUMBER=255MR08-90/10 E/D= .063 P/E=10.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .0266 LBM/SEC RE= 8520. QGE(R)= 214.8 BTU/HR-SQ FT
QGE(S)= 155.2 INLET TEMP= 77.5 F TATM= 73.0 F PATM=14.68 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.8 | 114.6 | 78.1 | 192.7 | 135.7 | 83.4 | 60.7 | 72.0 | .01163 |
| .95 | 120.6 | 120.7 | 79.4 | 209.5 | 149.9 | 82.7 | 59.0 | 70.9 | .01146 |
| 1.59 | 125.4 | 126.8 | 80.6 | 202.8 | 133.6 | 73.5 | 47.0 | 60.2 | .00976 |
| 2.22 | 129.4 | 130.9 | 81.8 | 200.0 | 143.5 | 68.1 | 47.4 | 57.7 | .00937 |
| 2.85 | 132.4 | 134.4 | 83.1 | 202.1 | 135.1 | 66.3 | 42.6 | 54.4 | .00885 |
| 3.49 | 134.6 | 136.2 | 84.3 | 198.0 | 145.0 | 63.6 | 45.1 | 54.3 | .00885 |
| 4.12 | 135.6 | 137.6 | 85.6 | 207.9 | 144.1 | 67.0 | 44.6 | 55.8 | .00910 |
| 4.76 | 136.5 | 136.5 | 86.8 | 209.8 | 148.0 | 67.9 | 46.0 | 56.9 | .00930 |
| 5.39 | 137.7 | 139.4 | 88.0 | 206.8 | 148.5 | 66.8 | 46.4 | 56.6 | .00927 |
| 6.66 | 139.8 | 141.5 | 90.5 | 206.0 | 147.6 | 66.8 | 46.3 | 56.6 | .00929 |
| 7.93 | 141.2 | 143.5 | 93.0 | 209.3 | 147.1 | 69.1 | 46.4 | 57.7 | .00951 |
| 9.20 | 143.6 | 145.4 | 95.5 | 206.2 | 147.6 | 67.9 | 46.9 | 57.4 | .00949 |
| 11.73 | 147.2 | 149.8 | 100.4 | 206.9 | 146.0 | 69.6 | 46.5 | 58.0 | .00966 |
| 14.27 | 151.5 | 152.7 | 105.4 | 203.2 | 146.3 | 68.8 | 48.2 | 58.5 | .00980 |
| 14.91 | 151.7 | 153.4 | 106.6 | 208.7 | 146.4 | 72.2 | 48.7 | 60.4 | .01014 |
| 16.81 | 154.1 | 155.6 | 110.3 | 201.3 | 141.5 | 71.2 | 48.4 | 59.8 | .01009 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 68.58 NU(S)A= 46.75 NU(AV)A= 57.67 ST(AV)A= .00955
E(+)= 64.19 ST(AV)/ST(4S)=2.09 F/F(4S)=3.51 (ST/ST(4S))/(F/F(4S))= .595
(F/F(4S))/(ST/ST(4S)) 3.0= .38 R(BAR)= 5.643 H(BAR)= 9.942

RUN NUMBER=256MR12-90/10 E/D= .063 P/E=10.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .0397 LBM/SEC RE= 12711. QGE(R)= 304.8 BTU/HR-SQ FT
QGE(S)= 207.8 INLET TEMP= 79.0 F TATM= 72.5 F PATM=14.68 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.8 | 113.0 | 79.6 | 266.2 | 181.1 | 119.6 | 88.1 | 103.8 | .01125 |
| .95 | 121.1 | 120.1 | 80.7 | 299.5 | 202.6 | 120.4 | 83.5 | 102.0 | .01107 |
| 1.59 | 126.4 | 127.2 | 81.9 | 290.2 | 180.4 | 105.6 | 64.5 | 85.0 | .00925 |
| 2.22 | 130.7 | 131.7 | 83.0 | 288.0 | 192.5 | 97.8 | 64.0 | 80.9 | .00881 |
| 2.85 | 133.6 | 135.0 | 84.2 | 291.4 | 188.7 | 95.2 | 60.0 | 77.6 | .00846 |
| 3.49 | 135.7 | 136.8 | 85.3 | 290.3 | 200.8 | 92.9 | 62.9 | 77.9 | .00851 |
| 4.12 | 136.9 | 138.6 | 86.5 | 297.7 | 194.1 | 95.1 | 59.9 | 77.5 | .00848 |
| 4.76 | 138.0 | 139.6 | 87.6 | 301.2 | 200.4 | 96.0 | 61.9 | 79.0 | .00866 |
| 5.39 | 139.6 | 140.6 | 88.8 | 294.8 | 201.4 | 93.0 | 62.3 | 77.6 | .00852 |
| 6.66 | 141.8 | 143.0 | 91.1 | 296.8 | 200.1 | 93.4 | 61.5 | 77.5 | .00853 |
| 7.93 | 143.8 | 145.4 | 93.4 | 297.8 | 199.4 | 94.0 | 61.0 | 77.5 | .00856 |
| 9.20 | 146.2 | 147.6 | 95.7 | 296.0 | 200.0 | 92.9 | 61.0 | 77.0 | .00853 |
| 11.73 | 150.0 | 152.6 | 100.3 | 297.2 | 198.5 | 94.1 | 59.7 | 76.9 | .00857 |
| 14.27 | 155.6 | 156.6 | 104.9 | 292.1 | 199.0 | 89.9 | 60.1 | 75.0 | .00842 |
| 14.91 | 155.9 | 157.7 | 106.0 | 298.7 | 198.1 | 93.3 | 59.8 | 76.5 | .00860 |
| 16.81 | 159.1 | 160.9 | 109.5 | 290.6 | 193.4 | 90.8 | 58.3 | 74.6 | .00842 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 93.10 NU(S)A= 60.53 NU(AV)A= 76.82 ST(AV)A= .00853
E(+)= 95.87 ST(AV)/ST(4S)=2.11 F/F(4S)=3.93 (ST/ST(4S))/(F/F(4S))= .536
(F/F(4S))/(ST/ST(4S)) 3.0= .42 R(BAR)= 5.643 H(BAR)=11.463

RUN NUMBER=257MR20-90/10 E/D= .063 P/E=10.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .0642 LBM/SEC RE= 20621. QGE(R)= 417.0 BTU/HR-SQ FT
QGE(S)= 235.5 INLET TEMP= 80.1 F TATM= 72.7 F PATM=14.68 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 114.4 | 108.8 | 80.6 | 333.4 | 196.5 | 160.0 | 113.0 | 136.5 | .00916 |
| .95 | 119.7 | 116.2 | 81.5 | 411.9 | 230.8 | 174.9 | 107.7 | 141.3 | .00950 |
| 1.59 | 124.9 | 123.6 | 82.4 | 399.7 | 202.9 | 152.2 | 79.6 | 115.9 | .00780 |
| 2.22 | 128.7 | 127.6 | 83.3 | 406.9 | 220.4 | 144.8 | 80.4 | 112.6 | .00759 |
| 2.85 | 132.0 | 130.5 | 84.2 | 395.3 | 219.8 | 133.5 | 76.6 | 105.1 | .00709 |
| 3.49 | 133.4 | 132.2 | 85.1 | 406.0 | 226.6 | 135.5 | 77.5 | 106.5 | .00719 |
| 4.12 | 134.3 | 133.6 | 86.0 | 410.3 | 225.2 | 136.9 | 76.2 | 106.5 | .00720 |
| 4.76 | 135.1 | 134.6 | 86.9 | 415.4 | 228.7 | 138.5 | 77.2 | 107.8 | .00730 |
| 5.39 | 136.6 | 135.5 | 87.8 | 406.3 | 228.8 | 133.6 | 77.0 | 105.3 | .00714 |
| 6.66 | 138.2 | 137.5 | 89.6 | 409.4 | 228.4 | 134.9 | 76.4 | 105.6 | .00718 |
| 7.93 | 139.6 | 139.4 | 91.4 | 411.7 | 228.3 | 136.4 | 75.9 | 106.2 | .00723 |
| 9.20 | 142.0 | 141.4 | 93.2 | 407.8 | 228.2 | 133.1 | 75.4 | 104.2 | .00712 |
| 11.73 | 144.4 | 145.7 | 96.9 | 410.4 | 226.8 | 136.6 | 73.4 | 105.0 | .00721 |
| 14.27 | 149.3 | 148.5 | 100.5 | 404.2 | 227.8 | 130.1 | 74.6 | 102.3 | .00706 |
| 14.91 | 149.2 | 149.4 | 101.4 | 413.8 | 227.5 | 135.9 | 74.3 | 105.1 | .00726 |
| 16.81 | 152.7 | 152.4 | 104.1 | 403.1 | 222.7 | 129.7 | 72.1 | 100.9 | .00699 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=134.38 NU(S)A= 75.10 NU(AV)A=104.74 ST(AV)A= .00716
E(+)= 155.96 ST(AV)/ST(4S)=2.03 F/F(4S)=4.47 (ST/ST(4S))/(F/F(4S))= .456
(F/F(4S))/(ST/ST(4S)) 3.0= .53 R(BAR)= 5.643 H(BAR)=14.152

RUN NUMBER=258HR40-90/10 E/D= .063 P/E=10.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .1220 LBM/SEC RE= 39211. QGE(R)= 698.3 BTU/HR-SQ FT
QGE(S)= 401.8 INLET TEMP= 81.1 F TATM= 71.5 F PATM=14.68 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 116.8 | 111.6 | 81.5 | 541.2 | 302.2 | 248.7 | 162.9 | 205.8 | .00728 |
| .95 | 122.7 | 119.7 | 82.3 | 692.7 | 396.5 | 278.0 | 171.8 | 224.9 | .00796 |
| 1.59 | 128.5 | 127.8 | 83.1 | 672.6 | 358.6 | 239.5 | 129.9 | 184.7 | .00655 |
| 2.22 | 132.0 | 131.1 | 83.9 | 688.4 | 388.0 | 231.4 | 132.8 | 182.1 | .00646 |
| 2.85 | 135.0 | 133.6 | 84.7 | 674.3 | 385.6 | 216.3 | 127.3 | 171.8 | .00610 |
| 3.49 | 135.9 | 134.9 | 85.5 | 689.2 | 395.6 | 220.4 | 129.1 | 174.8 | .00621 |
| 4.12 | 136.6 | 136.3 | 86.3 | 691.1 | 388.7 | 221.4 | 125.1 | 173.3 | .00617 |
| 4.76 | 137.2 | 137.0 | 87.1 | 700.3 | 394.6 | 224.7 | 127.3 | 176.0 | .00627 |
| 5.39 | 139.0 | 137.6 | 87.9 | 684.7 | 396.7 | 215.2 | 128.2 | 171.7 | .00613 |
| 6.66 | 140.3 | 139.7 | 89.5 | 690.5 | 394.3 | 217.7 | 125.8 | 171.8 | .00614 |
| 7.93 | 141.5 | 141.8 | 91.1 | 693.2 | 394.3 | 219.8 | 124.3 | 172.0 | .00617 |
| 9.20 | 144.0 | 144.0 | 92.7 | 689.1 | 394.3 | 214.1 | 122.5 | 168.3 | .00605 |
| 11.73 | 147.1 | 149.1 | 96.0 | 691.8 | 392.5 | 214.3 | 117.0 | 165.7 | .00598 |
| 14.27 | 153.9 | 152.6 | 99.2 | 683.5 | 394.1 | 196.8 | 116.3 | 156.6 | .00567 |
| 14.91 | 153.8 | 153.9 | 100.0 | 696.0 | 392.9 | 203.6 | 114.8 | 159.2 | .00577 |
| 16.81 | 158.6 | 157.8 | 102.4 | 681.9 | 387.7 | 190.2 | 109.7 | 150.0 | .00546 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=211.49 NU(S)A=120.77 NU(AV)A=166.13 ST(AV)A= .00597
E(+)= 296.89 ST(AV)/ST(4S)=2.01 F/F(4S)=5.23 (ST/ST(4S))/(F/F(4S))= .384
(F/F(4S))/(ST/ST(4S)) 3.0= .64 R(BAR)= 5.643 H(BAR)=17.502

RUN NUMBER=259HR60-90/10 E/D= .063 P/E=10.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .1800 LBM/SEC RE= 57891. QGE(R)= 969.9 BTU/HR-SQ FT
QGE(S)= 526.5 INLET TEMP= 81.5 F TATM= 73.0 F PATM=39.88 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 116.6 | 113.2 | 81.9 | 774.9 | 387.9 | 361.7 | 200.7 | 281.2 | .00674 |
| .95 | 123.5 | 121.4 | 82.6 | 964.3 | 521.2 | 381.7 | 217.5 | 299.6 | .00719 |
| 1.59 | 130.4 | 129.6 | 83.4 | 935.5 | 478.5 | 321.3 | 167.3 | 244.3 | .00587 |
| 2.22 | 133.8 | 132.4 | 84.1 | 963.4 | 514.6 | 313.0 | 171.9 | 242.5 | .00583 |
| 2.85 | 137.2 | 134.6 | 84.8 | 935.9 | 510.4 | 288.3 | 165.4 | 226.9 | .00546 |
| 3.49 | 137.2 | 135.6 | 85.6 | 964.4 | 522.8 | 301.0 | 168.4 | 234.7 | .00566 |
| 4.12 | 137.4 | 137.0 | 86.3 | 962.8 | 511.4 | 303.3 | 162.4 | 232.8 | .00562 |
| 4.76 | 137.6 | 137.4 | 87.1 | 978.7 | 519.4 | 311.2 | 165.8 | 238.5 | .00576 |
| 5.39 | 139.8 | 137.8 | 87.8 | 953.4 | 522.6 | 294.3 | 167.6 | 231.0 | .00559 |
| 6.66 | 140.8 | 139.8 | 89.3 | 961.8 | 519.1 | 299.0 | 164.6 | 231.8 | .00562 |
| 7.93 | 141.5 | 141.8 | 90.8 | 967.1 | 519.1 | 304.5 | 162.5 | 233.5 | .00567 |
| 9.20 | 144.6 | 143.9 | 92.2 | 959.7 | 519.3 | 292.1 | 160.2 | 226.2 | .00550 |
| 11.73 | 147.4 | 149.0 | 95.2 | 964.1 | 517.5 | 293.0 | 152.6 | 222.8 | .00544 |
| 14.27 | 155.1 | 152.8 | 98.2 | 953.6 | 519.0 | 264.4 | 150.0 | 207.2 | .00508 |
| 14.91 | 154.8 | 154.1 | 98.9 | 969.6 | 517.7 | 273.7 | 147.9 | 210.8 | .00517 |
| 16.81 | 160.3 | 158.2 | 101.1 | 952.4 | 512.6 | 252.9 | 141.1 | 197.0 | .00485 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=287.97 NU(S)A=157.12 NU(AV)A=222.54 ST(AV)A= .00542
E(+)= 438.63 ST(AV)/ST(4S)=2.01 F/F(4S)=5.72 (ST/ST(4S))/(F/F(4S))= .351
(F/F(4S))/(ST/ST(4S)) 3.0= .71 R(BAR)= 5.643 H(BAR)=19.564

RUN NUMBER=260HR80-90/10 E/D= .063 P/E=10.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .2520 LBM/SEC RE= 81093. QGE(R)=1163.8 BTU/HR-SQ FT
QGE(S)= 672.0 INLET TEMP= 82.4 F TATM= 74.1 F PATM=14.68 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 111.6 | 113.6 | 82.7 | 968.3 | 478.7 | 542.8 | 250.9 | 396.9 | .00681 |
| .95 | 119.9 | 121.5 | 83.4 | 1158.8 | 666.8 | 513.5 | 283.2 | 398.3 | .00684 |
| 1.59 | 128.1 | 129.3 | 84.0 | 1119.3 | 623.3 | 409.9 | 222.4 | 316.1 | .00543 |
| 2.22 | 131.5 | 131.7 | 84.7 | 1159.1 | 664.6 | 399.7 | 228.2 | 313.9 | .00540 |
| 2.85 | 135.0 | 133.9 | 85.3 | 1123.1 | 651.5 | 364.4 | 216.2 | 290.3 | .00500 |
| 3.49 | 134.2 | 134.4 | 86.0 | 1163.6 | 674.2 | 388.5 | 224.1 | 306.3 | .00528 |
| 4.12 | 134.2 | 136.0 | 86.6 | 1157.2 | 653.2 | 391.2 | 212.7 | 302.0 | .00521 |
| 4.76 | 134.2 | 136.1 | 87.3 | 1176.4 | 665.2 | 402.7 | 218.9 | 310.8 | .00536 |
| 5.39 | 136.6 | 136.2 | 87.9 | 1145.5 | 669.2 | 377.6 | 222.4 | 300.0 | .00518 |
| 6.66 | 137.1 | 137.9 | 89.2 | 1156.3 | 665.0 | 386.8 | 218.8 | 302.8 | .00524 |
| 7.93 | 137.3 | 139.6 | 90.5 | 1163.3 | 665.4 | 397.4 | 216.6 | 307.0 | .00532 |
| 9.20 | 140.7 | 141.6 | 91.8 | 1153.7 | 665.4 | 376.4 | 213.2 | 294.8 | .00512 |
| 11.73 | 143.3 | 146.9 | 94.4 | 1159.2 | 663.1 | 376.6 | 200.6 | 288.6 | .00503 |
| 14.27 | 151.9 | 150.5 | 97.0 | 1147.4 | 665.8 | 330.8 | 196.8 | 263.8 | .00461 |
| 14.91 | 151.5 | 152.1 | 97.7 | 1164.9 | 663.3 | 341.6 | 192.5 | 267.0 | .00467 |
| 16.81 | 157.7 | 156.8 | 99.6 | 1145.7 | 657.5 | 310.6 | 181.1 | 245.8 | .00431 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=367.97 NU(S)A=207.03 NU(AV)A=287.50 ST(AV)A= .00500
E(+)= 615.05 ST(AV)/ST(4S)=2.00 F/F(4S)=6.16 (ST/ST(4S))/(F/F(4S))= .325
(F/F(4S))/(ST/ST(4S)) 3.0= .76 R(BAR)= 5.643 H(BAR)=21.442

RUN NUMBER=305HK08-60/10 E/D= .063 P/E=10.00 ALPA= 60 D= 2.956 IN
PR=.71 MDOT= .0250 LBM/SEC RE= 7967. QGE(R)= 263.2 BTU/HR-SQ FT
QGE(S)= 152.4 INLET TEMP= 77.9 F TATM= 73.3 F PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 123.8 | 121.8 | 78.6 | 215.8 | 122.9 | 77.9 | 46.4 | 62.1 | .01068 |
| .95 | 129.5 | 128.5 | 80.1 | 257.1 | 146.3 | 84.6 | 49.2 | 66.9 | .01152 |
| 1.59 | 135.3 | 135.2 | 81.6 | 239.7 | 122.2 | 72.4 | 37.0 | 54.7 | .00944 |
| 2.22 | 138.9 | 138.9 | 83.1 | 255.0 | 140.1 | 73.9 | 40.6 | 57.3 | .00990 |
| 2.85 | 142.4 | 142.0 | 84.6 | 231.8 | 123.4 | 64.7 | 34.7 | 49.7 | .00861 |
| 3.49 | 142.9 | 142.4 | 86.0 | 248.0 | 141.6 | 70.2 | 40.5 | 55.3 | .00961 |
| 4.12 | 142.5 | 142.4 | 87.5 | 255.6 | 143.2 | 74.8 | 41.9 | 58.3 | .01015 |
| 4.76 | 142.0 | 142.2 | 89.0 | 259.3 | 144.8 | 78.4 | 43.6 | 61.0 | .01064 |
| 5.39 | 142.0 | 142.0 | 90.5 | 253.6 | 145.9 | 78.7 | 45.3 | 62.0 | .01083 |
| 6.66 | 141.2 | 142.0 | 93.5 | 258.2 | 144.9 | 86.0 | 47.5 | 66.7 | .01171 |
| 7.93 | 141.6 | 142.0 | 96.4 | 256.5 | 145.9 | 89.9 | 50.7 | 70.3 | .01238 |
| 9.20 | 142.4 | 142.5 | 99.4 | 257.5 | 147.3 | 94.3 | 53.8 | 74.1 | .01310 |
| 11.73 | 146.7 | 147.3 | 105.3 | 257.0 | 145.2 | 96.9 | 54.0 | 75.4 | .01345 |
| 14.27 | 154.7 | 153.9 | 111.2 | 251.2 | 143.4 | 89.4 | 52.0 | 70.7 | .01270 |
| 14.91 | 155.7 | 155.5 | 112.7 | 250.5 | 142.0 | 92.0 | 51.2 | 71.6 | .01289 |
| 16.81 | 160.6 | 159.3 | 117.2 | 247.2 | 137.3 | 87.2 | 49.9 | 68.5 | .01241 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 87.65 NU(S)A= 49.47 NU(AV)A= 68.56 ST(AV)A= .01216
E(+)= 74.58 ST(AV)/ST(4S)=2.60 F/F(4S)=5.34 (ST/ST(4S))/(F/F(4S))= .487
(F/F(4S))/(ST/ST(4S)) 3.0= .30 R(BAR)= 4.005 H(BAR)= 9.673

RUN NUMBER=306HR12-60/10 E/D= .063 P/E=10.00 ALPA= 60 D= 2.956 IN
PR=.71 MDOT= .0419 LBM/SEC RE= 13388. QGE(R)= 374.1 BTU/HR-SQ FT
QGE(S)= 214.8 INLET TEMP= 79.1 F TATM= 73.0 F PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 119.1 | 114.7 | 79.7 | 284.4 | 187.3 | 117.5 | 87.1 | 102.3 | .01051 |
| .95 | 125.0 | 122.3 | 81.0 | 368.4 | 209.3 | 135.9 | 82.2 | 109.0 | .01122 |
| 1.59 | 130.9 | 129.9 | 82.2 | 349.8 | 179.1 | 116.5 | 60.8 | 88.7 | .00914 |
| 2.22 | 134.5 | 133.8 | 83.5 | 370.3 | 200.6 | 117.3 | 64.4 | 90.9 | .00938 |
| 2.85 | 138.5 | 136.8 | 84.7 | 335.4 | 189.7 | 100.6 | 58.8 | 79.7 | .00824 |
| 3.49 | 138.5 | 137.5 | 86.0 | 362.1 | 206.1 | 111.0 | 64.4 | 87.7 | .00909 |
| 4.12 | 137.9 | 138.0 | 87.2 | 367.0 | 201.2 | 116.4 | 63.7 | 90.0 | .00935 |
| 4.76 | 137.3 | 137.7 | 88.5 | 371.0 | 207.6 | 121.9 | 67.7 | 94.8 | .00985 |
| 5.39 | 137.2 | 137.4 | 89.7 | 363.8 | 208.7 | 122.7 | 70.1 | 96.4 | .01004 |
| 6.66 | 135.8 | 137.2 | 92.2 | 370.4 | 207.7 | 135.5 | 73.6 | 104.6 | .01093 |
| 7.93 | 136.0 | 137.0 | 94.8 | 369.6 | 209.1 | 142.2 | 78.6 | 110.4 | .01158 |
| 9.20 | 137.4 | 137.5 | 97.3 | 369.3 | 211.6 | 145.5 | 83.1 | 114.3 | .01203 |
| 11.73 | 143.7 | 144.4 | 102.3 | 368.1 | 207.4 | 139.3 | 77.2 | 108.3 | .01147 |
| 14.27 | 153.5 | 152.3 | 107.3 | 360.2 | 205.1 | 121.2 | 70.8 | 96.0 | .01024 |
| 14.91 | 154.4 | 154.0 | 108.5 | 369.9 | 205.4 | 125.3 | 70.1 | 97.7 | .01044 |
| 16.81 | 160.5 | 158.8 | 112.3 | 357.1 | 200.0 | 114.3 | 66.4 | 90.4 | .00970 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=129.41 NU(S)A= 72.93 NU(AV)A=101.17 ST(AV)A= .01066
E(+)= 125.65 ST(AV)/ST(4S)=2.68 F/F(4S)=6.18 (ST/ST(4S))/(F/F(4S))= .433
(F/F(4S))/(ST/ST(4S)) 3.0= .32 R(BAR)= 4.005 H(BAR)=11.403

RUN NUMBER=307HK20-60/10 E/D= .063 P/E=10.00 ALPA= 60 D= 2.956 IN
PR=.71 MDOT= .0636 LBM/SEC RE= 20335. QGE(R)= 516.8 BTU/HR-SQ FT
QGE(S)= 295.1 INLET TEMP= 80.2 F TATM= 72.6 F PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 118.0 | 113.4 | 80.8 | 377.2 | 227.6 | 164.5 | 113.3 | 138.9 | .00941 |
| .95 | 124.3 | 121.5 | 81.9 | 511.1 | 289.7 | 195.6 | 118.7 | 157.1 | .01066 |
| 1.59 | 130.5 | 129.6 | 83.0 | 488.2 | 252.9 | 166.3 | 87.9 | 127.1 | .00864 |
| 2.22 | 134.0 | 133.1 | 84.2 | 513.5 | 283.9 | 166.5 | 93.8 | 130.1 | .00886 |
| 2.85 | 137.9 | 136.0 | 85.3 | 475.1 | 268.0 | 145.6 | 85.2 | 115.4 | .00787 |
| 3.49 | 137.4 | 136.4 | 86.5 | 504.9 | 288.1 | 159.4 | 92.8 | 126.1 | .00861 |
| 4.12 | 136.3 | 136.8 | 87.6 | 509.8 | 281.6 | 168.1 | 91.9 | 130.0 | .00889 |
| 4.76 | 135.2 | 136.4 | 88.7 | 520.3 | 288.1 | 179.5 | 96.9 | 138.2 | .00947 |
| 5.39 | 135.4 | 136.0 | 89.9 | 504.5 | 289.2 | 177.3 | 100.3 | 138.8 | .00953 |
| 6.66 | 133.8 | 135.6 | 92.1 | 513.3 | 288.2 | 196.4 | 105.7 | 151.1 | .01040 |
| 7.93 | 133.8 | 135.2 | 94.4 | 514.1 | 291.0 | 207.3 | 113.3 | 160.3 | .01107 |
| 9.20 | 135.8 | 136.2 | 96.7 | 511.8 | 292.1 | 207.1 | 117.0 | 162.0 | .01123 |
| 11.73 | 142.7 | 144.2 | 101.2 | 510.9 | 287.1 | 193.6 | 105.0 | 149.3 | .01041 |
| 14.27 | 153.2 | 151.9 | 105.8 | 502.1 | 286.0 | 165.3 | 96.7 | 131.0 | .00919 |
| 14.91 | 154.0 | 153.7 | 106.9 | 513.5 | 285.3 | 169.9 | 94.9 | 132.4 | .00930 |
| 16.81 | 160.6 | 158.4 | 110.3 | 499.4 | 280.8 | 153.9 | 90.5 | 122.2 | .00862 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=182.56 NU(S)A=102.00 NU(AV)A=142.28 ST(AV)A= .00987
E(+)= 191.09 ST(AV)/ST(4S)=2.79 F/F(4S)=6.90 (ST/ST(4S))/(F/F(4S))= .404
(F/F(4S))/(ST/ST(4S)) 3.0= .32 R(BAR)= 4.005 H(BAR)=12.537

RUN NUMBER=308HR40-60/10    E/D= .063   P/E=10.00   ALPA= 60   D= 2.956 IN
PR=.71   MDOT= .1240 LBM/SEC   RE= 39758.   QGE(R)= 814.7 BTU/HR-SQ FT
QGE(S)= 457.2   INLET TEMP= 81.3 F   TATM= 73.2 F   PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.0 | 114.2 | 81.8 | 622.0 | 336.0 | 303.3 | 167.9 | 235.6 | .00820 |
| .95 | 123.0 | 122.9 | 82.7 | 809.2 | 451.8 | 325.1 | 181.7 | 253.4 | .00883 |
| 1.59 | 130.9 | 131.6 | 83.6 | 771.5 | 406.7 | 263.4 | 136.8 | 200.1 | .00698 |
| 2.22 | 134.2 | 134.7 | 84.5 | 813.9 | 448.1 | 264.3 | 144.1 | 204.2 | .00714 |
| 2.85 | 138.2 | 137.4 | 85.4 | 762.7 | 426.9 | 232.8 | 132.3 | 182.6 | .00639 |
| 3.49 | 136.4 | 137.2 | 86.3 | 808.5 | 452.6 | 259.8 | 143.2 | 201.5 | .00706 |
| 4.12 | 134.7 | 137.3 | 87.2 | 807.9 | 443.0 | 273.5 | 142.2 | 207.9 | .00729 |
| 4.76 | 133.0 | 136.5 | 88.2 | 827.2 | 450.3 | 295.9 | 149.4 | 222.7 | .00782 |
| 5.39 | 133.7 | 135.7 | 89.1 | 800.6 | 453.3 | 287.3 | 155.7 | 221.5 | .00779 |
| 6.66 | 132.3 | 135.2 | 90.9 | 811.6 | 450.4 | 313.1 | 162.4 | 237.7 | .00838 |
| 7.93 | 132.6 | 134.7 | 92.7 | 814.0 | 454.7 | 325.1 | 172.5 | 248.8 | .00879 |
| 9.20 | 135.8 | 136.3 | 94.6 | 807.8 | 453.8 | 311.0 | 172.6 | 241.8 | .00857 |
| 11.73 | 142.2 | 144.7 | 98.2 | 809.2 | 448.3 | 290.4 | 152.2 | 221.3 | .00788 |
| 14.27 | 152.8 | 151.0 | 101.9 | 797.3 | 448.2 | 245.5 | 143.3 | 194.4 | .00695 |
| 14.91 | 152.8 | 152.4 | 102.8 | 816.7 | 448.9 | 255.8 | 141.8 | 198.8 | .00712 |
| 16.81 | 160.8 | 157.0 | 105.5 | 795.5 | 443.4 | 224.5 | 134.4 | 179.4 | .00645 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=281.06   NU(S)A=152.92   NU(AV)A=216.99   ST(AV)A= .00769
E(+)= 374.53   ST(AV)/ST(4S)=2.60   F/F(4S)=8.14   (ST/ST(4S))/(F/F(4S))= .319
(F/F(4S))/(ST/ST(4S)) 3.0= .46   R(BAR)= 4.005   H(BAR)=16.834

RUN NUMBER=309HR60-60/10    E/D= .063   P/E=10.00   ALPA= 60   D= 2.956 IN
PR=.71   MDOT= .1800 LBM/SEC   RE= 57645.   QGE(R)=1115.3 BTU/HR-SQ FT
QGE(S)= 583.3   INLET TEMP= 83.2 F   TATM= 73.0 F   PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 114.0 | 116.0 | 83.6 | 906.0 | 419.1 | 482.0 | 209.2 | 345.6 | .00831 |
| .95 | 123.5 | 124.7 | 84.5 | 1109.8 | 577.6 | 459.2 | 231.8 | 345.5 | .00832 |
| 1.59 | 132.9 | 133.4 | 85.3 | 1065.0 | 531.4 | 360.4 | 178.2 | 269.3 | .00649 |
| 2.22 | 136.8 | 136.2 | 86.1 | 1117.1 | 572.9 | 355.2 | 184.2 | 269.7 | .00651 |
| 2.85 | 141.7 | 138.6 | 87.0 | 1050.3 | 553.0 | 308.5 | 172.2 | 240.4 | .00581 |
| 3.49 | 139.0 | 138.1 | 87.8 | 1114.1 | 579.4 | 349.5 | 185.0 | 267.2 | .00646 |
| 4.12 | 137.1 | 138.0 | 88.7 | 1108.3 | 568.9 | 367.2 | 184.9 | 276.0 | .00668 |
| 4.76 | 135.1 | 137.0 | 89.5 | 1130.4 | 576.3 | 396.9 | 194.2 | 295.6 | .00716 |
| 5.39 | 135.9 | 136.0 | 90.3 | 1100.1 | 580.7 | 386.1 | 203.3 | 294.7 | .00715 |
| 6.66 | 134.4 | 135.6 | 92.0 | 1111.6 | 576.4 | 418.3 | 210.9 | 314.6 | .00765 |
| 7.93 | 134.4 | 135.2 | 93.7 | 1114.6 | 580.5 | 435.5 | 222.4 | 329.0 | .00802 |
| 9.20 | 137.4 | 136.8 | 95.4 | 1106.5 | 580.0 | 418.4 | 222.1 | 320.3 | .00783 |
| 11.73 | 143.8 | 145.5 | 98.8 | 1110.3 | 574.0 | 388.8 | 193.6 | 291.2 | .00715 |
| 14.27 | 155.7 | 151.5 | 102.1 | 1096.2 | 574.7 | 320.7 | 182.7 | 251.7 | .00621 |
| 14.91 | 155.6 | 153.0 | 103.0 | 1118.6 | 574.3 | 333.1 | 179.9 | 256.5 | .00633 |
| 16.81 | 164.4 | 157.3 | 105.5 | 1094.4 | 569.7 | 289.8 | 171.6 | 230.7 | .00571 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=374.10   NU(S)A=196.56   NU(AV)A=285.33   ST(AV)A= .00698
E(+)= 543.49   ST(AV)/ST(4S)=2.58   F/F(4S)=8.86   (ST/ST(4S))/(F/F(4S))= .291
(F/F(4S))/(ST/ST(4S)) 3.0= .52   R(BAR)= 4.005   H(BAR)=18.838

RUN NUMBER=310HR80-60/10    E/D= .063   P/E=10.00   ALPA= 60   D= 2.956 IN
PR=.71   MDOT= .2550 LBM/SEC   RE= 81819.   QGE(R)=1323.2 BTU/HR-SQ FT
QGE(S)= 762.0   INLET TEMP= 83.4 F   TATM= 72.4 F   PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 109.1 | 118.2 | 83.8 | 1140.9 | 544.7 | 727.7 | 255.6 | 491.7 | .00834 |
| .95 | 120.0 | 126.6 | 84.5 | 1317.9 | 756.1 | 598.8 | 289.8 | 444.3 | .00755 |
| 1.59 | 130.9 | 135.0 | 85.2 | 1267.6 | 709.7 | 447.0 | 229.9 | 338.4 | .00576 |
| 2.22 | 135.5 | 137.5 | 85.9 | 1322.6 | 752.7 | 430.1 | 235.0 | 332.5 | .00566 |
| 2.85 | 140.8 | 139.8 | 86.7 | 1251.0 | 730.3 | 371.7 | 221.1 | 296.4 | .00505 |
| 3.49 | 137.4 | 139.0 | 87.4 | 1325.6 | 761.1 | 425.9 | 237.0 | 331.5 | .00565 |
| 4.12 | 135.2 | 139.0 | 88.1 | 1316.3 | 745.1 | 448.7 | 235.0 | 341.9 | .00584 |
| 4.76 | 133.0 | 137.8 | 88.9 | 1341.9 | 754.8 | 487.2 | 247.2 | 367.2 | .00628 |
| 5.39 | 134.0 | 136.6 | 89.6 | 1305.7 | 760.3 | 470.6 | 258.9 | 364.8 | .00624 |
| 6.66 | 132.0 | 136.2 | 91.0 | 1320.6 | 755.0 | 515.0 | 267.0 | 391.0 | .00670 |
| 7.93 | 132.0 | 135.8 | 92.5 | 1324.2 | 759.5 | 534.2 | 279.5 | 406.8 | .00699 |
| 9.20 | 135.8 | 137.6 | 94.0 | 1314.9 | 758.2 | 499.5 | 276.2 | 387.8 | .00668 |
| 11.73 | 141.4 | 146.2 | 96.9 | 1319.1 | 752.2 | 468.7 | 241.3 | 355.0 | .00613 |
| 14.27 | 154.0 | 151.4 | 99.8 | 1301.9 | 754.1 | 377.9 | 230.2 | 304.1 | .00528 |
| 14.91 | 153.3 | 152.9 | 100.5 | 1328.6 | 753.2 | 395.7 | 226.1 | 310.9 | .00540 |
| 16.81 | 162.1 | 157.5 | 102.7 | 1301.7 | 747.9 | 343.5 | 213.9 | 278.7 | .00485 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=451.36   NU(S)A=247.20   NU(AV)A=349.28   ST(AV)A= .00602
E(+)= 772.36   ST(AV)/ST(4S)=2.42   F/F(4S)=9.58   (ST/ST(4S))/(F/F(4S))= .252
(F/F(4S))/(ST/ST(4S)) 3.0= .68   R(BAR)= 4.005   H(BAR)=22.272

RUN NUMBER=279HR08-45/10 E/D= .063 P/E=10.00 ALPA= 45 D= 2.956 IN
PR=.71 MDOT= .0274 LBM/SEC RE= 8761. QGE(R)= 243.9 BTU/HR-SQ FT
QGE(S)= 138.6 INLET TEMP= 77.3 F TATM= 72.4 F PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 114.2 | 113.5 | 77.9 | 185.2 | 119.2 | 83.3 | 54.7 | 69.0 | .01082 |
| .95 | 119.4 | 119.3 | 79.2 | 238.7 | 133.4 | 96.5 | 54.1 | 75.3 | .01184 |
| 1.59 | 124.7 | 125.2 | 80.4 | 219.0 | 112.6 | 80.4 | 40.9 | 60.6 | .00955 |
| 2.22 | 127.5 | 128.5 | 81.7 | 241.5 | 127.8 | 85.4 | 44.3 | 64.9 | .01023 |
| 2.85 | 130.8 | 131.2 | 82.9 | 212.8 | 115.1 | 71.9 | 38.6 | 55.2 | .00873 |
| 3.49 | 131.0 | 131.8 | 84.2 | 230.2 | 128.8 | 79.3 | 43.7 | 61.5 | .00974 |
| 4.12 | 130.3 | 132.0 | 85.4 | 237.5 | 128.0 | 85.2 | 44.3 | 64.7 | .01027 |
| 4.76 | 129.6 | 131.7 | 86.6 | 242.4 | 132.0 | 90.7 | 47.1 | 68.9 | .01095 |
| 5.39 | 129.5 | 131.4 | 87.9 | 235.7 | 133.9 | 90.9 | 49.4 | 70.2 | .01117 |
| 6.66 | 128.6 | 131.5 | 90.4 | 240.7 | 132.1 | 100.7 | 51.3 | 76.0 | .01214 |
| 7.93 | 129.2 | 131.6 | 92.9 | 242.4 | 135.0 | 106.2 | 55.5 | 80.9 | .01296 |
| 9.20 | 132.2 | 133.2 | 95.4 | 238.7 | 135.2 | 102.7 | 56.7 | 79.7 | .01282 |
| 11.73 | 140.3 | 141.4 | 100.3 | 235.7 | 129.6 | 92.8 | 49.7 | 71.3 | .01153 |
| 14.27 | 147.1 | 147.0 | 105.3 | 229.1 | 128.1 | 85.5 | 48.0 | 66.8 | .01088 |
| 14.91 | 146.8 | 147.7 | 106.6 | 241.8 | 130.2 | 93.6 | 49.3 | 71.5 | .01167 |
| 16.81 | 150.4 | 149.7 | 110.3 | 229.6 | 125.8 | 88.7 | 49.5 | 69.1 | .01133 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 93.12 NU(S)A= 50.04 NU(AV)A= 71.58 ST(AV)A= .01153
E(+)= 64.86 ST(AV)/ST(4S)=2.55 F/F(4S)=3.42 (ST/ST(4S))/(F/F(4S))= .745
(F/F(4S))/(ST/ST(4S)) 3.0= .21 R(BAR)= 5.790 H(BAR)= 7.601

RUN NUMBER=280HR12-45/10 E/D= .063 P/E=10.00 ALPA= 45 D= 2.956 IN
PR=.71 MDOT= .0412 LBM/SEC RE= 13207. QGE(R)= 332.5 BTU/HR-SQ FT
QGE(S)= 207.8 INLET TEMP= 77.9 F TATM= 71.6 F PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 113.3 | 111.8 | 78.5 | 239.4 | 166.0 | 112.1 | 81.2 | 96.7 | .01008 |
| .95 | 118.8 | 118.5 | 79.7 | 327.3 | 202.7 | 136.0 | 85.0 | 110.5 | .01154 |
| 1.59 | 124.3 | 125.1 | 80.8 | 304.3 | 175.5 | 113.6 | 64.3 | 88.9 | .00930 |
| 2.22 | 127.0 | 128.5 | 82.0 | 334.2 | 198.4 | 120.2 | 69.2 | 94.7 | .00992 |
| 2.85 | 130.7 | 131.4 | 83.2 | 296.3 | 184.2 | 100.8 | 61.8 | 81.3 | .00853 |
| 3.49 | 130.6 | 132.2 | 84.3 | 321.6 | 198.0 | 112.2 | 66.8 | 89.5 | .00941 |
| 4.12 | 130.0 | 132.6 | 85.5 | 326.1 | 196.7 | 118.2 | 67.3 | 92.7 | .00977 |
| 4.76 | 129.3 | 132.5 | 86.7 | 332.2 | 201.1 | 125.3 | 70.7 | 98.0 | .01033 |
| 5.39 | 129.4 | 132.3 | 87.8 | 323.0 | 202.4 | 124.7 | 73.0 | 98.9 | .01045 |
| 6.66 | 128.4 | 132.5 | 90.2 | 329.9 | 201.1 | 138.0 | 76.1 | 107.0 | .01134 |
| 7.93 | 129.2 | 132.6 | 92.5 | 331.6 | 204.4 | 144.0 | 81.2 | 112.6 | .01197 |
| 9.20 | 132.7 | 134.4 | 94.8 | 327.0 | 204.7 | 137.1 | 82.1 | 109.6 | .01169 |
| 11.73 | 141.5 | 143.6 | 99.5 | 324.5 | 198.4 | 121.8 | 70.9 | 96.3 | .01034 |
| 14.27 | 149.7 | 149.7 | 104.2 | 315.6 | 196.7 | 108.4 | 67.5 | 88.0 | .00950 |
| 14.91 | 149.1 | 150.5 | 105.4 | 332.1 | 200.3 | 118.4 | 69.3 | 93.8 | .01015 |
| 16.81 | 153.5 | 153.5 | 108.9 | 317.9 | 194.6 | 110.6 | 67.7 | 89.1 | .00969 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=123.64 NU(S)A= 72.48 NU(AV)A= 98.06 ST(AV)A= .01047
E(+)= 97.86 ST(AV)/ST(4S)=2.62 F/F(4S)=3.83 (ST/ST(4S))/(F/F(4S))= .683
(F/F(4S))/(ST/ST(4S)) 3.0= .21 R(BAR)= 5.790 H(BAR)= 8.635

RUN NUMBER=281HR20-45/10 E/D= .063 P/E=10.00 ALPA= 45 D= 2.956 IN
PR=.71 MDOT= .0645 LBM/SEC RE= 20689. QGE(R)= 473.8 BTU/HR-SQ FT
QGE(S)= 264.6 INLET TEMP= 79.5 F TATM= 72.4 F PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 113.2 | 110.2 | 80.0 | 337.6 | 213.4 | 165.4 | 114.9 | 140.2 | .00936 |
| .95 | 119.2 | 117.7 | 81.0 | 468.7 | 259.7 | 199.6 | 114.9 | 157.3 | .01051 |
| 1.59 | 125.1 | 125.2 | 82.1 | 442.0 | 225.8 | 166.4 | 84.8 | 125.6 | .00841 |
| 2.22 | 127.8 | 128.5 | 83.1 | 478.7 | 254.5 | 173.3 | 90.6 | 131.9 | .00884 |
| 2.85 | 131.8 | 131.3 | 84.1 | 433.3 | 241.4 | 146.7 | 82.6 | 114.6 | .00770 |
| 3.49 | 131.5 | 132.0 | 85.1 | 462.9 | 256.5 | 160.9 | 88.2 | 124.5 | .00837 |
| 4.12 | 130.7 | 132.5 | 86.1 | 467.4 | 252.0 | 169.0 | 87.5 | 128.2 | .00863 |
| 4.76 | 129.8 | 132.3 | 87.2 | 477.5 | 258.1 | 179.9 | 91.9 | 135.9 | .00917 |
| 5.39 | 130.2 | 132.0 | 88.2 | 463.2 | 259.5 | 176.8 | 95.0 | 135.9 | .00918 |
| 6.66 | 129.4 | 132.1 | 90.2 | 472.2 | 258.1 | 192.7 | 98.6 | 145.6 | .00986 |
| 7.93 | 130.9 | 132.1 | 92.3 | 472.6 | 262.6 | 194.9 | 105.0 | 150.0 | .01018 |
| 9.20 | 135.0 | 134.4 | 94.3 | 467.5 | 261.3 | 182.4 | 103.5 | 143.0 | .00973 |
| 11.73 | 144.0 | 144.2 | 98.4 | 465.3 | 254.6 | 160.9 | 87.7 | 124.3 | .00851 |
| 14.27 | 151.6 | 149.7 | 102.5 | 455.6 | 254.4 | 145.4 | 84.3 | 114.9 | .00791 |
| 14.91 | 150.5 | 150.6 | 103.5 | 477.6 | 257.0 | 158.8 | 85.4 | 122.1 | .00842 |
| 16.81 | 156.6 | 153.8 | 106.5 | 457.6 | 251.7 | 142.4 | 83.0 | 112.7 | .00780 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=168.06 NU(S)A= 91.88 NU(AV)A=129.97 ST(AV)A= .00886
E(+)= 153.55 ST(AV)/ST(4S)=2.52 F/F(4S)=4.31 (ST/ST(4S))/(F/F(4S))= .583
(F/F(4S))/(ST/ST(4S)) 3.0= .27 R(BAR)= 5.790 H(BAR)=10.698

RUN NUMBER=282HR40-45/10    E/D= .063   P/E=10.00   ALPA= 45   D= 2.956 IN
PR=.71   MDOT= .1220 LBM/SEC   RE= 39142.   QGE(R)= 717.7 BTU/HR-SQ FT
QGE(S)= 400.4   INLET TEMP= 82.2 F   TATM= 74.2 F   PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 112.2 | 111.2 | 82.6 | 519.5 | 294.1 | 284.2 | 166.5 | 225.4 | .00798 |
| .95 | 118.5 | 118.9 | 83.4 | 712.8 | 395.5 | 328.3 | 180.2 | 254.2 | .00901 |
| 1.59 | 124.9 | 126.6 | 84.2 | 683.6 | 358.2 | 271.7 | 136.4 | 204.1 | .00724 |
| 2.22 | 127.6 | 129.7 | 85.1 | 724.4 | 391.4 | 274.6 | 141.4 | 208.0 | .00739 |
| 2.85 | 131.9 | 132.4 | 85.9 | 669.4 | 376.5 | 234.2 | 130.3 | 182.3 | .00648 |
| 3.49 | 130.8 | 132.9 | 86.7 | 711.5 | 390.8 | 259.4 | 136.0 | 197.7 | .00704 |
| 4.12 | 129.7 | 133.0 | 87.5 | 711.6 | 389.1 | 270.9 | 137.4 | 204.1 | .00728 |
| 4.76 | 128.6 | 132.5 | 88.3 | 723.7 | 394.0 | 288.2 | 143.1 | 215.6 | .00770 |
| 5.39 | 129.0 | 132.0 | 89.1 | 708.2 | 396.7 | 284.6 | 148.3 | 216.4 | .00774 |
| 6.66 | 128.5 | 132.0 | 90.8 | 715.7 | 394.1 | 303.1 | 152.7 | 227.9 | .00816 |
| 7.93 | 130.0 | 132.0 | 92.4 | 718.4 | 399.7 | 304.5 | 160.8 | 232.7 | .00835 |
| 9.20 | 134.9 | 134.8 | 94.0 | 710.3 | 395.6 | 276.2 | 154.2 | 215.2 | .00775 |
| 11.73 | 143.6 | 143.2 | 97.3 | 709.3 | 391.1 | 242.2 | 134.7 | 188.5 | .00681 |
| 14.27 | 150.7 | 148.1 | 100.6 | 697.7 | 391.4 | 218.7 | 129.4 | 174.1 | .00632 |
| 14.91 | 148.9 | 149.1 | 101.4 | 726.7 | 392.8 | 240.2 | 129.3 | 184.8 | .00671 |
| 16.81 | 156.4 | 152.5 | 103.8 | 700.0 | 387.8 | 208.4 | 124.7 | 166.5 | .00607 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=258.92   NU(S)A=140.09   NU(AV)A=199.80   ST(AV)A= .00719
E(+)= 291.18   ST(AV)/ST(45)=2.42   F/F(45)=5.05   (ST/ST(45))/(F/F(45))= .480
(F/F(45))/(ST/ST(45))  3.0= .36   R(BAR)= 5.790   H(BAR)=13.786

RUN NUMBER=283HR60-45/10    E/D= .063   P/E=10.00   ALPA= 45   D= 2.956 IN
PR=.71   MDOT= .1760 LBM/SEC   RE= 56433.   QGE(R)= 951.9 BTU/HR-SQ FT
QGE(S)= 500.2   INLET TEMP= 83.8 F   TATM= 74.2 F   PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 112.5 | 112.8 | 84.2 | 720.1 | 355.4 | 410.4 | 200.5 | 305.4 | .00752 |
| .95 | 119.6 | 120.7 | 84.9 | 946.9 | 495.1 | 439.9 | 223.4 | 331.7 | .00817 |
| 1.59 | 126.7 | 128.5 | 85.6 | 912.6 | 454.8 | 357.8 | 170.9 | 264.3 | .00652 |
| 2.22 | 129.6 | 131.3 | 86.4 | 962.8 | 489.9 | 358.4 | 175.4 | 266.9 | .00659 |
| 2.85 | 134.6 | 133.6 | 87.1 | 893.3 | 476.1 | 302.3 | 164.6 | 233.4 | .00577 |
| 3.49 | 132.8 | 133.7 | 87.8 | 949.0 | 493.6 | 338.8 | 172.8 | 255.8 | .00633 |
| 4.12 | 131.5 | 133.8 | 88.6 | 945.6 | 486.4 | 353.6 | 172.4 | 263.0 | .00651 |
| 4.76 | 130.1 | 133.0 | 89.3 | 963.6 | 493.7 | 378.3 | 181.0 | 279.7 | .00693 |
| 5.39 | 131.0 | 132.2 | 90.0 | 938.9 | 498.9 | 366.7 | 189.3 | 278.0 | .00690 |
| 6.66 | 130.3 | 132.5 | 91.5 | 950.5 | 493.8 | 391.1 | 192.2 | 291.7 | .00725 |
| 7.93 | 132.0 | 132.8 | 93.0 | 952.5 | 498.7 | 388.7 | 199.4 | 294.0 | .00732 |
| 9.20 | 137.2 | 135.6 | 94.5 | 943.6 | 494.6 | 350.6 | 190.9 | 270.8 | .00676 |
| 11.73 | 145.6 | 143.0 | 97.4 | 943.7 | 491.7 | 309.4 | 170.4 | 239.9 | .00601 |
| 14.27 | 153.4 | 148.5 | 100.3 | 929.3 | 490.6 | 275.7 | 160.1 | 217.9 | .00548 |
| 14.91 | 151.0 | 149.5 | 101.1 | 964.1 | 492.3 | 303.4 | 159.9 | 231.6 | .00583 |
| 16.81 | 159.6 | 152.6 | 103.3 | 932.0 | 487.9 | 259.1 | 154.9 | 207.0 | .00523 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=330.94   NU(S)A=176.11   NU(AV)A=253.52   ST(AV)A= .00633
E(+)= 420.19   ST(AV)/ST(45)=2.33   F/F(45)=5.49   (ST/ST(45))/(F/F(45))= .425
(F/F(45))/(ST/ST(45))  3.0= .43   R(BAR)= 5.790   H(BAR)=16.030

RUN NUMBER=284HR80-45/10    E/D= .063   P/E=10.00   ALPA= 45   D= 2.956 IN
PR=.71   MDOT= .2510 LBM/SEC   RE= 80834.   QGE(R)=1094.6 BTU/HR-SQ FT
QGE(S)= 623.5   INLET TEMP= 82.4 F   TATM= 72.5 F   PATM=14.61 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 106.6 | 112.3 | 82.7 | 894.8 | 448.0 | 606.1 | 245.1 | 425.6 | .00733 |
| .95 | 114.2 | 119.6 | 83.3 | 1090.0 | 618.3 | 570.4 | 275.6 | 423.0 | .00729 |
| 1.59 | 121.8 | 126.9 | 83.9 | 1053.2 | 579.2 | 448.8 | 217.7 | 333.3 | .00575 |
| 2.22 | 124.9 | 129.3 | 84.5 | 1100.8 | 616.4 | 440.5 | 222.2 | 331.4 | .00572 |
| 2.85 | 129.4 | 131.6 | 85.1 | 1038.3 | 595.5 | 378.2 | 206.7 | 292.5 | .00505 |
| 3.49 | 127,4 | 131.2 | 85.8 | 1093.3 | 621.0 | 422.9 | 220.1 | 321.5 | .00556 |
| 4.12 | 126.0 | 131.3 | 86.4 | 1088.7 | 609.0 | 442.0 | 218.1 | 330.0 | .00571 |
| 4.76 | 124.6 | 130.4 | 87.0 | 1108.0 | 617.1 | 473.3 | 228.4 | 350.9 | .00608 |
| 5.39 | 125.6 | 129.5 | 87.6 | 1081.5 | 623.0 | 456.8 | 238.7 | 347.8 | .00603 |
| 6.66 | 124.9 | 129.9 | 88.8 | 1094.0 | 617.2 | 485.7 | 241.0 | 363.4 | .00631 |
| 7.93 | 126.8 | 130.2 | 90.0 | 1094.8 | 621.4 | 476.2 | 247.4 | 361.8 | .00629 |
| 9.20 | 131.8 | 132.7 | 91.2 | 1086.0 | 617.7 | 427.5 | 237.9 | 332.7 | .00580 |
| 11.73 | 138.8 | 139.0 | 93.7 | 1087.9 | 615.6 | 383.4 | 216.0 | 299.7 | .00524 |
| 14.27 | 147.1 | 144.2 | 96.1 | 1070.9 | 614.7 | 332.7 | 202.4 | 267.5 | .00469 |
| 14.91 | 144.4 | 145.3 | 96.7 | 1108.7 | 615.7 | 368.3 | 200.7 | 284.5 | .00499 |
| 16.81 | 152.9 | 148.5 | 98.6 | 1074.8 | 611.3 | 312.1 | 193.1 | 252.6 | .00444 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=407.17   NU(S)A=221.30   NU(AV)A=314.24   ST(AV)A= .00548
E(+)= 602.68   ST(AV)/ST(45)=2.20   F/F(45)=5.95   (ST/ST(45))/(F/F(45))= .369
(F/F(45))/(ST/ST(45))  3.0= .56   R(BAR)= 5.790   H(BAR)=18.943

RUN NUMBER=227HR08-30/10 E/D= .063 P/E=10.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .0237 LBM/SEC RE= 7567. QGE(R)= 209.2 BTU/HR-SQ FT
QGE(S)= 124.7 INLET TEMP= 79.6 F TATM= 73.8 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.2 | 113.6 | 80.2 | 170.8 | 101.5 | 79.4 | 49.5 | 64.4 | .01170 |
| .95 | 120.0 | 119.1 | 81.5 | 204.1 | 119.7 | 86.0 | 51.6 | 68.8 | .01253 |
| 1.59 | 124.7 | 124.6 | 82.7 | 192.9 | 106.3 | 74.4 | 41.1 | 57.7 | .01053 |
| 2.22 | 128.2 | 128.5 | 84.0 | 204.0 | 113.1 | 74.6 | 41.0 | 57.8 | .01056 |
| 2.85 | 131.7 | 131.7 | 85.2 | 185.0 | 103.1 | 64.2 | 35.8 | 50.0 | .00915 |
| 3.49 | 133.0 | 133.0 | 86.5 | 197.9 | 115.8 | 68.5 | 40.1 | 54.3 | .00995 |
| 4.12 | 133.7 | 134.0 | 87.8 | 202.6 | 113.3 | 70.8 | 39.3 | 55.1 | .01011 |
| 4.76 | 134.4 | 134.4 | 89.0 | 197.7 | 118.0 | 69.8 | 41.7 | 55.7 | .01025 |
| 5.39 | 134.5 | 134.8 | 90.3 | 200.7 | 116.6 | 72.5 | 41.9 | 57.2 | .01054 |
| 6.66 | 134.0 | 135.1 | 92.8 | 205.2 | 118.0 | 79.3 | 44.4 | 61.8 | .01143 |
| 7.93 | 134.8 | 135.4 | 95.3 | 202.1 | 118.3 | 81.1 | 46.8 | 64.0 | .01187 |
| 9.20 | 135.4 | 135.9 | 97.8 | 204.6 | 119.9 | 85.9 | 49.7 | 67.8 | .01263 |
| 11.73 | 139.8 | 140.0 | 102.8 | 203.3 | 119.0 | 86.2 | 50.2 | 68.2 | .01278 |
| 14.27 | 147.0 | 147.3 | 107.8 | 199.9 | 116.1 | 79.4 | 45.7 | 62.6 | .01181 |
| 14.91 | 148.4 | 149.0 | 109.1 | 202.4 | 115.2 | 80.0 | 44.8 | 62.4 | .01179 |
| 16.81 | 153.6 | 153.1 | 112.9 | 194.5 | 110.5 | 73.7 | 42.4 | 58.0 | .01102 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 78.97 NU(S)A= 45.37 NU(AV)A= 62.17 ST(AV)A= .01160
E(+)= 53.88 ST(AV)/ST(4S)=2.44 F/F(4S)=3.03 (ST/ST(4S))/(F/F(4S))= .806
(F/F(4S))/(ST/ST(4S)) 3.0= .21 R(BAR)= 6.125 H(BAR)= 7.151

RUN NUMBER=228HR12-30/10 E/D= .063 P/E=10.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .0427 LBM/SEC RE= 13674. QGE(R)= 297.9 BTU/HR-SQ FT
QGE(S)= 180.1 INLET TEMP= 81.0 F TATM= 73.2 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 113.1 | 110.9 | 81.5 | 242.2 | 156.1 | 124.3 | 86.1 | 105.2 | .01063 |
| .95 | 118.3 | 117.4 | 82.5 | 292.9 | 175.3 | 132.5 | 81.3 | 106.9 | .01082 |
| 1.59 | 123.5 | 123.9 | 83.5 | 277.2 | 153.6 | 112.0 | 61.4 | 86.7 | .00879 |
| 2.22 | 126.8 | 127.8 | 84.5 | 291.2 | 167.4 | 111.1 | 62.4 | 86.8 | .00880 |
| 2.85 | 130.0 | 130.8 | 85.5 | 271.7 | 157.5 | 98.4 | 56.0 | 77.2 | .00784 |
| 3.49 | 130.7 | 131.8 | 86.5 | 290.0 | 170.5 | 105.5 | 60.5 | 83.0 | .00845 |
| 4.12 | 131.2 | 132.4 | 87.5 | 291.5 | 171.2 | 107.1 | 61.2 | 84.2 | .00857 |
| 4.76 | 131.7 | 132.7 | 88.5 | 283.4 | 173.6 | 105.2 | 62.9 | 84.1 | .00858 |
| 5.39 | 131.2 | 133.0 | 89.5 | 293.1 | 172.5 | 112.5 | 63.4 | 88.0 | .00899 |
| 6.66 | 130.8 | 133.2 | 91.5 | 293.4 | 173.5 | 119.0 | 66.4 | 92.7 | .00950 |
| 7.93 | 131.3 | 133.4 | 93.5 | 292.9 | 174.3 | 123.1 | 69.4 | 96.3 | .00989 |
| 9.20 | 132.5 | 134.0 | 95.5 | 293.7 | 176.2 | 125.7 | 72.5 | 99.1 | .01021 |
| 11.73 | 138.4 | 139.4 | 99.5 | 291.3 | 173.8 | 117.8 | 68.5 | 93.2 | .00965 |
| 14.27 | 145.5 | 146.7 | 103.4 | 286.9 | 170.8 | 106.7 | 61.8 | 84.2 | .00877 |
| 14.91 | 146.4 | 148.1 | 104.4 | 293.8 | 170.6 | 109.5 | 61.0 | 85.3 | .00889 |
| 16.81 | 151.8 | 151.5 | 107.4 | 282.5 | 165.7 | 99.1 | 58.5 | 78.8 | .00825 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=113.43 NU(S)A= 65.07 NU(AV)A= 89.25 ST(AV)A= .00920
E(+)= 92.28 ST(AV)/ST(4S)=2.33 F/F(4S)=3.20 (ST/ST(4S))/(F/F(4S))= .727
(F/F(4S))/(ST/ST(4S)) 3.0= .25 R(BAR)= 6.636 H(BAR)= 9.023

RUN NUMBER=229HR20-30/10 E/D= .063 P/E=10.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .0631 LBM/SEC RE= 20162. QGE(R)= 487.7 BTU/HR-SQ FT
QGE(S)= 252.2 INLET TEMP= 82.0 F TATM= 74.3 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 118.0 | 112.4 | 82.5 | 374.3 | 211.9 | 170.8 | 114.8 | 142.8 | .00978 |
| .95 | 124.2 | 120.6 | 83.6 | 482.2 | 247.1 | 191.8 | 108.0 | 149.9 | .01028 |
| 1.59 | 130.4 | 128.7 | 84.6 | 460.2 | 217.6 | 162.1 | 79.6 | 120.8 | .00830 |
| 2.22 | 134.0 | 133.2 | 85.7 | 490.0 | 236.3 | 163.4 | 80.0 | 121.7 | .00837 |
| 2.85 | 138.6 | 136.6 | 86.7 | 444.3 | 225.7 | 137.7 | 72.7 | 105.2 | .00725 |
| 3.49 | 138.6 | 137.5 | 87.7 | 484.6 | 244.4 | 153.0 | 78.9 | 115.9 | .00800 |
| 4.12 | 139.1 | 138.3 | 88.8 | 480.6 | 239.9 | 153.1 | 77.7 | 115.4 | .00797 |
| 4.76 | 139.6 | 138.5 | 89.8 | 471.7 | 245.1 | 151.7 | 80.7 | 116.2 | .00804 |
| 5.39 | 139.0 | 138.6 | 90.9 | 481.7 | 244.7 | 159.9 | 81.9 | 120.9 | .00837 |
| 6.66 | 138.2 | 138.8 | 93.0 | 483.9 | 245.1 | 170.3 | 85.2 | 127.8 | .00888 |
| 7.93 | 139.0 | 138.9 | 95.1 | 482.0 | 246.6 | 174.0 | 89.2 | 131.6 | .00917 |
| 9.20 | 140.5 | 139.8 | 97.1 | 483.7 | 248.7 | 176.4 | 92.2 | 134.3 | .00938 |
| 11.73 | 146.4 | 147.2 | 101.3 | 479.6 | 244.4 | 160.0 | 83.7 | 121.9 | .00856 |
| 14.27 | 156.5 | 155.2 | 105.5 | 477.4 | 241.9 | 146.2 | 76.0 | 111.1 | .00785 |
| 14.91 | 158.1 | 156.7 | 106.6 | 479.8 | 240.2 | 145.0 | 74.6 | 109.8 | .00777 |
| 16.81 | 164.0 | 159.3 | 109.7 | 469.4 | 238.3 | 133.9 | 74.4 | 104.2 | .00740 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=157.72 NU(S)A= 81.97 NU(AV)A=119.65 ST(AV)A= .00838
E(+)= 131.07 ST(AV)/ST(4S)=2.36 F/F(4S)=3.29 (ST/ST(4S))/(F/F(4S))= .719
(F/F(4S))/(ST/ST(4S)) 3.0= .25 R(BAR)= 6.965 H(BAR)= 9.705

RUN NUMBER=230HR40-30/10 E/D= .063 P/E=10.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .1220 LBM/SEC RE= 39085. QGE(R)= 720.5 BTU/HR-SQ FT
QGE(S)= 422.6 INLET TEMP= 83.0 F TATM= 73.5 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 114.7 | 113.5 | 83.4 | 552.9 | 320.2 | 285.8 | 172.1 | 228.9 | .00812 |
| .95 | 121.3 | 121.6 | 84.3 | 715.2 | 417.3 | 312.0 | 180.3 | 246.2 | .00874 |
| 1.59 | 127.8 | 129.7 | 85.1 | 687.0 | 380.9 | 259.2 | 137.6 | 198.4 | .00705 |
| 2.22 | 130.9 | 133.3 | 85.9 | 723.5 | 413.3 | 258.8 | 140.4 | 199.6 | .00710 |
| 2.85 | 135.2 | 136.6 | 86.8 | 674.9 | 391.3 | 224.0 | 126.2 | 175.1 | .00624 |
| 3.49 | 134.5 | 136.8 | 87.6 | 722.6 | 421.2 | 247.4 | 137.5 | 192.4 | .00686 |
| 4.12 | 134.9 | 137.7 | 88.4 | 713.7 | 406.3 | 246.3 | 132.2 | 189.3 | .00676 |
| 4.76 | 135.3 | 137.5 | 89.3 | 701.7 | 415.5 | 244.1 | 138.1 | 191.1 | .00683 |
| 5.39 | 134.2 | 137.2 | 90.1 | 716.5 | 416.9 | 259.8 | 141.6 | 200.7 | .00718 |
| 6.66 | 133.0 | 137.2 | 91.8 | 717.9 | 415.6 | 277.7 | 145.9 | 211.8 | .00760 |
| 7.93 | 133.8 | 137.2 | 93.4 | 715.8 | 418.8 | 282.1 | 152.2 | 217.2 | .00781 |
| 9.20 | 135.6 | 138.8 | 95.1 | 717.6 | 419.3 | 281.1 | 152.2 | 216.7 | .00781 |
| 11.73 | 145.2 | 147.8 | 98.4 | 712.6 | 413.1 | 240.5 | 132.1 | 186.3 | .00674 |
| 14.27 | 154.9 | 154.2 | 101.8 | 704.2 | 410.8 | 208.2 | 123.0 | 165.6 | .00602 |
| 14.91 | 155.0 | 154.9 | 102.6 | 717.9 | 413.4 | 214.8 | 123.9 | 169.4 | .00617 |
| 16.81 | 160.2 | 156.8 | 105.1 | 702.4 | 410.1 | 199.1 | 123.9 | 161.5 | .00590 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=245.29 NU(S)A=136.36 NU(AV)A=190.83 ST(AV)A= .00688
E(+)= 239.09 ST(AV)/ST(4S)=2.31 F/F(4S)=3.41 (ST/ST(4S))/(F/F(4S))= .678
(F/F(4S))/(ST/ST(4S)) 3.0= .28 R(BAR)= 7.614 H(BAR)=11.481

RUN NUMBER=231HR60-30/10 E/D= .063 P/E=10.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .1740 LBM/SEC RE= 55837. QGE(R)= 831.3 BTU/HR-SQ FT
QGE(S)= 496.0 INLET TEMP= 84.0 F TATM= 73.5 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 113.6 | 113.8 | 84.3 | 645.6 | 365.6 | 356.2 | 200.3 | 278.3 | .00693 |
| .95 | 120.3 | 121.6 | 85.0 | 826.2 | 490.7 | 378.0 | 216.3 | 297.2 | .00740 |
| 1.59 | 126.9 | 129.4 | 85.7 | 796.4 | 454.3 | 311.1 | 167.4 | 239.3 | .00597 |
| 2.22 | 129.9 | 132.7 | 86.4 | 833.7 | 486.8 | 308.0 | 169.2 | 238.6 | .00596 |
| 2.85 | 134.0 | 135.6 | 87.1 | 785.9 | 465.9 | 269.1 | 154.3 | 211.7 | .00529 |
| 3.49 | 133.1 | 135.6 | 87.7 | 837.2 | 496.4 | 296.3 | 166.5 | 231.4 | .00579 |
| 4.12 | 133.8 | 136.5 | 88.4 | 824.7 | 477.9 | 291.7 | 159.4 | 225.6 | .00565 |
| 4.76 | 134.4 | 136.0 | 89.1 | 810.6 | 489.1 | 286.6 | 167.1 | 226.9 | .00568 |
| 5.39 | 133.3 | 135.5 | 89.8 | 826.6 | 491.2 | 303.9 | 171.9 | 237.9 | .00597 |
| 6.66 | 131.8 | 135.3 | 91.1 | 830.3 | 489.2 | 326.0 | 177.1 | 251.5 | .00632 |
| 7.93 | 133.0 | 135.0 | 92.5 | 826.4 | 494.2 | 325.0 | 185.2 | 255.1 | .00642 |
| 9.20 | 135.0 | 137.2 | 93.9 | 828.4 | 491.6 | 320.1 | 180.3 | 250.2 | .00631 |
| 11.73 | 144.8 | 145.5 | 96.6 | 822.4 | 486.7 | 269.9 | 157.4 | 213.7 | .00541 |
| 14.27 | 152.4 | 151.0 | 99.3 | 816.0 | 485.8 | 242.1 | 148.1 | 195.1 | .00496 |
| 14.91 | 152.2 | 151.8 | 100.0 | 831.3 | 487.3 | 250.4 | 148.0 | 199.2 | .00507 |
| 16.81 | 158.2 | 154.2 | 102.0 | 812.9 | 483.8 | 227.0 | 145.4 | 186.2 | .00475 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=283.44 NU(S)A=163.67 NU(AV)A=223.55 ST(AV)A= .00564
E(+)= 330.68 ST(AV)/ST(4S)=2.07 F/F(4S)=3.46 (ST/ST(4S))/(F/F(4S))= .599
(F/F(4S))/(ST/ST(4S)) 3.0= .39 R(BAR)= 7.970 H(BAR)=14.011

RUN NUMBER=232HR80-30/10 E/D= .063 P/E=10.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .2500 LBM/SEC RE= 80211. QGE(R)=1017.0 BTU/HR-SQ FT
QGE(S)= 622.1 INLET TEMP= 85.5 F TATM= 74.4 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 111.4 | 114.3 | 85.8 | 816.4 | 445.3 | 514.7 | 251.6 | 383.1 | .00665 |
| .95 | 118.9 | 121.8 | 86.4 | 1012.1 | 616.9 | 501.5 | 280.3 | 390.9 | .00679 |
| 1.59 | 126.3 | 129.3 | 87.0 | 976.1 | 579.4 | 398.8 | 220.1 | 309.5 | .00538 |
| 2.22 | 129.3 | 132.1 | 87.5 | 1023.5 | 613.6 | 394.0 | 221.3 | 307.6 | .00535 |
| 2.85 | 133.8 | 134.6 | 88.1 | 963.2 | 592.2 | 338.4 | 204.4 | 271.4 | .00473 |
| 3.49 | 132.2 | 134.2 | 88.7 | 1029.0 | 622.7 | 379.3 | 219.4 | 299.4 | .00522 |
| 4.12 | 132.9 | 134.7 | 89.3 | 1010.5 | 606.3 | 371.1 | 213.8 | 292.5 | .00510 |
| 4.76 | 133.6 | 134.1 | 89.9 | 996.1 | 615.5 | 364.5 | 223.0 | 293.7 | .00513 |
| 5.39 | 132.5 | 133.4 | 90.5 | 1010.8 | 619.4 | 384.4 | 230.6 | 307.5 | .00537 |
| 6.66 | 130.4 | 133.5 | 91.6 | 1017.6 | 615.6 | 418.8 | 234.6 | 326.7 | .00572 |
| 7.93 | 131.7 | 133.6 | 92.8 | 1012.5 | 620.0 | 414.5 | 242.0 | 328.2 | .00575 |
| 9.20 | 133.9 | 135.9 | 94.0 | 1014.2 | 617.1 | 403.7 | 233.9 | 318.8 | .00560 |
| 11.73 | 144.0 | 143.2 | 96.3 | 1007.7 | 613.5 | 334.6 | 207.1 | 270.8 | .00477 |
| 14.27 | 150.9 | 148.4 | 98.6 | 1001.2 | 612.9 | 302.0 | 194.2 | 248.1 | .00438 |
| 14.91 | 150.4 | 149.4 | 99.2 | 1019.8 | 613.4 | 314.3 | 192.7 | 253.5 | .00448 |
| 16.81 | 157.1 | 152.0 | 101.0 | 998.0 | 610.2 | 279.5 | 187.9 | 233.7 | .00414 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=357.05 NU(S)A=215.05 NU(AV)A=286.05 ST(AV)A= .00502
E(+)= 459.39 ST(AV)/ST(4S)=2.01 F/F(4S)=3.50 (ST/ST(4S))/(F/F(4S))= .575
(F/F(4S))/(ST/ST(4S)) 3.0= .43 R(BAR)= 8.344 H(BAR)=15.423

RUN NUMBER=267HR08-90/20 E/D= .063 P/E=20.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .0252 LBM/SEC RE= 8060. QGE(R)= 202.3 BTU/HR-SQ FT
QGE(S)= 142.7 INLET TEMP= 78.8 F TATM= 73.2 F PATM=14.65 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 120.2 | 119.4 | 79.4 | 194.6 | 134.3 | 77.7 | 54.7 | 66.2 | .01130 |
| .95 | 125.7 | 125.7 | 80.6 | 196.5 | 136.9 | 70.8 | 49.4 | 60.1 | .01027 |
| 1.59 | 131.2 | 131.9 | 81.8 | 179.5 | 122.1 | 58.9 | 39.5 | 49.2 | .00843 |
| 2.22 | 134.7 | 136.4 | 83.1 | 199.0 | 129.9 | 62.4 | 39.4 | 50.9 | .00873 |
| 2.85 | 138.6 | 140.2 | 84.3 | 176.0 | 119.6 | 52.3 | 34.5 | 43.4 | .00746 |
| 3.49 | 140.1 | 142.0 | 85.5 | 192.1 | 130.3 | 56.7 | 37.2 | 46.9 | .00808 |
| 4.12 | 141.3 | 143.2 | 86.7 | 194.8 | 132.6 | 57.5 | 37.8 | 47.6 | .00821 |
| 4.76 | 142.4 | 144.1 | 87.9 | 198.3 | 134.9 | 58.4 | 38.6 | 48.5 | .00838 |
| 5.39 | 144.0 | 145.0 | 89.2 | 190.0 | 135.2 | 55.5 | 38.8 | 47.1 | .00816 |
| 6.66 | 145.5 | 147.0 | 91.6 | 194.7 | 134.6 | 57.6 | 38.8 | 48.2 | .00837 |
| 7.93 | 147.2 | 148.9 | 94.0 | 194.7 | 134.3 | 58.2 | 38.9 | 48.6 | .00846 |
| 9.20 | 149.2 | 150.8 | 96.5 | 193.4 | 134.1 | 58.1 | 39.1 | 48.6 | .00849 |
| 11.73 | 152.4 | 154.5 | 101.4 | 194.1 | 133.2 | 59.7 | 39.4 | 49.6 | .00872 |
| 14.27 | 156.6 | 157.2 | 106.2 | 189.0 | 133.2 | 58.4 | 40.8 | 49.6 | .00878 |
| 14.91 | 156.4 | 157.7 | 107.5 | 197.7 | 133.6 | 62.8 | 41.3 | 52.1 | .00924 |
| 16.81 | 159.1 | 159.6 | 111.1 | 187.1 | 128.0 | 60.3 | 40.8 | 50.6 | .00901 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 58.55 NU(S)A= 39.28 NU(AV)A= 48.91 ST(AV)A= .00857
E(+)= 56.96 ST(AV)/ST(4S)=1.84 F/F(4S)=3.04 (ST/ST(4S))/(F/F(4S))= .606
(F/F(4S))/(ST/ST(4S)) 3.0= .49 R(BAR)= 6.194 H(BAR)=10.520

RUN NUMBER=268HR12-90/20 E/D= .063 P/E=10.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .0413 LBM/SEC RE= 13254. QGE(R)= 277.1 BTU/HR-SQ FT
QGE(S)= 180.1 INLET TEMP= 79.6 F TATM= 74.2 F PATM=14.65 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.0 | 112.3 | 80.1 | 254.9 | 168.8 | 118.7 | 85.2 | 101.9 | .01063 |
| .95 | 121.1 | 119.6 | 81.1 | 271.9 | 175.1 | 110.2 | 73.8 | 92.0 | .00960 |
| 1.59 | 127.3 | 126.9 | 82.1 | 246.1 | 152.0 | 88.2 | 55.0 | 71.6 | .00749 |
| 2.22 | 130.2 | 131.4 | 83.1 | 283.7 | 166.6 | 97.3 | 55.8 | 76.5 | .00801 |
| 2.85 | 134.8 | 135.0 | 84.0 | 241.5 | 158.3 | 76.8 | 50.2 | 63.5 | .00666 |
| 3.49 | 135.7 | 136.7 | 85.0 | 273.1 | 172.4 | 86.9 | 53.8 | 70.4 | .00739 |
| 4.12 | 137.0 | 138.3 | 86.0 | 270.2 | 169.1 | 85.4 | 52.1 | 68.7 | .00722 |
| 4.76 | 138.2 | 139.4 | 87.0 | 282.5 | 172.9 | 88.7 | 53.0 | 70.9 | .00746 |
| 5.39 | 141.0 | 140.5 | 88.0 | 259.3 | 172.7 | 78.5 | 52.8 | 65.6 | .00692 |
| 6.66 | 142.7 | 142.7 | 90.0 | 270.4 | 172.6 | 82.0 | 52.4 | 67.2 | .00710 |
| 7.93 | 144.8 | 144.8 | 91.9 | 270.3 | 173.3 | 81.5 | 52.3 | 66.9 | .00709 |
| 9.20 | 147.4 | 147.4 | 93.9 | 267.8 | 171.5 | 79.6 | 51.0 | 65.3 | .00694 |
| 11.73 | 150.8 | 151.8 | 97.8 | 269.3 | 171.1 | 80.3 | 50.1 | 65.2 | .00697 |
| 14.27 | 155.5 | 155.2 | 101.8 | 261.8 | 170.3 | 76.5 | 50.0 | 63.2 | .00679 |
| 14.91 | 154.7 | 155.8 | 102.8 | 276.6 | 172.6 | 83.4 | 51.0 | 67.2 | .00723 |
| 16.81 | 158.6 | 158.6 | 105.7 | 261.2 | 165.8 | 77.1 | 48.9 | 63.0 | .00680 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 80.73 NU(S)A= 51.15 NU(AV)A= 65.94 ST(AV)A= .00702
E(+)= 93.91 ST(AV)/ST(4S)=1.76 F/F(4S)=3.50 (ST/ST(4S))/(F/F(4S))= .503
(F/F(4S))/(ST/ST(4S)) 3.0= .64 R(BAR)= 6.194 H(BAR)=13.433

RUN NUMBER=269HR20-90/20 E/D= .063 P/E=20.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .0649 LBM/SEC RE= 20856. QGE(R)= 381.0 BTU/HR-SQ FT
QGE(S)= 224.5 INLET TEMP= 80.8 F TATM= 72.6 F PATM=14.65 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 113.2 | 108.5 | 81.2 | 321.2 | 199.2 | 162.9 | 118.5 | 140.7 | .00935 |
| .95 | 119.4 | 116.3 | 82.0 | 375.9 | 219.7 | 162.9 | 104.1 | 133.5 | .00888 |
| 1.59 | 125.7 | 124.0 | 82.9 | 344.9 | 189.2 | 130.4 | 74.4 | 102.4 | .00682 |
| 2.22 | 128.1 | 128.0 | 83.7 | 391.9 | 210.3 | 142.8 | 76.8 | 109.8 | .00732 |
| 2.85 | 132.6 | 131.0 | 84.5 | 340.4 | 206.8 | 114.3 | 71.8 | 93.1 | .00621 |
| 3.49 | 132.8 | 132.6 | 85.4 | 381.6 | 217.9 | 129.7 | 74.3 | 102.0 | .00682 |
| 4.12 | 133.9 | 134.2 | 86.2 | 374.3 | 211.3 | 126.3 | 70.8 | 98.6 | .00660 |
| 4.76 | 135.0 | 135.0 | 87.0 | 390.9 | 217.6 | 131.0 | 72.9 | 102.0 | .00683 |
| 5.39 | 138.2 | 135.8 | 87.9 | 361.0 | 219.5 | 115.1 | 73.5 | 94.3 | .00633 |
| 6.66 | 139.8 | 138.2 | 89.5 | 374.8 | 217.2 | 119.4 | 71.5 | 95.4 | .00642 |
| 7.93 | 142.0 | 140.5 | 91.2 | 374.2 | 217.1 | 117.6 | 70.3 | 93.9 | .00633 |
| 9.20 | 144.6 | 142.9 | 92.9 | 371.6 | 216.7 | 114.3 | 68.9 | 91.6 | .00619 |
| 11.73 | 147.6 | 147.7 | 96.2 | 374.0 | 215.6 | 115.2 | 66.3 | 90.7 | .00615 |
| 14.27 | 153.0 | 151.4 | 99.5 | 363.5 | 214.9 | 107.0 | 65.3 | 86.1 | .00587 |
| 14.91 | 151.6 | 152.0 | 100.3 | 384.3 | 217.5 | 117.8 | 66.2 | 92.0 | .00628 |
| 16.81 | 156.5 | 155.2 | 102.8 | 364.2 | 210.9 | 106.3 | 63.1 | 84.7 | .00580 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=116.10 NU(S)A= 68.61 NU(AV)A= 92.36 ST(AV)A= .00624
E(+)= 148.03 ST(AV)/ST(4S)=1.78 F/F(4S)=3.94 (ST/ST(4S))/(F/F(4S))= .452
(F/F(4S))/(ST/ST(4S)) 3.0= .70 R(BAR)= 6.194 H(BAR)=15.428

RUN NUMBER=270HR40-90/20 E/D= .063 P/E=20.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .1290 LBM/SEC RE= 41512. QGE(R)= 623.5 BTU/HR-SQ FT
QGE(S)= 346.4 INLET TEMP= 82.1 F TATM= 72.6 F PATM=14.65 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 112.4 | 107.3 | 82.4 | 496.8 | 284.1 | 268.5 | 185.0 | 226.8 | .00759 |
| .95 | 119.4 | 115.2 | 83.1 | 618.3 | 341.7 | 276.0 | 172.1 | 224.1 | .00751 |
| 1.59 | 126.3 | 123.1 | 83.8 | 569.0 | 301.4 | 216.2 | 123.7 | 170.0 | .00570 |
| 2.22 | 126.9 | 126.0 | 84.4 | 651.6 | 334.4 | 247.5 | 129.9 | 188.7 | .00634 |
| 2.85 | 131.9 | 128.1 | 85.1 | 567.4 | 332.3 | 195.5 | 124.6 | 160.1 | .00538 |
| 3.49 | 130.4 | 129.2 | 85.8 | 633.5 | 341.0 | 228.7 | 126.5 | 177.6 | .00597 |
| 4.12 | 131.0 | 130.4 | 86.5 | 617.1 | 334.8 | 223.1 | 122.6 | 172.8 | .00582 |
| 4.76 | 131.5 | 131.0 | 87.1 | 645.1 | 340.0 | 233.6 | 124.7 | 179.1 | .00604 |
| 5.39 | 135.6 | 131.5 | 87.8 | 597.3 | 342.2 | 200.6 | 125.7 | 163.1 | .00550 |
| 6.66 | 136.6 | 133.5 | 89.1 | 617.2 | 339.7 | 208.3 | 122.8 | 165.5 | .00560 |
| 7.93 | 138.0 | 135.4 | 90.5 | 617.9 | 339.6 | 207.8 | 120.8 | 164.3 | .00556 |
| 9.20 | 140.2 | 137.4 | 91.8 | 614.8 | 339.4 | 202.7 | 118.7 | 160.7 | .00545 |
| 11.73 | 142.8 | 141.6 | 94.5 | 617.5 | 338.6 | 203.0 | 114.1 | 158.6 | .00540 |
| 14.27 | 148.8 | 145.3 | 97.2 | 602.6 | 337.7 | 184.5 | 110.9 | 147.7 | .00505 |
| 14.91 | 146.4 | 146.1 | 97.8 | 634.0 | 340.2 | 206.2 | 111.4 | 158.8 | .00543 |
| 16.81 | 153.3 | 149.7 | 99.9 | 604.3 | 333.8 | 178.0 | 105.4 | 141.7 | .00486 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=203.13 NU(S)A=117.34 NU(AV)A=160.23 ST(AV)A= .00544
E(+)= 295.17 ST(AV)/ST(4S)=1.86 F/F(4S)=4.66 (ST/ST(4S))/(F/F(4S))= .399
(F/F(4S))/(ST/ST(4S)) 3.0= .73 R(BAR)= 6.194 H(BAR)=18.097

RUN NUMBER=271HR60-90/20 E/D= .063 P/E=20.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .1710 LBM/SEC RE= 54959. QGE(R)= 831.3 BTU/HR-SQ FT
QGE(S)= 429.5 INLET TEMP= 83.2 F TATM= 73.3 F PATM=14.65 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.6 | 110.3 | 83.5 | 673.9 | 328.5 | 339.7 | 198.4 | 269.0 | .00681 |
| .95 | 123.7 | 118.8 | 84.2 | 825.8 | 424.5 | 337.3 | 198.0 | 267.7 | .00678 |
| 1.59 | 131.8 | 127.3 | 84.8 | 764.5 | 377.7 | 262.4 | 143.5 | 203.0 | .00514 |
| 2.22 | 131.9 | 129.9 | 85.5 | 870.0 | 417.4 | 302.1 | 151.6 | 226.9 | .00576 |
| 2.85 | 137.8 | 131.7 | 86.2 | 759.8 | 415.6 | 236.8 | 146.9 | 191.8 | .00487 |
| 3.49 | 135.0 | 132.6 | 86.8 | 850.3 | 427.0 | 283.7 | 149.9 | 216.8 | .00551 |
| 4.12 | 135.5 | 134.0 | 87.5 | 824.5 | 414.8 | 276.0 | 143.2 | 209.6 | .00533 |
| 4.76 | 135.9 | 134.4 | 88.1 | 860.1 | 422.8 | 288.9 | 146.6 | 217.7 | .00554 |
| 5.39 | 140.9 | 134.8 | 88.8 | 799.1 | 425.4 | 245.8 | 148.2 | 197.0 | .00502 |
| 6.66 | 141.6 | 136.6 | 90.1 | 825.2 | 422.5 | 256.3 | 145.3 | 200.8 | .00513 |
| 7.93 | 143.0 | 138.4 | 91.4 | 826.1 | 423.2 | 255.5 | 143.7 | 199.6 | .00511 |
| 9.20 | 145.6 | 140.6 | 92.7 | 821.5 | 422.0 | 247.4 | 140.4 | 193.9 | .00497 |
| 11.73 | 148.0 | 144.8 | 95.4 | 825.3 | 421.6 | 248.6 | 135.2 | 191.9 | .00494 |
| 14.27 | 154.7 | 149.0 | 98.0 | 807.4 | 420.0 | 224.7 | 130.1 | 177.4 | .00458 |
| 14.91 | 151.8 | 149.6 | 98.6 | 845.2 | 423.6 | 250.9 | 131.0 | 191.0 | .00493 |
| 16.81 | 160.0 | 153.5 | 100.6 | 809.3 | 416.4 | 214.3 | 123.8 | 169.0 | .00438 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=248.60 NU(S)A=138.49 NU(AV)A=193.55 ST(AV)A= .00496
E(+)= 390.84 ST(AV)/ST(4S)=1.82 F/F(4S)=4.97 (ST/ST(4S))/(F/F(4S))= .365
(F/F(4S))/(ST/ST(4S)) 3.0= .83 R(BAR)= 6.194 H(BAR)=20.091

RUN NUMBER=272HR80-90/20 E/D= .063 P/E=20.00 ALPA= 90 D= 2.956 IN
PR=.71 MDOT= .2500 LBM/SEC RE= 80413. QGE(R)=1011.4 BTU/HR-SQ FT
QGE(S)= 581.9 INLET TEMP= 83.9 F TATM= 73.4 F PATM=14.65 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 112.6 | 112.5 | 84.2 | 847.1 | 424.1 | 481.4 | 241.9 | 361.6 | .00626 |
| .95 | 122.2 | 120.9 | 84.8 | 1006.1 | 576.7 | 433.4 | 257.6 | 345.5 | .00599 |
| 1.59 | 131.8 | 129.2 | 85.3 | 930.3 | 524.7 | 322.6 | 192.6 | 257.6 | .00447 |
| 2.22 | 131.0 | 130.9 | 85.9 | 1058.6 | 576.1 | 377.6 | 206.0 | 291.8 | .00507 |
| 2.85 | 137.3 | 132.7 | 86.5 | 931.1 | 566.1 | 294.6 | 196.9 | 245.8 | .00427 |
| 3.49 | 133.4 | 133.3 | 87.0 | 1035.6 | 580.9 | 358.9 | 201.8 | 280.3 | .00488 |
| 4.12 | 133.4 | 134.6 | 87.6 | 1004.8 | 566.0 | 352.2 | 193.3 | 272.8 | .00475 |
| 4.76 | 133.4 | 134.8 | 88.2 | 1049.7 | 575.2 | 372.2 | 198.1 | 285.2 | .00497 |
| 5.39 | 139.2 | 134.9 | 88.7 | 974.2 | 578.6 | 309.4 | 200.9 | 255.1 | .00445 |
| 6.66 | 139.5 | 136.5 | 89.9 | 1005.8 | 575.0 | 324.2 | 197.2 | 260.7 | .00455 |
| 7.93 | 140.6 | 138.1 | 91.0 | 1007.0 | 575.4 | 324.2 | 195.1 | 259.7 | .00454 |
| 9.20 | 143.2 | 140.0 | 92.1 | 1001.7 | 575.1 | 312.7 | 191.5 | 252.1 | .00442 |
| 11.73 | 145.4 | 144.5 | 94.4 | 1006.3 | 573.8 | 313.4 | 181.9 | 247.7 | .00435 |
| 14.27 | 153.1 | 148.4 | 96.7 | 984.3 | 572.8 | 276.1 | 175.4 | 225.7 | .00398 |
| 14.91 | 149.3 | 149.1 | 97.2 | 1030.0 | 576.8 | 312.6 | 176.0 | 244.3 | .00431 |
| 16.81 | 158.6 | 153.6 | 98.9 | 987.7 | 568.0 | 261.0 | 163.9 | 212.5 | .00376 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=312.41 NU(S)A=186.94 NU(AV)A=249.67 ST(AV)A= .00437
E(+)= 572.42 ST(AV)/ST(4S)=1.75 F/F(4S)=5.41 (ST/ST(4S))/(F/F(4S))= .324
(F/F(4S))/(ST/ST(4S)) 3.0=1.00 R(BAR)= 6.194 H(BAR)=23.149

RUN NUMBER=317HR08-60/20 E/D= .063 P/E=20.00 ALPA= 60 D= 2.956 IN
PR=.71 MDOT= .0249 LBM/SEC RE= 7939. QGE(R)= 236.9 BTU/HR-SQ FT
QGE(S)= 155.2 INLET TEMP= 78.6 F TATM= 72.8 F PATM=14.66 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 124.0 | 122.2 | 79.3 | 224.4 | 134.2 | 81.7 | 50.9 | 66.3 | .01146 |
| .95 | 130.2 | 129.6 | 80.7 | 230.6 | 148.9 | 75.6 | 49.5 | 62.5 | .01082 |
| 1.59 | 136.5 | 137.0 | 82.1 | 215.8 | 128.8 | 64.3 | 38.0 | 51.2 | .00887 |
| 2.22 | 140.9 | 142.0 | 83.5 | 234.2 | 141.7 | 65.9 | 39.1 | 52.5 | .00913 |
| 2.85 | 146.0 | 146.3 | 84.9 | 193.8 | 126.7 | 51.2 | 33.3 | 42.2 | .00735 |
| 3.49 | 146.6 | 148.0 | 86.3 | 226.4 | 138.9 | 60.4 | 36.2 | 48.3 | .00843 |
| 4.12 | 146.9 | 148.7 | 87.7 | 228.8 | 142.0 | 62.1 | 37.4 | 49.7 | .00869 |
| 4.76 | 147.2 | 148.8 | 89.1 | 237.6 | 146.8 | 65.5 | 39.4 | 52.5 | .00919 |
| 5.39 | 148.6 | 148.9 | 90.5 | 220.6 | 146.9 | 60.7 | 40.2 | 50.5 | .00885 |
| 6.66 | 148.4 | 149.2 | 93.3 | 229.0 | 146.8 | 66.2 | 41.8 | 54.0 | .00951 |
| 7.93 | 148.4 | 149.4 | 96.1 | 228.8 | 145.8 | 69.3 | 43.4 | 56.4 | .00996 |
| 9.20 | 148.5 | 149.2 | 98.9 | 229.5 | 148.4 | 73.0 | 46.6 | 59.8 | .01061 |
| 11.73 | 150.0 | 151.3 | 104.6 | 230.0 | 146.9 | 79.1 | 49.1 | 64.1 | .01146 |
| 14.27 | 154.6 | 154.2 | 110.2 | 224.7 | 148.2 | 78.4 | 52.1 | 65.3 | .01176 |
| 14.91 | 154.7 | 155.5 | 111.6 | 234.3 | 145.9 | 84.0 | 51.3 | 67.6 | .01221 |
| 16.81 | 159.9 | 159.4 | 115.8 | 220.5 | 140.1 | 76.7 | 49.3 | 63.0 | .01144 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 72.09 NU(S)A= 45.52 NU(AV)A= 58.60 ST(AV)A= .01047
E(+)= 62.92 ST(AV)/ST(4S)=2.24 F/F(4S)=3.82 (ST/ST(4S))/(F/F(4S))= .586
(F/F(4S))/(ST/ST(4S)) 3.0= .34 R(BAR)= 5.219 H(BAR)= 9.458

RUN NUMBER=318HR12-60/20 E/D= .063 P/E=20.00 ALPA= 60 D= 2.956 IN
PR=.71 MDOT= .0397 LBM/SEC RE= 12662. QGE(R)= 360.2 BTU/HR-SQ FT
QGE(S)= 214.8 INLET TEMP= 79.9 F TATM= 72.7 F PATM=14.66 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 123.3 | 118.5 | 80.5 | 321.3 | 185.4 | 122.1 | 79.4 | 100.7 | .01093 |
| .95 | 130.6 | 127.4 | 81.8 | 353.9 | 208.7 | 117.7 | 74.3 | 96.0 | .01044 |
| 1.59 | 137.9 | 136.2 | 83.1 | 330.1 | 180.8 | 97.6 | 55.1 | 76.3 | .00831 |
| 2.22 | 142.3 | 141.7 | 84.4 | 366.4 | 197.8 | 102.2 | 55.7 | 79.0 | .00862 |
| 2.85 | 148.4 | 146.0 | 85.7 | 303.2 | 188.4 | 77.9 | 50.3 | 64.1 | .00701 |
| 3.49 | 148.2 | 148.0 | 87.0 | 355.1 | 198.5 | 93.3 | 52.3 | 72.8 | .00797 |
| 4.12 | 148.4 | 149.0 | 88.3 | 351.9 | 200.4 | 93.9 | 52.9 | 73.4 | .00805 |
| 4.76 | 148.6 | 149.3 | 89.6 | 369.4 | 206.3 | 100.2 | 55.3 | 77.8 | .00855 |
| 5.39 | 151.0 | 149.5 | 90.9 | 336.7 | 205.4 | 89.4 | 56.0 | 72.7 | .00800 |
| 6.66 | 150.2 | 149.7 | 93.4 | 352.5 | 206.3 | 98.8 | 58.4 | 78.6 | .00868 |
| 7.93 | 149.8 | 149.8 | 96.0 | 353.6 | 206.4 | 104.2 | 60.8 | 82.5 | .00915 |
| 9.20 | 150.3 | 150.0 | 98.6 | 352.2 | 207.9 | 107.5 | 63.8 | 85.6 | .00953 |
| 11.73 | 152.0 | 152.8 | 103.8 | 353.9 | 206.8 | 114.8 | 66.0 | 90.4 | .01013 |
| 14.27 | 158.5 | 157.3 | 108.9 | 347.1 | 207.5 | 108.7 | 66.6 | 87.7 | .00989 |
| 14.91 | 159.0 | 159.0 | 110.2 | 358.9 | 205.9 | 114.0 | 65.3 | 89.7 | .01013 |
| 16.81 | 166.5 | 164.8 | 114.1 | 341.4 | 198.7 | 100.3 | 60.3 | 80.3 | .00912 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=104.13 NU(S)A= 61.28 NU(AV)A= 82.70 ST(AV)A= .00922
E(+)= 100.48 ST(AV)/ST(4S)=2.28 F/F(4S)=4.36 (ST/ST(4S))/(F/F(4S))= .523
(F/F(4S))/(ST/ST(4S)) 3.0= .37 R(BAR)= 5.219 H(BAR)=11.094

RUN NUMBER=319HR20-60/20 E/D= .063 P/E=20.00 ALPA= 60 D= 2.956 IN
PR=.71 MDOT= .0618 LBM/SEC RE= 19775. QGE(R)= 484.9 BTU/HR-SQ FT
QGE(S)= 266.0 INLET TEMP= 80.4 F TATM= 72.3 F PATM=14.66 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 121.2 | 114.6 | 80.9 | 417.2 | 218.6 | 168.3 | 105.4 | 136.8 | .00955 |
| .95 | 129.1 | 124.1 | 82.0 | 476.7 | 260.3 | 164.9 | 100.2 | 132.6 | .00926 |
| 1.59 | 136.9 | 133.6 | 83.1 | 451.7 | 226.8 | 135.7 | 72.6 | 104.2 | .00729 |
| 2.22 | 141.5 | 139.0 | 84.2 | 489.6 | 242.4 | 137.9 | 71.4 | 104.7 | .00733 |
| 2.85 | 147.6 | 142.4 | 85.3 | 420.0 | 245.8 | 108.6 | 69.3 | 89.0 | .00624 |
| 3.49 | 146.2 | 144.2 | 86.4 | 485.6 | 252.5 | 130.6 | 70.2 | 100.4 | .00706 |
| 4.12 | 145.9 | 145.3 | 87.4 | 476.8 | 249.2 | 131.0 | 69.2 | 100.1 | .00705 |
| 4.76 | 145.6 | 145.3 | 88.5 | 503.8 | 258.0 | 141.5 | 72.9 | 107.2 | .00756 |
| 5.39 | 148.7 | 145.3 | 89.6 | 456.6 | 257.6 | 123.7 | 74.0 | 98.8 | .00698 |
| 6.66 | 147.4 | 145.2 | 91.8 | 479.3 | 258.0 | 137.4 | 77.1 | 107.2 | .00759 |
| 7.93 | 147.4 | 145.0 | 93.9 | 477.7 | 259.1 | 142.0 | 80.7 | 111.3 | .00791 |
| 9.20 | 147.9 | 145.4 | 96.1 | 477.5 | 259.4 | 146.0 | 83.4 | 114.7 | .00817 |
| 11.73 | 150.2 | 148.4 | 100.4 | 478.9 | 259.1 | 151.3 | 85.0 | 118.2 | .00847 |
| 14.27 | 157.5 | 154.4 | 104.8 | 471.6 | 258.0 | 139.8 | 81.2 | 110.5 | .00796 |
| 14.91 | 158.0 | 156.2 | 105.8 | 485.1 | 257.8 | 145.0 | 79.9 | 112.4 | .00811 |
| 16.81 | 167.0 | 162.3 | 109.1 | 464.6 | 250.7 | 124.5 | 73.1 | 98.8 | .00716 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=139.08 NU(S)A= 78.73 NU(AV)A=108.91 ST(AV)A= .00777
E(+)= 157.29 ST(AV)/ST(4S)=2.18 F/F(4S)=4.90 (ST/ST(4S))/(F/F(4S))= .445
(F/F(4S))/(ST/ST(4S)) 3.0= .47 R(BAR)= 5.219 H(BAR)=13.666

RUN NUMBER=320HK40-60/20  E/D= .063  P/E=20.00  ALPA= 60  D= 2.956 IN
PR=.71  MDOT= .1160 LBM/SEC  RE= 37163.  QGE(R)= 789.7 BTU/HR-SQ FT
QGE(S)= 436.4  INLET TEMP= 81.5 F  TATM= 71.9 F  PATM=14.66 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 121.0 | 115.6 | 82.0 | 640.4 | 325.7 | 265.9 | 157.0 | 211.5 | .00787 |
| .95 | 130.1 | 125.9 | 82.9 | 783.3 | 430.5 | 268.8 | 162.1 | 215.4 | .00803 |
| 1.59 | 139.1 | 136.2 | 83.9 | 745.5 | 389.0 | 217.9 | 120.1 | 169.0 | .00631 |
| 2.22 | 143.5 | 141.3 | 84.8 | 796.9 | 412.3 | 219.5 | 117.6 | 168.6 | .00630 |
| 2.85 | 150.0 | 144.4 | 85.7 | 708.3 | 412.0 | 177.5 | 113.1 | 145.3 | .00544 |
| 3.49 | 146.4 | 145.4 | 86.7 | 800.7 | 423.5 | 215.6 | 116.0 | 165.8 | .00621 |
| 4.12 | 145.2 | 145.8 | 87.6 | 781.7 | 421.9 | 218.0 | 116.4 | 167.2 | .00627 |
| 4.76 | 144.0 | 145.4 | 88.6 | 820.8 | 428.4 | 237.4 | 120.8 | 179.1 | .00673 |
| 5.39 | 147.8 | 145.0 | 89.5 | 757.0 | 430.0 | 207.9 | 124.0 | 166.0 | .00624 |
| 6.66 | 146.2 | 144.8 | 91.4 | 784.0 | 428.4 | 228.3 | 128.0 | 178.1 | .00672 |
| 7.93 | 145.8 | 144.6 | 93.3 | 783.6 | 429.6 | 237.4 | 133.2 | 185.3 | .00700 |
| 9.20 | 146.4 | 145.0 | 95.2 | 783.0 | 431.1 | 242.4 | 137.2 | 189.8 | .00719 |
| 11.73 | 149.8 | 149.8 | 98.9 | 784.0 | 428.5 | 243.0 | 132.8 | 187.9 | .00716 |
| 14.27 | 158.8 | 155.9 | 102.7 | 775.7 | 429.0 | 216.6 | 126.4 | 171.5 | .00657 |
| 14.91 | 159.7 | 158.0 | 103.6 | 790.0 | 426.3 | 220.5 | 122.7 | 171.6 | .00658 |
| 16.81 | 169.8 | 163.8 | 106.5 | 766.8 | 421.3 | 188.6 | 114.5 | 151.5 | .00583 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=224.83  NU(S)A=126.71  NU(AV)A=175.77  ST(AV)A= .00667
E(+)= 296.05  ST(AV)/ST(4S)=2.21  F/F(4S)=5.73  (ST/ST(4S))/(F/F(4S))= .386
(F/F(4S))/(ST/ST(4S)) 3.0= .53  R(BAR)= 5.219  H(BAR)=16.361

RUN NUMBER=321HR60-60/20  E/D= .063  P/E=20.00  ALPA= 60  D= 2.956 IN
PR=.71  MDOT= .1820 LBM/SEC  RE= 58479.  QGE(R)=1025.3 BTU/HR-SQ FT
QGE(S)= 543.1  INLET TEMP= 81.8 F  TATM= 72.0 F  PATM=14.66 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 117.8 | 114.6 | 82.2 | 847.0 | 396.6 | 385.3 | 198.2 | 291.8 | .00692 |
| .95 | 128.3 | 124.8 | 83.0 | 1019.1 | 537.3 | 363.9 | 207.7 | 285.8 | .00679 |
| 1.59 | 138.7 | 135.0 | 83.7 | 972.0 | 492.5 | 285.5 | 155.1 | 220.3 | .00524 |
| 2.22 | 143.3 | 139.6 | 84.5 | 1033.4 | 516.3 | 283.8 | 151.1 | 217.4 | .00518 |
| 2.85 | 149.8 | 141.8 | 85.3 | 935.9 | 521.3 | 233.7 | 148.6 | 191.2 | .00456 |
| 3.49 | 144.8 | 142.2 | 86.0 | 1044.2 | 536.2 | 286.0 | 153.7 | 219.8 | .00524 |
| 4.12 | 143.2 | 142.7 | 86.8 | 1017.5 | 525.7 | 290.0 | 151.2 | 220.6 | .00527 |
| 4.76 | 141.6 | 142.0 | 87.6 | 1066.7 | 535.4 | 317.0 | 157.9 | 237.5 | .00568 |
| 5.39 | 146.4 | 141.3 | 88.3 | 986.0 | 538.2 | 272.3 | 162.9 | 217.6 | .00521 |
| 6.66 | 144.2 | 140.9 | 89.9 | 1020.8 | 535.5 | 300.5 | 167.9 | 234.2 | .00562 |
| 7.93 | 143.7 | 140.5 | 91.4 | 1021.2 | 537.8 | 311.6 | 174.8 | 243.2 | .00584 |
| 9.20 | 145.1 | 141.2 | 92.9 | 1017.7 | 538.3 | 310.6 | 177.5 | 244.1 | .00588 |
| 11.73 | 148.6 | 146.7 | 96.0 | 1019.8 | 535.1 | 307.1 | 167.2 | 237.2 | .00574 |
| 14.27 | 157.9 | 152.5 | 99.1 | 1010.9 | 535.6 | 271.0 | 157.9 | 214.5 | .00521 |
| 14.91 | 158.6 | 154.4 | 99.8 | 1026.4 | 533.3 | 274.9 | 153.9 | 214.4 | .00521 |
| 16.81 | 169.0 | 159.4 | 102.1 | 1000.8 | 529.1 | 234.8 | 145.0 | 189.9 | .00463 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=288.88  NU(S)A=162.74  NU(AV)A=225.81  ST(AV)A= .00544
E(+)= 466.76  ST(AV)/ST(4S)=2.02  F/F(4S)=6.36  (ST/ST(4S))/(F/F(4S))= .318
(F/F(4S))/(ST/ST(4S)) 3.0= .77  R(BAR)= 5.219  H(BAR)=20.649

RUN NUMBER=322HR60-60/20  E/D= .063  P/E=20.00  ALPA= 60  D= 2.956 IN
PR=.71  MDOT= .2440 LBM/SEC  RE= 78573.  QGE(R)=1219.3 BTU/HR-SQ FT
QGE(S)= 672.0  INLET TEMP= 81.3 F  TATM= 71.6 F  PATM=14.66 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 113.3 | 114.7 | 81.6 | 1035.6 | 481.4 | 530.5 | 236.2 | 383.3 | .00678 |
| .95 | 125.1 | 124.8 | 82.3 | 1213.4 | 666.1 | 459.4 | 254.4 | 356.9 | .00632 |
| 1.59 | 136.9 | 134.8 | 83.0 | 1158.0 | 618.7 | 347.5 | 193.3 | 270.4 | .00479 |
| 2.22 | 141.7 | 138.9 | 83.7 | 1227.5 | 646.0 | 342.3 | 189.3 | 265.8 | .00471 |
| 2.85 | 148.4 | 140.6 | 84.4 | 1122.9 | 650.5 | 283.3 | 186.9 | 235.1 | .00417 |
| 3.49 | 142.2 | 140.6 | 85.1 | 1244.5 | 669.2 | 351.4 | 194.4 | 272.9 | .00485 |
| 4.12 | 140.2 | 141.2 | 85.8 | 1211.7 | 652.3 | 358.7 | 189.6 | 274.1 | .00488 |
| 4.76 | 138.2 | 140.3 | 86.5 | 1270.6 | 664.4 | 395.2 | 198.6 | 296.9 | .00529 |
| 5.39 | 144.0 | 139.4 | 87.2 | 1174.5 | 668.3 | 332.1 | 205.6 | 268.9 | .00479 |
| 6.66 | 141.6 | 139.0 | 88.6 | 1214.8 | 664.6 | 367.1 | 211.2 | 289.2 | .00516 |
| 7.93 | 140.8 | 138.6 | 89.9 | 1217.3 | 667.0 | 382.8 | 219.3 | 301.0 | .00539 |
| 9.20 | 142.8 | 139.4 | 91.3 | 1211.2 | 667.6 | 375.5 | 221.6 | 298.5 | .00535 |
| 11.73 | 146.4 | 145.6 | 94.1 | 1214.1 | 663.4 | 368.7 | 204.6 | 286.7 | .00516 |
| 14.27 | 156.2 | 150.9 | 96.8 | 1204.8 | 664.6 | 321.3 | 194.4 | 257.8 | .00466 |
| 14.91 | 157.0 | 152.7 | 97.5 | 1219.8 | 662.0 | 324.1 | 189.6 | 256.9 | .00464 |
| 16.81 | 167.0 | 157.2 | 99.6 | 1194.5 | 658.3 | 279.1 | 180.0 | 229.6 | .00416 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=349.20  NU(S)A=202.46  NU(AV)A=275.83  ST(AV)A= .00495
E(+)= 627.66  ST(AV)/ST(4S)=1.97  F/F(4S)=6.80  (ST/ST(4S))/(F/F(4S))= .290
(F/F(4S))/(ST/ST(4S)) 3.0= .89  R(BAR)= 5.219  H(BAR)=22.984

RUN NUMBER=293HR08-45/20    E/D= .063   P/E=20.00   ALPA= 45   D= 2.956 IN
PR=.71   MDOT= .0292 LBM/SEC   RE= 9384.   QGE(R)= 238.3 BTU/HR-SQ FT
QGE(S)= 138.6   INLET TEMP= 76.3 F   TATM= 70.0 F   PATM=14.62 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 118.0 | 115.0 | 76.9 | 218.7 | 127.2 | 86.9 | 54.5 | 70.7 | .01038 |
| .95 | 123.3 | 121.6 | 78.0 | 232.4 | 132.9 | 83.7 | 49.8 | 66.7 | .00981 |
| 1.59 | 128.7 | 126.1 | 79.2 | 227.6 | 119.0 | 74.9 | 39.6 | 57.2 | .00843 |
| 2.22 | 133.5 | 133.0 | 80.3 | 227.6 | 121.2 | 69.6 | 37.4 | 53.5 | .00789 |
| 2.85 | 137.8 | 136.6 | 81.5 | 206.0 | 116.0 | 59.3 | 34.1 | 46.7 | .00690 |
| 3.49 | 139.0 | 138.3 | 82.6 | 221.1 | 121.4 | 63.5 | 35.3 | 49.4 | .00731 |
| 4.12 | 139.0 | 138.8 | 83.8 | 230.7 | 128.6 | 67.5 | 37.8 | 52.6 | .00780 |
| 4.76 | 139.0 | 139.0 | 84.9 | 233.9 | 131.0 | 69.8 | 39.1 | 54.4 | .00808 |
| 5.39 | 139.4 | 139.2 | 86.1 | 226.4 | 129.3 | 68.3 | 39.2 | 53.8 | .00800 |
| 6.66 | 138.6 | 139.0 | 88.4 | 232.2 | 131.0 | 74.1 | 41.5 | 57.8 | .00862 |
| 7.93 | 138.5 | 138.8 | 90.7 | 232.4 | 131.8 | 77.6 | 43.8 | 60.7 | .00908 |
| 9.20 | 139.2 | 139.0 | 93.0 | 231.8 | 132.6 | 79.8 | 45.8 | 62.8 | .00943 |
| 11.73 | 142.2 | 141.8 | 97.6 | 232.4 | 132.4 | 82.3 | 47.3 | 64.8 | .00979 |
| 14.27 | 149.3 | 148.0 | 102.2 | 224.0 | 129.2 | 74.6 | 44.2 | 59.4 | .00903 |
| 14.91 | 149.3 | 149.4 | 103.3 | 236.6 | 129.7 | 80.5 | 44.1 | 62.3 | .00949 |
| 16.81 | 154.7 | 153.3 | 106.8 | 221.8 | 123.8 | 72.1 | 41.4 | 56.8 | .00868 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 75.27   NU(S)A= 42.89   NU(AV)A= 59.08   ST(AV)A= .00889
E(+)= 61.64   ST(AV)/ST(4S)=2.00   F/F(4S)=2.74   (ST/ST(4S))/(F/F(4S))= .732
(F/F(4S))/(ST/ST(4S)) 3.0= .34   R(BAR)= 6.873   H(BAR)= 9.140

RUN NUMBER=294HR12-45/20    E/D= .063   P/E=20.00   ALPA= 45   D= 2.956 IN
PR=.71   MDOT= .0412 LBM/SEC   RE= 13227.   QGE(R)= 311.7 BTU/HR-SQ FT
QGE(S)= 194.0   INLET TEMP= 77.8 F   TATM= 70.8 F   PATM=14.62 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.8 | 111.6 | 78.3 | 271.2 | 172.5 | 118.0 | 84.6 | 101.3 | .01056 |
| .95 | 121.5 | 119.2 | 79.4 | 306.2 | 188.7 | 118.4 | 77.3 | 97.9 | .01022 |
| 1.59 | 127.2 | 126.7 | 80.5 | 300.9 | 168.7 | 104.7 | 59.3 | 82.0 | .00857 |
| 2.22 | 132.4 | 131.9 | 81.6 | 297.8 | 173.1 | 95.2 | 55.8 | 75.5 | .00791 |
| 2.85 | 136.6 | 135.3 | 82.7 | 276.5 | 174.9 | 83.1 | 53.8 | 68.5 | .00718 |
| 3.49 | 137.3 | 137.2 | 83.8 | 297.2 | 176.3 | 89.8 | 53.3 | 71.6 | .00752 |
| 4.12 | 137.1 | 137.8 | 84.9 | 304.4 | 183.4 | 94.1 | 55.9 | 75.0 | .00789 |
| 4.76 | 136.9 | 138.0 | 86.0 | 313.3 | 186.6 | 99.1 | 57.8 | 78.4 | .00827 |
| 5.39 | 137.8 | 138.2 | 87.1 | 298.8 | 186.2 | 94.7 | 58.5 | 76.6 | .00809 |
| 6.66 | 137.5 | 138.5 | 89.3 | 306.0 | 186.5 | 101.6 | 60.8 | 81.2 | .00860 |
| 7.93 | 138.0 | 138.7 | 91.5 | 305.8 | 186.2 | 104.9 | 62.9 | 83.9 | .00891 |
| 9.20 | 139.2 | 138.8 | 93.7 | 304.6 | 188.2 | 106.4 | 66.3 | 86.3 | .00919 |
| 11.73 | 142.2 | 141.6 | 98.0 | 306.5 | 188.6 | 109.6 | 68.4 | 89.0 | .00953 |
| 14.27 | 150.4 | 149.2 | 102.4 | 298.8 | 184.9 | 97.7 | 61.9 | 79.8 | .00860 |
| 14.91 | 151.1 | 151.0 | 103.5 | 308.1 | 184.7 | 101.3 | 60.9 | 81.1 | .00875 |
| 16.81 | 157.2 | 156.0 | 106.8 | 294.8 | 179.1 | 91.0 | 56.7 | 73.8 | .00800 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=100.61   NU(S)A= 61.80   NU(AV)A= 81.21   ST(AV)A= .00866
E(+)= 86.95   ST(AV)/ST(4S)=2.17   F/F(4S)=3.01   (ST/ST(4S))/(F/F(4S))= .719
(F/F(4S))/(ST/ST(4S)) 3.0= .30   R(BAR)= 6.873   H(BAR)= 9.446

RUN NUMBER=295HR20-45/20    E/D= .063   P/E=20.00   ALPA= 45   D= 2.956 IN
PR=.71   MDOT= .0655 LBM/SEC   RE= 21057.   QGE(R)= 429.5 BTU/HR-SQ FT
QGE(S)= 239.7   INLET TEMP= 79.4 F   TATM= 72.0 F   PATM=14.62 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.0 | 109.2 | 79.9 | 354.9 | 197.2 | 164.2 | 109.3 | 136.8 | .00899 |
| .95 | 121.1 | 117.4 | 80.8 | 424.1 | 234.7 | 170.8 | 103.9 | 137.4 | .00904 |
| 1.59 | 127.2 | 125.7 | 81.7 | 418.0 | 208.1 | 149.0 | 76.7 | 112.8 | .00743 |
| 2.22 | 132.6 | 130.7 | 82.6 | 411.9 | 216.7 | 133.4 | 73.0 | 103.2 | .00681 |
| 2.85 | 136.6 | 133.6 | 83.5 | 389.1 | 222.2 | 118.5 | 71.7 | 95.1 | .00628 |
| 3.49 | 136.4 | 135.2 | 84.4 | 419.6 | 224.7 | 130.3 | 71.4 | 100.8 | .00667 |
| 4.12 | 135.9 | 135.8 | 85.3 | 422.5 | 228.7 | 134.8 | 73.0 | 103.9 | .00688 |
| 4.76 | 135.3 | 135.9 | 86.2 | 435.7 | 232.7 | 142.9 | 75.4 | 109.1 | .00724 |
| 5.39 | 136.4 | 136.0 | 87.1 | 414.9 | 232.3 | 135.4 | 76.4 | 105.9 | .00703 |
| 6.66 | 135.8 | 136.1 | 89.0 | 424.9 | 232.6 | 145.3 | 79.2 | 112.2 | .00747 |
| 7.93 | 136.4 | 136.1 | 90.8 | 425.0 | 233.1 | 148.8 | 82.2 | 115.5 | .00771 |
| 9.20 | 138.3 | 136.4 | 92.6 | 422.6 | 235.5 | 147.3 | 95.6 | 116.5 | .00779 |
| 11.73 | 142.6 | 141.3 | 96.2 | 424.2 | 233.7 | 144.9 | 82.1 | 113.5 | .00763 |
| 14.27 | 151.8 | 149.4 | 99.9 | 416.1 | 230.3 | 126.1 | 73.2 | 99.6 | .00673 |
| 14.91 | 152.7 | 151.2 | 100.8 | 426.0 | 229.2 | 129.0 | 71.5 | 100.2 | .00678 |
| 16.81 | 159.3 | 155.2 | 103.5 | 411.1 | 226.0 | 115.4 | 68.5 | 91.9 | .00624 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=137.10   NU(S)A= 77.42   NU(AV)A=107.26   ST(AV)A= .00718
E(+)= 138.70   ST(AV)/ST(4S)=2.05   F/F(4S)=3.41   (ST/ST(4S))/(F/F(4S))= .602
(F/F(4S))/(ST/ST(4S)) 3.0= .39   R(BAR)= 6.873   H(BAR)=11.942

RUN NUMBER=296HR40-45/20 E/D= .063 P/E=20.00 ALPA= 45 D= 2.956 IN
PR=.71 MDOT= .1220 LBM/SEC RE= 39288. QGE(R)= 651.2 BTU/HR-SQ FT
QGE(S)= 360.2 INLET TEMP= 80.6 F TATM= 72.4 F PATM=14.62 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 113.6 | 108.2 | 81.0 | 517.4 | 277.7 | 257.4 | 165.5 | 211.5 | .00747 |
| .95 | 119.8 | 116.6 | 81.7 | 646.0 | 355.4 | 274.8 | 165.1 | 219.9 | .00778 |
| 1.59 | 126.0 | 125.0 | 82.4 | 642.0 | 323.3 | 238.5 | 122.9 | 180.7 | .00640 |
| 2.22 | 131.8 | 129.5 | 83.2 | 626.1 | 335.9 | 208.2 | 117.3 | 162.7 | .00577 |
| 2.85 | 135.3 | 131.7 | 83.9 | 611.5 | 346.5 | 192.3 | 117.2 | 154.7 | .00549 |
| 3.49 | 134.6 | 133.0 | 84.7 | 642.7 | 345.6 | 207.7 | 115.4 | 161.5 | .00574 |
| 4.12 | 133.7 | 133.3 | 85.4 | 644.5 | 349.1 | 215.0 | 117.5 | 166.3 | .00591 |
| 4.76 | 132.8 | 133.1 | 86.1 | 661.3 | 353.6 | 228.1 | 121.3 | 174.7 | .00622 |
| 5.39 | 134.0 | 132.8 | 86.9 | 636.9 | 355.1 | 217.3 | 124.3 | 170.8 | .00609 |
| 6.66 | 133.6 | 132.9 | 88.4 | 646.1 | 353.6 | 229.0 | 127.5 | 178.2 | .00636 |
| 7.93 | 134.0 | 132.9 | 89.8 | 648.0 | 354.9 | 234.8 | 131.8 | 183.3 | .00656 |
| 9.20 | 136.2 | 133.6 | 91.3 | 644.4 | 356.5 | 229.1 | 134.6 | 181.9 | .00652 |
| 11.73 | 141.0 | 139.5 | 94.3 | 646.3 | 353.6 | 219.7 | 124.2 | 171.9 | .00619 |
| 14.27 | 151.2 | 146.9 | 97.2 | 636.5 | 351.2 | 186.6 | 111.8 | 149.2 | .00539 |
| 14.91 | 151.8 | 148.4 | 98.0 | 648.3 | 348.6 | 190.0 | 109.1 | 149.5 | .00541 |
| 16.81 | 158.2 | 150.7 | 100.2 | 631.9 | 348.7 | 171.4 | 108.6 | 140.0 | .00508 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=211.61 NU(S)A=121.57 NU(AV)A=166.59 ST(AV)A= .00598
E(+)= 259.27 ST(AV)/ST(4S)=2.01 F/F(4S)=3.97 (ST/ST(4S))/(F/F(4S))= .507
(F/F(4S))/(ST/ST(4S)) 3.0= .49 R(BAR)= 6.873 H(BAR)=14.889

RUN NUMBER=297HR60-45/20 E/D= .063 P/E=20.00 ALPA= 45 D= 2.956 IN
PR=.71 MDOT= .1760 LBM/SEC RE= 56691. QGE(R)= 859.0 BTU/HR-SQ FT
QGE(S)= 464.1 INLET TEMP= 81.4 F TATM= 70.6 F PATM=14.62 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 114.0 | 110.8 | 81.7 | 707.3 | 339.6 | 355.4 | 189.4 | 272.4 | .00668 |
| .95 | 120.8 | 119.2 | 82.4 | 853.5 | 458.8 | 359.9 | 202.0 | 280.9 | .00690 |
| 1.59 | 127.6 | 127.6 | 83.1 | 850.5 | 425.2 | 308.8 | 154.6 | 231.7 | .00569 |
| 2.22 | 134.2 | 131.8 | 83.7 | 826.6 | 438.8 | 264.9 | 147.6 | 206.2 | .00507 |
| 2.85 | 137.5 | 133.7 | 84.4 | 813.9 | 447.6 | 247.5 | 146.6 | 197.0 | .00485 |
| 3.49 | 136.0 | 134.4 | 85.1 | 855.8 | 456.3 | 271.0 | 149.2 | 210.1 | .00518 |
| 4.12 | 135.0 | 135.0 | 85.8 | 851.9 | 447.9 | 278.6 | 146.5 | 212.6 | .00524 |
| 4.76 | 134.0 | 134.5 | 86.4 | 872.7 | 457.1 | 295.1 | 153.1 | 224.1. | .00553 |
| 5.39 | 135.6 | 133.9 | 87.1 | 842.3 | 460.7 | 279.1 | 158.2 | 218.6 | .00540 |
| 6.66 | 135.2 | 134.1 | 88.4 | 854.1 | 457.2 | 292.9 | 160.5 | 226.7 | .00561 |
| 7.93 | 135.9 | 134.3 | 89.8 | 855.0 | 458.5 | 296.6 | 164.8 | 230.7 | .00572 |
| 9.20 | 138.2 | 135.2 | 91.1 | 851.9 | 460.1 | 288.9 | 166.6 | 227.8 | .00566 |
| 11.73 | 143.3 | 141.6 | 93.8 | 853.6 | 456.5 | 274.1 | 151.8 | 213.0 | .00531 |
| 14.27 | 153.5 | 148.4 | 96.5 | 844.5 | 454.6 | 234.3 | 138.6 | 186.5 | .00467 |
| 14.91 | 154.4 | 149.7 | 97.1 | 854.1 | 452.2 | 235.9 | 136.0 | 185.9 | .00466 |
| 16.81 | 160.2 | 151.4 | 99.2 | 838.9 | 452.8 | 216.6 | 136.6 | 176.6 | .00444 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=267.89 NU(S)A=151.62 NU(AV)A=209.75 ST(AV)A= .00521
E(+)= 374.41 ST(AV)/ST(4S)=1.92 F/F(4S)=4.32 (ST/ST(4S))/(F/F(4S))= .445
(F/F(4S))/(ST/ST(4S)) 3.0= .61 R(BAR)= 6.873 H(BAR)=17.455

RUN NUMBER=298HR80-45/20 E/D= .063 P/E=20.00 ALPA= 45 D= 2.956 IN
PR=.71 MDOT= .2510 LBM/SEC RE= 80858. QGE(R)= 976.8 BTU/HR-SQ FT
QGE(S)= 580.5 INLET TEMP= 83.0 F TATM= 72.0 F PATM=14.62 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 109.8 | 110.6 | 83.3 | 812.5 | 418.1 | 495.4 | 247.5 | 371.4 | .00640 |
| .95 | 117.4 | 118.8 | 83.8 | 971.8 | 575.4 | 467.7 | 266.1 | 366.9 | .00633 |
| 1.59 | 125.0 | 126.9 | 84.4 | 965.6 | 540.2 | 383.8 | 204.9 | 294.3 | .00508 |
| 2.22 | 131.9 | 130.7 | 84.9 | 939.7 | 555.5 | 322.5 | 195.6 | 259.0 | .00447 |
| 2.85 | 135.0 | 132.2 | 85.5 | 929.6 | 565.4 | 302.5 | 195.0 | 248.8 | .00430 |
| 3.49 | 132.9 | 132.6 | 86.0 | 977.7 | 574.7 | 335.9 | 198.7 | 267.3 | .00462 |
| 4.12 | 131.8 | 133.1 | 86.6 | 970.2 | 569.4 | 345.6 | 196.9 | 271.3 | .00470 |
| 4.76 | 130.6 | 133.1 | 87.1 | 998.4 | 573.8 | 369.2 | 200.9 | 285.1 | .00494 |
| 5.39 | 133.0 | 133.0 | 87.7 | 955.7 | 574.5 | 338.7 | 203.6 | 271.2 | .00470 |
| 6.66 | 132.4 | 133.2 | 88.8 | 973.2 | 573.8 | 357.8 | 207.4 | 282.6 | .00491 |
| 7.93 | 133.3 | 133.3 | 89.9 | 973.1 | 578.3 | 358.8 | 213.2 | 286.0 | .00497 |
| 9.20 | 135.7 | 135.7 | 91.0 | 969.9 | 573.6 | 346.6 | 205.0 | 275.8 | .00480 |
| 11.73 | 140.6 | 140.6 | 93.2 | 971.8 | 573.6 | 326.4 | 192.7 | 259.5 | .00453 |
| 14.27 | 150.6 | 146.7 | 95.4 | 962.8 | 575.9 | 276.8 | 178.2 | 227.5 | .00399 |
| 14.91 | 151.4 | 149.3 | 96.0 | 971.6 | 571.2 | 277.6 | 169.7 | 223.7 | .00392 |
| 16.81 | 156.6 | 156.6 | 97.6 | 957.7 | 559.6 | 256.7 | 150.0 | 203.3 | .00357 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=322.69 NU(S)A=192.12 NU(AV)A=257.40 ST(AV)A= .00448
E(+)= 534.71 ST(AV)/ST(4S)=1.80 F/F(4S)=4.67 (ST/ST(4S))/(F/F(4S))= .385
(F/F(4S))/(ST/ST(4S)) 3.0= .80 R(BAR)= 6.873 H(BAR)=20.724

RUN NUMBER=239HR08-30/20 E/D= .063 P/E=20.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .0267 LBM/SEC RE= 8559. QGE(R)= 221.7 BTU/HR-SQ FT
QGE(S)= 138.6 INLET TEMP= 77.4 F TATM= 69.4 F PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 119.0 | 115.8 | 78.0 | 202.8 | 124.8 | 80.7 | 53.8 | 67.3 | .01082 |
| .95 | 124.7 | 122.7 | 79.2 | 215.6 | 132.7 | 77.2 | 49.7 | 63.4 | .01022 |
| 1.59 | 130.4 | 129.6 | 80.4 | 208.7 | 120.5 | 67.9 | 39.8 | 53.8 | .00868 |
| 2.22 | 135.3 | 135.1 | 81.6 | 203.5 | 120.7 | 61.5 | 36.6 | 49.0 | .00793 |
| 2.85 | 138.8 | 139.2 | 82.8 | 200.2 | 113.8 | 57.9 | 32.7 | 45.3 | .00733 |
| 3.49 | 140.6 | 141.2 | 84.0 | 205.4 | 122.6 | 58.6 | 34.6 | 46.6 | .00756 |
| 4.12 | 141.4 | 142.2 | 85.2 | 213.8 | 125.7 | 61.4 | 35.6 | 48.5 | .00787 |
| 4.76 | 142.1 | 142.6 | 86.4 | 208.5 | 130.5 | 60.2 | 37.4 | 48.8 | .00794 |
| 5.39 | 142.2 | 143.0 | 87.6 | 211.0 | 128.7 | 62.1 | 37.3 | 49.7 | .00810 |
| 6.66 | 141.4 | 143.2 | 90.0 | 216.6 | 130.4 | 67.4 | 39.3 | 53.3 | .00872 |
| 7.93 | 142.0 | 143.3 | 92.4 | 213.3 | 130.1 | 68.6 | 40.8 | 54.7 | .00897 |
| 9.20 | 142.4 | 143.3 | 94.8 | 215.1 | 131.8 | 71.8 | 43.1 | 57.4 | .00946 |
| 11.73 | 145.3 | 145.3 | 99.6 | 214.5 | 131.9 | 74.0 | 45.5 | 59.7 | .00990 |
| 14.27 | 150.4 | 150.7 | 104.4 | 213.8 | 130.5 | 72.7 | 44.1 | 58.4 | .00973 |
| 14.91 | 152.0 | 152.3 | 105.6 | 212.0 | 127.6 | 71.3 | 42.7 | 57.0 | .00952 |
| 16.81 | 156.4 | 155.9 | 109.3 | 206.0 | 123.5 | 67.8 | 41.1 | 54.4 | .00913 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 68.56 NU(S)A= 41.20 NU(AV)A= 54.88 ST(AV)A= .00905
E(+)= 49.98 ST(AV)/ST(4S)=1.98 F/F(4S)=2.11 (ST/ST(4S))/(F/F(4S))= .940
(F/F(4S))/(ST/ST(4S)) 3.0= .27 R(BAR)= 8.058 H(BAR)= 7.643

RUN NUMBER=240HR12-30/20 E/D= .063 P/E=20.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .0396 LBM/SEC RE= 12707. QGE(R)= 295.1 BTU/HR-SQ FT
QGE(S)= 184.3 INLET TEMP= 78.4 F TATM= 72.2 F PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 115.6 | 111.0 | 78.9 | 279.8 | 180.3 | 124.3 | 91.6 | 108.0 | .01172 |
| .95 | 121.8 | 118.9 | 80.0 | 289.7 | 179.1 | 112.7 | 74.8 | 93.8 | .01020 |
| 1.59 | 128.0 | 126.9 | 81.1 | 278.8 | 159.1 | 96.5 | 56.4 | 76.5 | .00832 |
| 2.22 | 132.9 | 132.4 | 82.2 | 279.1 | 167.0 | 89.1 | 53.9 | 71.5 | .00779 |
| 2.85 | 136.7 | 136.6 | 83.3 | 269.9 | 159.6 | 81.7 | 48.4 | 65.0 | .00710 |
| 3.49 | 138.2 | 138.6 | 84.3 | 282.2 | 172.2 | 84.6 | 51.2 | 67.9 | .00743 |
| 4.12 | 139.0 | 140.0 | 85.4 | 287.8 | 169.6 | 86.5 | 50.1 | 68.3 | .00748 |
| 4.76 | 139.8 | 140.5 | 86.5 | 284.5 | 176.8 | 85.8 | 52.6 | 69.2 | .00760 |
| 5.39 | 140.2 | 141.0 | 87.6 | 285.0 | 175.2 | 86.9 | 52.7 | 69.8 | .00767 |
| 6.66 | 140.0 | 141.5 | 89.7 | 288.5 | 176.7 | 91.8 | 54.7 | 73.2 | .00807 |
| 7.93 | 140.2 | 141.9 | 91.9 | 288.8 | 176.3 | 95.3 | 56.2 | 75.8 | .00837 |
| 9.20 | 141.0 | 142.2 | 94.0 | 288.8 | 177.4 | 97.7 | 58.5 | 78.1 | .00866 |
| 11.73 | 144.4 | 144.0 | 98.4 | 288.7 | 179.0 | 99.0 | 61.9 | 80.4 | .00897 |
| 14.27 | 150.9 | 151.0 | 102.7 | 287.1 | 176.3 | 93.2 | 57.1 | 75.2 | .00843 |
| 14.91 | 152.8 | 153.0 | 103.7 | 287.0 | 173.9 | 91.6 | 55.2 | 73.4 | .00825 |
| 16.81 | 158.8 | 157.8 | 107.0 | 278.8 | 169.4 | 83.8 | 51.9 | 67.8 | .00765 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A= 92.21 NU(S)A= 55.92 NU(AV)A= 74.07 ST(AV)A= .00822
E(+)= 72.27 ST(AV)/ST(4S)=2.03 F/F(4S)=2.23 (ST/ST(4S))/(F/F(4S))= .912
(F/F(4S))/(ST/ST(4S)) 3.0= .27 R(BAR)= 8.360 H(BAR)= 8.371

RUN NUMBER=241HR20-30/20 E/D= .063 P/E=20.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .0634 LBM/SEC RE= 20382. QGE(R)= 399.0 BTU/HR-SQ FT
QGE(S)= 248.0 INLET TEMP= 79.4 F TATM= 72.7 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 114.0 | 109.0 | 79.9 | 357.3 | 215.0 | 170.2 | 119.9 | 145.1 | .00985 |
| .95 | 120.7 | 117.5 | 80.8 | 393.8 | 243.1 | 160.2 | 107.6 | 133.9 | .00910 |
| 1.59 | 127.4 | 125.9 | 81.7 | 378.0 | 216.8 | 134.1 | 79.4 | 106.8 | .00727 |
| 2.22 | 132.2 | 131.2 | 82.6 | 380.8 | 229.8 | 124.3 | 76.5 | 100.4 | .00684 |
| 2.85 | 135.5 | 135.0 | 83.5 | 374.3 | 225.2 | 116.4 | 70.7 | 93.5 | .00638 |
| 3.49 | 136.6 | 136.8 | 84.4 | 388.0 | 234.5 | 120.0 | 72.3 | 96.1 | .00657 |
| 4.12 | 137.2 | 137.8 | 85.3 | 391.9 | 234.4 | 121.7 | 72.0 | 96.9 | .00663 |
| 4.76 | 137.8 | 138.0 | 86.2 | 385.5 | 240.8 | 120.3 | 74.9 | 97.6 | .00668 |
| 5.39 | 137.6 | 138.2 | 87.1 | 392.4 | 240.7 | 125.0 | 75.7 | 100.3 | .00688 |
| 6.66 | 137.4 | 138.6 | 88.9 | 392.5 | 240.8 | 129.8 | 77.8 | 103.8 | .00714 |
| 7.93 | 137.5 | 138.9 | 90.8 | 394.3 | 241.0 | 134.8 | 80.0 | 107.4 | .00740 |
| 9.20 | 138.8 | 139.4 | 92.6 | 393.1 | 242.3 | 135.5 | 82.4 | 109.0 | .00753 |
| 11.73 | 143.4 | 142.8 | 96.2 | 392.8 | 242.6 | 131.8 | 82.5 | 107.2 | .00744 |
| 14.27 | 151.0 | 150.8 | 99.9 | 391.7 | 240.4 | 120.6 | 74.3 | 97.5 | .00680 |
| 14.91 | 153.3 | 153.1 | 100.8 | 389.9 | 235.6 | 116.7 | 70.8 | 93.8 | .00655 |
| 16.81 | 160.0 | 157.3 | 103.5 | 381.2 | 233.6 | 105.6 | 68.0 | 86.8 | .00609 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=125.30 NU(S)A= 76.66 NU(AV)A=100.98 ST(AV)A= .00699
E(+)= 112.34 ST(AV)/ST(4S)=1.98 F/F(4S)=2.36 (ST/ST(4S))/(F/F(4S))= .836
(F/F(4S))/(ST/ST(4S)) 3.0= .31 R(BAR)= 8.733 H(BAR)= 9.902

RUN NUMBER=242HR40-30/20 E/D= .063 P/E=20.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .1190 LBM/SEC RE= 38327. QGE(R)= 602.7 BTU/HR-SQ FT
QGE(S)= 374.1 INLET TEMP= 80.6 F TATM= 71.8 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 113.8 | 109.6 | 81.0 | 505.3 | 287.5 | 249.8 | 163.0 | 206.4 | .00748 |
| .95 | 120.7 | 118.0 | 81.7 | 597.3 | 369.0 | 248.6 | 165.0 | 206.8 | .00750 |
| 1.59 | 127.5 | 126.3 | 82.4 | 581.3 | 341.4 | 208.9 | 125.9 | 167.4 | .00608 |
| 2.22 | 132.4 | 131.3 | 83.2 | 581.1 | 352.9 | 190.8 | 118.5 | 154.6 | .00562 |
| 2.85 | 135.5 | 134.5 | 83.9 | 580.0 | 353.1 | 181.6 | 112.7 | 147.1 | .00535 |
| 3.49 | 136.6 | 135.9 | 84.6 | 591.6 | 361.4 | 183.7 | 113.7 | 148.7 | .00541 |
| 4.12 | 137.2 | 136.6 | 85.4 | 595.5 | 362.6 | 185.1 | 114.0 | 149.6 | .00545 |
| 4.76 | 137.8 | 136.8 | 86.1 | 585.8 | 366.9 | 182.4 | 116.6 | 149.5 | .00545 |
| 5.39 | 137.2 | 136.9 | 86.8 | 598.2 | 367.2 | 190.9 | 117.9 | 154.4 | .00564 |
| 6.66 | 137.0 | 137.3 | 88.3 | 595.9 | 366.9 | 196.2 | 120.1 | 158.1 | .00579 |
| 7.93 | 137.0 | 137.7 | 89.7 | 598.9 | 367.0 | 202.8 | 122.5 | 162.6 | .00596 |
| 9.20 | 138.7 | 138.2 | 91.2 | 596.2 | 369.3 | 200.4 | 125.5 | 162.9 | .00599 |
| 11.73 | 143.4 | 143.0 | 94.1 | 597.0 | 368.0 | 192.5 | 119.6 | 156.1 | .00576 |
| 14.27 | 152.5 | 151.2 | 97.1 | 593.4 | 365.7 | 169.2 | 106.7 | 138.0 | .00511 |
| 14.91 | 154.6 | 153.4 | 97.8 | 593.8 | 360.2 | 165.0 | 102.3 | 133.6 | .00496 |
| 16.81 | 161.2 | 156.2 | 100.0 | 584.0 | 360.6 | 150.2 | 101.0 | 125.6 | .00467 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=184.84 NU(S)A=115.28 NU(AV)A=150.06 ST(AV)A= .00552
E(+)= 202.47 ST(AV)/ST(4S)=1.85 F/F(4S)=2.53 (ST/ST(4S))/(F/F(4S))= .731
(F/F(4S))/(ST/ST(4S)) 3.0= .40 R(BAR)= 9.250 H(BAR)=12.552

RUN NUMBER=243HR60-30/20 E/D= .063 P/E=20.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .1820 LBM/SEC RE= 58737. QGE(R)= 737.1 BTU/HR-SQ FT
QGE(S)= 460.0 INLET TEMP= 81.2 F TATM= 71.2 F PATM=14.70 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 110.9 | 108.5 | 81.5 | 607.8 | 350.7 | 335.3 | 210.6 | 272.9 | .00647 |
| .95 | 117.6 | 116.2 | 82.1 | 732.0 | 455.0 | 334.1 | 215.9 | 275.0 | .00652 |
| 1.59 | 124.3 | 124.0 | 82.7 | 717.8 | 429.1 | 279.3 | 168.2 | 223.7 | .00531 |
| 2.22 | 129.3 | 128.5 | 83.3 | 712.6 | 440.1 | 250.5 | 157.2 | 203.8 | .00484 |
| 2.85 | 132.0 | 131.4 | 83.8 | 715.8 | 436.9 | 240.1 | 148.4 | 194.3 | .00462 |
| 3.49 | 132.9 | 132.2 | 84.4 | 729.9 | 452.5 | 243.0 | 152.9 | 198.0 | .00471 |
| 4.12 | 133.8 | 132.9 | 85.0 | 730.2 | 447.6 | 241.6 | 150.7 | 196.2 | .00467 |
| 4.76 | 134.6 | 132.9 | 85.6 | 713.0 | 453.2 | 234.4 | 154.4 | 194.4 | .00463 |
| 5.39 | 133.3 | 132.9 | 86.2 | 735.9 | 454.4 | 251.4 | 156.6 | 204.0 | .00487 |
| 6.66 | 132.8 | 133.4 | 87.4 | 732.1 | 453.2 | 258.8 | 158.3 | 208.5 | .00498 |
| 7.93 | 133.2 | 133.8 | 88.5 | 731.9 | 454.0 | 262.7 | 160.8 | 211.7 | .00507 |
| 9.20 | 134.4 | 134.7 | 89.7 | 732.1 | 455.1 | 262.1 | 161.8 | 212.0 | .00508 |
| 11.73 | 139.8 | 139.6 | 92.0 | 731.4 | 453.6 | 244.1 | 152.1 | 198.1 | .00477 |
| 14.27 | 148.8 | 146.8 | 94.4 | 726.9 | 452.0 | 212.2 | 136.9 | 174.5 | .00421 |
| 14.91 | 150.5 | 148.7 | 95.0 | 729.8 | 446.6 | 208.4 | 131.8 | 170.1 | .00411 |
| 16.81 | 156.8 | 150.8 | 96.7 | 718.5 | 447.9 | 189.3 | 131.1 | 160.2 | .00388 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=238.25 NU(S)A=149.83 NU(AV)A=194.04 ST(AV)A= .00465
E(+)= 301.59 ST(AV)/ST(4S)=1.73 F/F(4S)=2.63 (ST/ST(4S))/(F/F(4S))= .659
(F/F(4S))/(ST/ST(4S)) 3.0= .51 R(BAR)= 9.613 H(BAR)=14.840

RUN NUMBER=244HR80-30/20 E/D= .063 P/E=20.00 ALPA= 30 D= 2.956 IN
PR=.71 MDOT= .2510 LBM/SEC RE= 81042. QGE(R)= 907.5 BTU/HR-SQ FT
QGE(S)= 581.9 INLET TEMP= 81.7 F TATM= 72.7 F PATM=14.58 PSIA

| X/D | TW(R) | TW(S) | TBULK | QGAS(R) | QGAS(S) | NU(R) | NU(S) | NU(AV) | ST(AV) |
|---|---|---|---|---|---|---|---|---|---|
| .32 | 109.5 | 109.4 | 82.0 | 751.6 | 429.8 | 442.4 | 253.9 | 348.1 | .00599 |
| .95 | 116.7 | 117.1 | 82.5 | 902.7 | 577.0 | 426.9 | 270.3 | 348.6 | .00600 |
| 1.59 | 124.0 | 124.7 | 83.0 | 884.3 | 548.5 | 349.4 | 212.7 | 281.1 | .00484 |
| 2.22 | 129.0 | 128.9 | 83.6 | 883.5 | 560.8 | 314.2 | 199.9 | 257.1 | .00443 |
| 2.85 | 131.8 | 131.2 | 84.1 | 880.3 | 561.9 | 297.9 | 192.6 | 245.3 | .00423 |
| 3.49 | 132.0 | 131.8 | 84.6 | 905.4 | 575.4 | 308.3 | 196.8 | 252.5 | .00436 |
| 4.12 | 132.8 | 132.4 | 85.1 | 900.9 | 567.3 | 305.1 | 193.5 | 249.3 | .00431 |
| 4.76 | 133.5 | 132.0 | 85.7 | 886.0 | 575.4 | 298.4 | 200.0 | 249.2 | .00431 |
| 5.39 | 132.4 | 131.6 | 86.2 | 905.2 | 579.4 | 315.3 | 205.4 | 260.4 | .00450 |
| 6.66 | 131.8 | 132.3 | 87.3 | 902.4 | 575.4 | 325.5 | 205.2 | 265.3 | .00460 |
| 7.93 | 131.9 | 133.0 | 88.3 | 903.8 | 575.7 | 332.6 | 206.6 | 269.6 | .00468 |
| 9.20 | 133.4 | 133.9 | 89.4 | 902.4 | 577.4 | 328.1 | 207.6 | 267.9 | .00465 |
| 11.73 | 138.7 | 139.0 | 91.5 | 902.6 | 575.7 | 305.0 | 193.3 | 249.2 | .00434 |
| 14.27 | 148.7 | 146.2 | 93.6 | 896.3 | 574.0 | 258.8 | 173.5 | 216.2 | .00378 |
| 14.91 | 150.3 | 148.1 | 94.1 | 900.2 | 568.2 | 254.8 | 167.4 | 211.1 | .00369 |
| 16.81 | 156.0 | 149.6 | 95.7 | 889.5 | 570.5 | 233.8 | 167.8 | 200.8 | .00352 |

FULLY DEVELOPED REGION (BASED ON AVERAGE DATA FROM X/D=2.85 TO X/D=16.81) :
NU(R)A=297.54 NU(S)A=192.21 NU(AV)A=244.88 ST(AV)A= .00426
E(+)= 407.07 ST(AV)/ST(4S)=1.71 F/F(4S)=2.70 (ST/ST(4S))/(F/F(4S))= .634
(F/F(4S))/(ST/ST(4S)) 3.0= .54 R(BAR)= 9.894 H(BAR)=16.047

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15. Supplementary Notes

Final report. Project Manager, Robert J. Boyle, Aerothermodynamics and Fuels Division, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

Repeated rib roughness elements have been used in advanced turbine cooling designs to enhance the internal heat transfer. Often the ribs are perpendicular to the main flow direction so that they have an angle-of-attack of 90°. The objective of the project was to investigate the effect of rib angle-of-attack on the pressure drop and the average heat transfer coefficients in a square duct with two opposite rib-roughened walls for Reynolds number varied from 8000 to 80 000. The rib height-to-equivalent diameter ratio (e/D) was kept at a constant value of 0.063, the rib pitch-to-height ratio (P/e) was varied from 10 to 20, and the rib angle-of-attack ($\alpha$) was varied from 90° to 60° to 45° to 30°, respectively. Two types of entrance conditions were examined, namely, long duct and sudden contraction. The heat transfer coefficient distribution on the smooth side wall and the rough side wall at the entrance and the fully developed regions were measured. Thermal performance comparison indicated that the pumping power requirement for the rib with an oblique angle to the flow ($\alpha$ = 45° to 30°) was about 20 to 50 percent lower than the rib with a 90° angle to the flow for a given heat transfer duty. Semi-empirical correlations for friction factor and heat transfer coefficients were developed to account for rib spacing and rib angle-of-attack. The correlations can be used in the design of turbine blade cooling passages.

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