EVALUATION OF HIGH REYNOLDS NUMBER FLOW IN A 180 DEGREE TURN-AROUND-DUCT

by

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ABSTRACT

Mean and turbulent velocities were measured for the flow in a 180 degree turn-around-duct over a Reynolds number range from 600,000 to greater than 900,000. The measurements were made in water using a forward scattering laser velocimeter. A duct of 100x10 centimeters constant cross-section, with a mean radius of curvature (centerline) of 10 centimeters was employed for the study. The measurements are in agreement with previous studies in that the use of the local bulk velocity to non-dimensionalize the mean and turbulent velocities reduce the Reynolds number variations. The basic phenomenon of relaminarization along the inner surface at the start of the turn, and flow separation along the inner surface at the exit of the turn are similar to the flow observed at low Reynolds numbers. The separation bubble region shows a systematic variation with Reynolds number, however the Reynolds number effect may be of second order in the calculation of the overall flow.

Large tangential, radial and lateral turbulent velocities are measured along the outer surface of the turn.

INTRODUCTION

The development of computer codes to predict complex shear flows require experimental data over a wide range of Reynolds numbers. The present study was a continuation of the documentation of the flow in a turn-around-duct for high Reynolds numbers. The flow in the duct at lower Reynolds was reported by Sandborn and Shin (1990).

Early attempts to compute the flow in turn-around-ducts, (see Monson, et al. (1990) for a review of the earlier work), using the k-e models for turbulent flow, were not able to accurately predict the pressure drop through the duct. Difficulty was also encountered in predicting a separation bubble at the exit of the duct. More recent computations employing a curvature term, referred to as a turbulent Richardson number, have greatly improved the ability to predict both the pressure distribution and the separation, Cheng (1990) and Monson, et al. (1990).

The present study extends the measurements in the turn-around-duct from Reynolds numbers of 500,000 to near 1,000,000. A forward scattering, laser velocimeter was employed to measure the tangential and radial mean and turbulent velocities. Hot, film and wire anemometers were employed to determine the lateral turbulent component in the duct’s curved section. Estimates of the surface shear stress along the surface of the turn were obtained using a Stanton tube.
EXPERIMENTAL STUDY

Flow Facility.- Detailed descriptions of the flow facility were given by Sandborn and Shin (1990). The duct was nominally 100x10 cm in cross-section and produced a near two-dimensional flow. Measurements of the two-dimensional character of the flow were demonstrated by Sandborn and Shin. For the present study the dimensions of the duct are slightly altered, as noted on figure 1. The lateral distance of 100 cm was maintained, but the radial spacing could not be held accurately to 10 cm once the facility was cleaned and strengthened for the high Reynolds number runs. Trip wires, 1.3 mm in diameter, were employed at the inlet of the facility for the present tests. These trip wires were also employed for some of the previous low Reynolds number flows. A 12.7 mm mesh screen was employed at the exit of the duct for the present tests. Location of all instrumentation was the same at that used in the earlier studies.

Using the 12.7 mm mesh screen, the inlet pressure in the duct is approximately 1.5 atmospheres for the highest flow rates (-1.37 cubic meters per second, Re = 950,000). For these flow conditions very small bubbles of cavitation were observed close to the inner surface near the start of the turn. No measurements were made in the turn once cavitation occurred, although there was no evidence to suggest that the flow was affected by the cavitation. The safety limits of the duct were being approached for these high flow rates, so no attempt was made to increase the duct pressure by increasing the exit screen resistance.

Velocity, Pressure and Surface Shear Stress Evaluation.- The tangential and radial mean and turbulent velocities, as well as the Reynolds turbulent shear stress were measured with the forward scattering laser velocimeter. A 20 milliwatt He-Ne laser was employed for the light source. The doppler signals were sensed with a photodiode and evaluated with a commercial doppler frequency counter system. Details of the velocimeter, signal evaluation and uncertainties in the measurements were given by Shin (1990). For the present high flow rates the uncertainties are greater due to an increase in the facility vibrations and also difficulties in excessive water being splashed on the laser optics.

The static pressure distributions around the duct were evaluated both with diaphragm pressure transducers and with mercury and heavy oil manometers.

A "razor blade" type Stanton tube described by Shin (1990) was employed to evaluate the surface shear stress at a number of locations around the outer surface of the turn. The Stanton tube was calibrated at a location upstream of the turn where the local surface shear stress was determined by fitting the measured mean velocity profiles to the "law of the wall".

Lateral Turbulent Velocity Evaluation.- It was impossible to measure the lateral velocity component with the laser velocimeter, so single yawed hot, film and wires were employed. The sensors were placed in the flow at the same location as the sampling volume of the laser velocimeter - set to measure the tangential velocity component. The velocity obtained from the laser velocimeter was employed to calibrate the thermal anemometer. Calibration of the thermal sensor sensitivity for both velocity and angle fluctuations were obtained. It was not possible to maintain the thermal sensor calibrations for extended periods of time. The laser provides an update of the calibration at each measured point. Only the thermal sensor sensitivity to the velocity fluctuations needed to be determined for most of the measurements. The sensor sensitivity to velocity at the yaw angle (30 degrees) and the sensitivity to angle are proportional to the sensitivity when the wire is normal to the flow, Sandborn (1972) (page 290). The sensors were limited in strength, so it was impossible to extend the measurements to the highest Reynolds numbers.
RESULTS

Tables I through VII list the measurements obtained during the course of the study. The measured pressure coefficients are listed in Table Ia, and extrapolated values for specific Reynolds numbers are listed in Table Ib. The measured values of the mean and turbulent properties obtained with the laser velocimeter are listed in Table II. Table III lists the extrapolated values of the mean and turbulent tangential velocities divided by the local bulk velocities for specific Reynolds numbers. Table IV lists the velocities measured in the separation bubble region, and Table V gives the extrapolated values. Table VI lists the values of surface shear obtained from the Stanton tube. Table VII lists the values of the velocities obtained during the evaluation of the lateral velocities.

Figure 2 shows the static pressure coefficient variation around the turn on both the inside and outside walls for the range of Reynolds numbers from 600,000 to 1,000,000. The effect of Reynolds number on the pressure distribution is extremely small. The pressure difference between the present results and the earlier, lower Reynolds numbers, Sandborn and Shin (1990), is also noted on figure 2. The slight difference between the present results and the earlier data may be due in part to the small change in the duct dimensions.

Figure 3 shows the mean velocity distributions obtained at several locations around the duct. The use of the local bulk velocity and duct height to nondimensionalize the profiles result in near similar distributions at each location. The lower Reynolds number results are also noted on figure 3. The deviations between the earlier data and the present measurements might have been expected from the slight change in the pressure distribution.

Only when the separation bubble appears does a measurable deviation with Reynolds number occur. Figure 4 shows the mean velocity variations measured in the separation bubble region. The previous low Reynolds number data indicated a large variation in the separation region velocities up to Re = 300,000, and a lesser variation for the higher values of Re. The present results indicate the maximum bubble thickness occurs around a Reynolds number of 600,000 and the bubble decreases slightly for greater values of Re. The increase in separation bubble thickness with increasing Reynolds number is contrary to that observed for normal turbulent boundary layers. It would appear that the separation in the turn-around-duct is at least in part governed by the inertia effects of the turn. The flow along the inner surface proceeds for an appreciable distance in the adverse pressure gradient and only separates when it is required to turn quickly. The thickening of the separation bubble may indicate the failure of the higher speed flow to make the turn. Above a Reynolds number of 600,000 the flow responds more closely to what is expected in a viscous dominated separation.

The separation bubble region for the turn-around-duct is a highly time dependent flow. As reported by Sandborn and Shin (1990), the tangential turbulent velocities at the height of the zero velocity location may be as great as 0.6Um. At this height the flow was reversed approximately 65 percent of the time. Even very close to the surface the flow was reversed only 80 to 85 percent of the time. It appears that the flow fluctuates in a coherent manner, since the correlation between the tangential and radial velocities is extremely large and positive. The large positive correlations require that when a positive tangential velocity occurs a corresponding positive radial velocity is present.

Figure 5 compares the present measurements in the separation region at the exit of the turn with the measurements of Monson, et al. (1989). Although, comparison of the flow in the present water duct and the air duct of Monson, et al. appear similar upstream of separation, it is apparent that the character of
the separated regions are different. The present flow separation bubble is not as large, nor is the reverse flow as great as that reported for the air duct. The water duct employs an exit screen 4.3H downstream of the turn. The measurements of Sandborn and Shin (1990) found only secondary changes in the separation for flows with and without the screen in place. The air facility contained a straight exit section of approximately 14H in length. The static pressure coefficient downstream of the turn for the air facility reaches a constant value of -0.05, while the water facility indicated values of the order of -0.03 to -0.04.

Figure 6 shows the values of surface shear stress obtained with the Stanton tube. In the turn region the affect of Re on the skin friction coefficient was very small. The data for the location 1.7H upstream of the turn is not included on figure 6, since it was employed to calibrate the Stanton tube.

It was not possible to measure the surface shear along the inner wall of the turn. Shin (1990) made estimates for the low Reynolds number flows, assuming an empirical turbulent boundary layer, skin friction equation could be employed. It is questionable whether the flow along the inner surface can be considered a turbulent boundary layer. As a first approximation for the surface shear on the inner wall at the 90 degree location, a simple laminar approximation was made, as noted on the insert of figure 6. Values of the surface shear on the inner wall would appear to be of the similar magnitude as those on the outer wall. The values of surface shear noted on the insert at 170 and 180 degrees around the turn, 5.08cm and 7cm downstream of the turn were estimated from the slope of the velocity distributions at the surface.

Figure 7 shows the tangential turbulent velocity distributions obtained for a number of locations around the duct. Only secondary effects of Reynolds number are observed at a given location. The previous low Reynolds number measurements of Sandborn and Shin indicated a more pronounced variation of the turbulent velocities with Reynolds number. Although, the low Reynolds number measurements suggested an uncoupling between the turbulent velocities and the mean flow, the higher flows indicate near similarity for both mean and turbulent quantities with Reynolds number.

Figure 8 is a plot of the tangential, u, radial, v, and lateral, w, turbulent velocity components evaluated at 50, 90, and 130 degrees around the turn. Measurements with the hot wires and films proved very difficult in the high Reynolds number flow regime. It was impossible to maintain the calibration of either wires or films for any appreciable length of run time. The film sensors failed before a profile could be completed. Although the accuracy of the lateral turbulent velocities was poor, it appears that the peak magnitude of the lateral and radial velocities are roughly equal in the outer part of the shear layer along the outer wall. Very close to the outer wall the lateral velocity component was larger than either of the other two velocity components. It appears incorrect to employ the approximation that the lateral component is the average of the tangential and radial components, as is the case for normal turbulent boundary layers. The large values of both the lateral, w', and radial, v', velocities would be consistent with the presence of a vortex type motion along the outer wall in the turn. At the 50 degree location around the turn, which is just downstream of the apparent start of the large disturbances, all three components of the turbulence are found to be of the same magnitude. Further around the turn the radial and lateral components remain large, while the tangential velocity fluctuations are reduced in intensity.
CONCLUSIONS

The mean and turbulent velocities in a 180 degree, turn-around-duct for a Reynolds number range from 600,000 to greater than 900,000 have been documented. Tabulated values are given for the static pressure, mean and turbulent velocities, and surface shear stress on the outer surface.

The effects of Reynolds number are reduced by employing the local bulk velocity and duct height as the characteristic velocity and length. Systematic variation with Reynolds number of the flow field in the separation bubble, which occurred along the inner surface at the exit of the turn, was documented in detail.

REFERENCES


LIST OF SYMBOLS

- $C_f$: Skin friction coefficient, $\tau_w/\frac{1}{2} \rho U_m^2$
- $C_p$: Static pressure coefficient, $\Delta p/\frac{1}{2} \rho U_m^2$
- $H$: Duct height
- $p$: Local static pressure
- $Re$: Reynolds number
- $T$: Water Temperature
- $u'$: Root-mean-square of the tangential turbulent velocity
- $U$: Local mean tangential velocity
- $U_m$: Local mean bulk velocity
- $U_{max}$: Local maximum velocity at the 90 degree location
- $Ur$: Local mean radial velocity
- $U_c$: Shear stress velocity, $\sqrt{\tau_w/\rho}$
- $\tau_{uv}$: Reynolds turbulent stress
- $v'$: Root-mean-square of the radial turbulent velocity
- $w'$: Root-mean-square of the lateral turbulent velocity
- $x$: Tangential distance along the duct
- $y$: Radial distance from the inner wall of the duct
- $y'$: Radial distance from the outer wall of the duct
- $\alpha$: Angle between the mean flow and the tangential direction
- $\delta$: Laminar boundary layer thickness, taken as point of $U_{max}$
- $\rho$: Water density
- $\tau_w$: Surface shear stress
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b) Extrapolated values of Cp

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| Cp      | +0.0113 | +0.0117 |
| Cp      | 1.1.977 | 1.1.96 |
| Cp      | -2.388 | -2.358 |
| Cp      | 2.208 | 2.173 |
| Cp      | 1.790 | 1.851 |
| Cp      | 1.437 | 1.680 |
| Cp      | 0.141 | 0.745 |
| Cp      | 0.525 | 0.513 |
| Cp      | +0.0010 | +0.0052 |
| Cp      | 0.0003 | 0.0003 |
| Cp      | 0.0062 | 0.0043 |
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| Cp      | +0.344 | +0.350 |
| Cp      | +0.369 | +0.372 |
| Cp      | 0.368 | 0.368 |
| Cp      | 0.376 | 0.380 |
| Cp      | 0.383 | 0.389 |
| Cp      | 0.358 | 0.358 |
| Cp      | 0.358 | 0.368 |
| Cp      | 0.377 | 0.371 |
| Cp      | 0.257 | 0.263 |
| Cp      | 0.375 | 0.375 |
| Cp      | 0.412 | 0.403 |
| Cp      | 0.287 | 0.287 |
| Cp      | 0.287 | 0.287 |
### TABLE II. VELOCITY FIELD MEASUREMENTS

**a) Upstream Inlet (-101.6 cm)

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**b) -17 cm upstream of the turn

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<th>V'</th>
<th>U'</th>
<th>( \bar{U} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.104</td>
<td>308,000</td>
<td>6.584</td>
<td>.6660</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.508</td>
<td>624,000</td>
<td>11.20</td>
<td>.2622</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.27</td>
<td>605,000</td>
<td>10.57</td>
<td>.2350</td>
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<tr>
<td>2.54</td>
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<td>9.885</td>
<td>.1860</td>
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<td></td>
</tr>
<tr>
<td>4.99</td>
<td>590,000</td>
<td>8.321</td>
<td>.2160</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.62</td>
<td>637,000</td>
<td>5.233</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.14</td>
<td>622,000</td>
<td>5.532</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.65</td>
<td>635,000</td>
<td>4.478</td>
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</tr>
</tbody>
</table>

**Repeat run (T = 6.3°C)

<table>
<thead>
<tr>
<th>y (cm)</th>
<th>Re</th>
<th>U_t</th>
<th>U_r</th>
<th>α</th>
<th>V'</th>
<th>U'</th>
<th>( \bar{U} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.62</td>
<td>612,000</td>
<td>8.099</td>
<td>.3088</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>9.14</td>
<td>625,000</td>
<td>6.367</td>
<td>.5127</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: Table entries are velocity values in cm/sec, with subscripts t, r, and mean indicating tangential, radial, and mean, respectively.
### TABLE II. (CONCLUDED) VELOCITY FIELD MEASUREMENTS

<table>
<thead>
<tr>
<th>( T = 9.0^\circ C )</th>
<th>( \rho = 1.9999 \text{gm/cm}^3 )</th>
<th>( V = 1.355 \times 10^{-4} \text{m/sec} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y )</td>
<td>( \text{Re} )</td>
<td>( \text{U} )</td>
</tr>
<tr>
<td>cm</td>
<td>m/sec</td>
<td>m/sec</td>
</tr>
<tr>
<td>0.051</td>
<td>573,000</td>
<td>13.54</td>
</tr>
<tr>
<td>0.102</td>
<td>596,000</td>
<td>14.49</td>
</tr>
<tr>
<td>0.203</td>
<td>596,000</td>
<td>14.50</td>
</tr>
<tr>
<td>0.381</td>
<td>602,000</td>
<td>14.50</td>
</tr>
<tr>
<td>0.965</td>
<td>627,000</td>
<td>14.17</td>
</tr>
<tr>
<td>2.34</td>
<td>607,000</td>
<td>9.571</td>
</tr>
<tr>
<td>4.98</td>
<td>635,000</td>
<td>7.797</td>
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<tr>
<td>7.62</td>
<td>627,000</td>
<td>5.471</td>
</tr>
<tr>
<td>8.64</td>
<td>628,000</td>
<td>5.451</td>
</tr>
</tbody>
</table>

Repeat run \( T = 6.1^\circ C \)

| 7.62 | 595,000 | 5.788 | 0.9211 | 667,000 | 6.683 | 1.348 | 760,000 | 7.321 | 1.177 |
| 8.89 | 593,000 | 5.124 | 0.8425 | 680,000 | 5.864 | 0.8358 | 763,000 | 6.514 | 0.9613 |
| 9.27 | 599,000 | 5.148 | 0.8603 | 687,000 | 5.435 | 0.6665 | 701,000 | 5.916 | 0.830 |

f) +3.06H downstream of the turn

<table>
<thead>
<tr>
<th>( T = 10.6^\circ C )</th>
<th>( \rho = 0.9997 \text{gm/cm}^3 )</th>
<th>( V = 1.294 \times 10^{-5} \text{m/sec} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y )</td>
<td>( \text{Re} )</td>
<td>( \text{U} )</td>
</tr>
<tr>
<td>cm</td>
<td>m/sec</td>
<td>m/sec</td>
</tr>
<tr>
<td>1.02</td>
<td>714,000</td>
<td>0.286</td>
</tr>
<tr>
<td>2.03</td>
<td>723,000</td>
<td>11.72</td>
</tr>
<tr>
<td>3.03</td>
<td>712,000</td>
<td>13.37</td>
</tr>
<tr>
<td>4.99</td>
<td>710,000</td>
<td>10.88</td>
</tr>
<tr>
<td>6.92</td>
<td>725,000</td>
<td>9.315</td>
</tr>
<tr>
<td>9.80</td>
<td>710,000</td>
<td>9.616</td>
</tr>
<tr>
<td>9.25</td>
<td>725,000</td>
<td>9.315</td>
</tr>
</tbody>
</table>

\* Exit of the turn (above the separation bubble)

<table>
<thead>
<tr>
<th>( T = 10.6^\circ C )</th>
<th>( \rho = 0.9997 \text{gm/cm}^3 )</th>
<th>( V = 1.294 \times 10^{-5} \text{m/sec} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y )</td>
<td>( \text{Re} )</td>
<td>( \text{U} )</td>
</tr>
<tr>
<td>cm</td>
<td>m/sec</td>
<td>m/sec</td>
</tr>
<tr>
<td>1.02</td>
<td>10.86</td>
<td>7300</td>
</tr>
<tr>
<td>7.67</td>
<td>725,000</td>
<td>9.851</td>
</tr>
<tr>
<td>9.37</td>
<td>725,000</td>
<td>9.385</td>
</tr>
<tr>
<td>9.25</td>
<td>725,000</td>
<td>9.315</td>
</tr>
<tr>
<td>9.80</td>
<td>710,000</td>
<td>9.616</td>
</tr>
</tbody>
</table>

\( \text{f) +3.06H downstream of the turn} \)
### TABLE III. EXTRAPOLATED MEAN AND TURBULENT VELOCITY PROFILES

#### a) Upstream inlet (-101.6cm)

<table>
<thead>
<tr>
<th>Re</th>
<th>700,000</th>
<th>800,000</th>
<th>900,000</th>
<th>980,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Um</td>
<td>9.138m/s</td>
<td>10.64m/s</td>
<td>11.75m/s</td>
<td>12.79m/s</td>
</tr>
<tr>
<td>y</td>
<td>U</td>
<td>U'</td>
<td>U</td>
<td>U'</td>
</tr>
<tr>
<td>H</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
</tr>
<tr>
<td></td>
<td>0.0102</td>
<td>0.886</td>
<td>0.05220</td>
<td>0.9113</td>
</tr>
<tr>
<td></td>
<td>0.0305</td>
<td>0.9566</td>
<td>0.05330</td>
<td>0.9752</td>
</tr>
<tr>
<td></td>
<td>0.0762</td>
<td>1.016</td>
<td>0.03412</td>
<td>1.017</td>
</tr>
<tr>
<td></td>
<td>0.152</td>
<td>1.025</td>
<td>0.01915</td>
<td>1.011</td>
</tr>
<tr>
<td></td>
<td>0.838</td>
<td>1.072</td>
<td>0.0147</td>
<td>1.028</td>
</tr>
<tr>
<td></td>
<td>0.953</td>
<td>0.9566</td>
<td>0.9813</td>
<td>0.9935</td>
</tr>
<tr>
<td></td>
<td>0.979</td>
<td>0.8799</td>
<td>0.06731</td>
<td>0.8984</td>
</tr>
<tr>
<td></td>
<td>0.991</td>
<td>0.8409</td>
<td>0.07128</td>
<td>0.8669</td>
</tr>
</tbody>
</table>

#### b) -17cm upstream of the turn

<table>
<thead>
<tr>
<th>Re</th>
<th>600,000</th>
<th>700,000</th>
<th>800,000</th>
<th>850,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Um</td>
<td>8.035m/s</td>
<td>9.374m/s</td>
<td>10.71m/s</td>
<td>11.36m/s</td>
</tr>
<tr>
<td>y</td>
<td>U</td>
<td>U'</td>
<td>U</td>
<td>U'</td>
</tr>
<tr>
<td>H</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
</tr>
<tr>
<td></td>
<td>0.0204</td>
<td>0.8906</td>
<td>0.0508</td>
<td>0.8771</td>
</tr>
<tr>
<td></td>
<td>0.0304</td>
<td>0.9416</td>
<td>0.0478</td>
<td>0.9168</td>
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<tr>
<td></td>
<td>0.0510</td>
<td>0.9522</td>
<td>0.0580</td>
<td>0.9379</td>
</tr>
<tr>
<td></td>
<td>0.112</td>
<td>1.026</td>
<td>0.0240</td>
<td>0.9993</td>
</tr>
<tr>
<td></td>
<td>0.240</td>
<td>1.043</td>
<td>0.0161</td>
<td>1.038</td>
</tr>
<tr>
<td></td>
<td>0.501</td>
<td>1.076</td>
<td>0.0147</td>
<td>1.057</td>
</tr>
<tr>
<td></td>
<td>0.750</td>
<td>1.041</td>
<td>0.0346</td>
<td>1.020</td>
</tr>
<tr>
<td></td>
<td>0.903</td>
<td>1.112</td>
<td>0.0579</td>
<td>0.9021</td>
</tr>
<tr>
<td></td>
<td>0.984</td>
<td>0.7367</td>
<td>0.0620</td>
<td>0.7373</td>
</tr>
<tr>
<td></td>
<td>0.989</td>
<td>0.7102</td>
<td>0.0717</td>
<td>0.7139</td>
</tr>
<tr>
<td></td>
<td>0.994</td>
<td>0.6495</td>
<td>0.0683</td>
<td>0.6640</td>
</tr>
<tr>
<td></td>
<td>0.999</td>
<td>0.5827</td>
<td>0.0519</td>
<td>0.5774</td>
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</tbody>
</table>

#### c) Start of the turn

<table>
<thead>
<tr>
<th>Re</th>
<th>600,000</th>
<th>700,000</th>
<th>800,000</th>
<th>850,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Um</td>
<td>8.138m/s</td>
<td>9.495m/s</td>
<td>10.85m/s</td>
<td>11.53m/s</td>
</tr>
<tr>
<td>y</td>
<td>U</td>
<td>U'</td>
<td>U</td>
<td>U'</td>
</tr>
<tr>
<td>H</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
</tr>
<tr>
<td></td>
<td>0.014</td>
<td>1.370</td>
<td>0.0576</td>
<td>1.352</td>
</tr>
<tr>
<td></td>
<td>0.0510</td>
<td>1.328</td>
<td>0.0281</td>
<td>1.308</td>
</tr>
<tr>
<td></td>
<td>0.128</td>
<td>1.286</td>
<td>0.0284</td>
<td>1.272</td>
</tr>
<tr>
<td></td>
<td>0.255</td>
<td>1.175</td>
<td>0.0235</td>
<td>1.170</td>
</tr>
<tr>
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<td>0.501</td>
<td>1.013</td>
<td>0.0257</td>
<td>1.026</td>
</tr>
<tr>
<td></td>
<td>0.765</td>
<td>0.810</td>
<td>0.085</td>
<td>0.848</td>
</tr>
<tr>
<td></td>
<td>0.918</td>
<td>0.695</td>
<td>0.055</td>
<td>0.651</td>
</tr>
<tr>
<td></td>
<td>0.943</td>
<td>0.612</td>
<td>0.057</td>
<td>0.598</td>
</tr>
<tr>
<td></td>
<td>0.969</td>
<td>0.525</td>
<td>0.053</td>
<td>0.513</td>
</tr>
</tbody>
</table>

#### d) 90 degrees around the turn

<table>
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<tr>
<th>Re</th>
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<th>700,000</th>
<th>800,000</th>
<th>850,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Um</td>
<td>8.126m/s</td>
<td>9.482m/s</td>
<td>10.84m/s</td>
<td>11.51m/s</td>
</tr>
<tr>
<td>y</td>
<td>U</td>
<td>U'</td>
<td>U</td>
<td>U'</td>
</tr>
<tr>
<td>H</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
</tr>
<tr>
<td></td>
<td>0.052</td>
<td>1.77</td>
<td>0.0485</td>
<td>1.70</td>
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<td></td>
<td>0.010</td>
<td>1.81</td>
<td>0.0381</td>
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<td>0.0443</td>
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</tr>
<tr>
<td></td>
<td>0.0388</td>
<td>1.79</td>
<td>0.0501</td>
<td>1.78</td>
</tr>
<tr>
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<td>0.0983</td>
<td>1.647</td>
<td>0.0444</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td>0.238</td>
<td>1.33</td>
<td>0.0217</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td>0.509</td>
<td>0.908</td>
<td>0.0199</td>
<td>0.921</td>
</tr>
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<td>0.776</td>
<td>0.645</td>
<td>0.0748</td>
<td>0.654</td>
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<td>0.880</td>
<td>0.762</td>
<td>0.0585</td>
<td>0.666</td>
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<td>0.931</td>
<td>0.581</td>
<td>0.0767</td>
<td>0.580</td>
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</table>

#### e) Exit of the turn

<table>
<thead>
<tr>
<th>Re</th>
<th>700,000</th>
<th>800,000</th>
<th>900,000</th>
<th>1,000,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Um</td>
<td>9.094m/s</td>
<td>10.39m/s</td>
<td>11.69m/s</td>
<td>12.99m/s</td>
</tr>
<tr>
<td>y</td>
<td>U</td>
<td>U'</td>
<td>U</td>
<td>U'</td>
</tr>
<tr>
<td>H</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
</tr>
<tr>
<td></td>
<td>0.153</td>
<td>1.06</td>
<td>0.0958</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>0.204</td>
<td>1.24</td>
<td>0.0700</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>0.332</td>
<td>1.24</td>
<td>0.0382</td>
<td>1.21</td>
</tr>
<tr>
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<td>0.749</td>
<td>1.05</td>
<td>0.0636</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>0.902</td>
<td>1.01</td>
<td>0.0616</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
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<td>1.01</td>
<td>0.0612</td>
<td>0.995</td>
</tr>
<tr>
<td></td>
<td>0.966</td>
<td>0.992</td>
<td>0.0636</td>
<td>0.997</td>
</tr>
</tbody>
</table>

#### f) +3.06m downstream of the turn

<table>
<thead>
<tr>
<th>Re</th>
<th>700,000</th>
<th>800,000</th>
<th>900,000</th>
<th>950,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Um</td>
<td>9.092m/s</td>
<td>10.39m/s</td>
<td>11.69m/s</td>
<td>12.34m/s</td>
</tr>
<tr>
<td>y</td>
<td>U</td>
<td>U'</td>
<td>U</td>
<td>U'</td>
</tr>
<tr>
<td>H</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
<td>Um</td>
</tr>
<tr>
<td></td>
<td>0.110</td>
<td>0.530</td>
<td>0.167</td>
<td>0.506</td>
</tr>
<tr>
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<td>0.0255</td>
<td>0.600</td>
<td>0.257</td>
<td>0.560</td>
</tr>
<tr>
<td></td>
<td>0.102</td>
<td>0.682</td>
<td>0.167</td>
<td>0.564</td>
</tr>
<tr>
<td></td>
<td>0.204</td>
<td>0.810</td>
<td>0.200</td>
<td>0.760</td>
</tr>
<tr>
<td></td>
<td>0.253</td>
<td>0.852</td>
<td>0.200</td>
<td>0.818</td>
</tr>
<tr>
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<td>0.383</td>
<td>0.955</td>
<td>0.200</td>
<td>0.946</td>
</tr>
<tr>
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<td>1.07</td>
<td>0.184</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>0.739</td>
<td>1.20</td>
<td>0.128</td>
<td>1.19</td>
</tr>
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<td>0.961</td>
<td>1.22</td>
<td>0.128</td>
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</tr>
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<td>0.987</td>
<td>1.20</td>
<td>0.128</td>
<td>1.19</td>
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</table>
TABLE IV. VELOCITY MEASUREMENTS IN THE SEPARATION BUBBLE

<table>
<thead>
<tr>
<th>a) 170 degrees around the turn</th>
<th>c) 5.08 cm downstream of the turn</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T = 8.4^\circ C )</td>
<td>( T = 8.7^\circ C )</td>
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<td>U</td>
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<td>Um</td>
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### TABLE VII. EVALUATION OF THE LATERAL TURBULENT VELOCITY

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#### b) 90 degrees around the turn

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#### c) 130 degrees around the turn

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#### 130 degrees with film probe

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Figure 2. Static pressure distribution around the turn.
Figure 3. Mean velocity distributions.
Figure 3. (Cont.) Mean velocity distributions.

c) 90 degrees Around the Turn

Re

- 600,000
- 700,000
- 800,000
- 850,000

Re=500,000 (Previous Study)
d) Exit of the Turn

Figure 3. (Cont.) Mean velocity distributions.
Figure 3. (Concluded) Mean velocity distributions.
Figure 4. Measurements in the separation bubble region.
Figure 5. Comparison of the velocity distributions at the turn exit with measurements of Monson, et al (1989).
Figure 6. Skin friction coefficient variation with Reynolds number on the outer wall.
Figure 7. Tangential turbulent velocity distributions.
Figure 7. (Cont.) Tangential turbulent velocity distributions.
Figure 7. (Concluded) Tangential turbulent velocity distributions.

e) 3.05 H Downstream of the Turn
Figure 8. Summary of Turbulent Velocity Fluctuations in the Outer Part of the Turn.