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Prof. Alexander J. Smits

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Mechanical & Aerospace Engr.
Olden Street
Princeton, NJ 08544

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14. ABSTRACT
The objectives of the grant were to provide a systematic study to fill the gap between existing research on low Reynolds number turbulent flows to the kinds of turbulent flows encountered on full-scale vehicles. We report specifically on (1) the behavior of wakes at high Reynolds numbers with increasing complexity, varying from axisymmetric wakes, to wakes typical of appended undersea platforms; and (2) the effects of roughness at high Reynolds numbers. We have gained a better understanding of complex flow interactions in wakes typical of naval platform flow fields, especially wakes with concentrated regions of streamwise vorticity. We have also made progress in the understanding of high Reynolds number flows over rough surfaces, especially pipes and flat plates with roughness that relate to marine surfaces. We expect these studies to lead to improved flow prediction and improved flow control. The work was performed in two unique facilities: the Superpipe and the High Reynolds number Test Facility (HRTF) that can obtain very high Reynolds numbers on a laboratory scale using compressed air as the working fluid.

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Reynolds number, turbulent flows, wake behavior

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Principal Investigator	Alexander J. Smits
Organization	Princeton University
Program Officer	Ron Joslin

Name: Alexander J. Smits
Organization: THE TRUSTEES OF PRINCETON UNIVERSITY
City/State/Country: Princeton/NJ/USA
Title: Professor
Zip Code: 08544
Phone: (609) 258-5117
Fax: (609) 258-6123
Email: asmits@princeton.edu
Website: http://gasdyn.princeton.edu/

Technical Section

Technical Objectives

The objectives of the grant were to provide a systematic study to fill the gap between existing research on low Reynolds number turbulent flows to the kinds of turbulent flows encountered on full-scale vehicles. We report specifically on (1) the behavior of wakes at high Reynolds numbers with increasing complexity, varying from axisymmetric wakes, to wakes typical of appended undersea platforms; and (2) the effects of roughness at high Reynolds numbers. We have gained a better understanding of complex flow interactions in wakes typical of naval platform flow fields, especially wakes with concentrated regions of streamwise vorticity. We have also made progress in the understanding of high Reynolds number flows over rough surfaces, especially pipes and flat plates with roughness that relate to marine surfaces. We expect these studies to lead to improved flow prediction and improved flow control. The work was performed in two unique facilities: the Superpipe and the High Reynolds number Test Facility (HRTF) that can obtain very high Reynolds numbers on a laboratory scale using compressed air as the working fluid.

Technical Approach

Our studies are performed in two facilities constructed at Princeton under ONR funding. The Superpipe facility enables very accurate measurements in fully developed turbulent pipe flow across a wide range of Reynolds numbers, from 31×10^3 to 35×10^6. High Reynolds numbers are achieved at a moderate cost by using compressed air at ambient temperatures as the working fluid, thereby decreasing the kinematic viscosity by over two orders of magnitude as compared to air at STP. The maximum static pressure is

200 atm. The test pipe has a nominal diameter of 129 mm, and a length of 202 D. A diagram of the facility is shown in Figure 1.

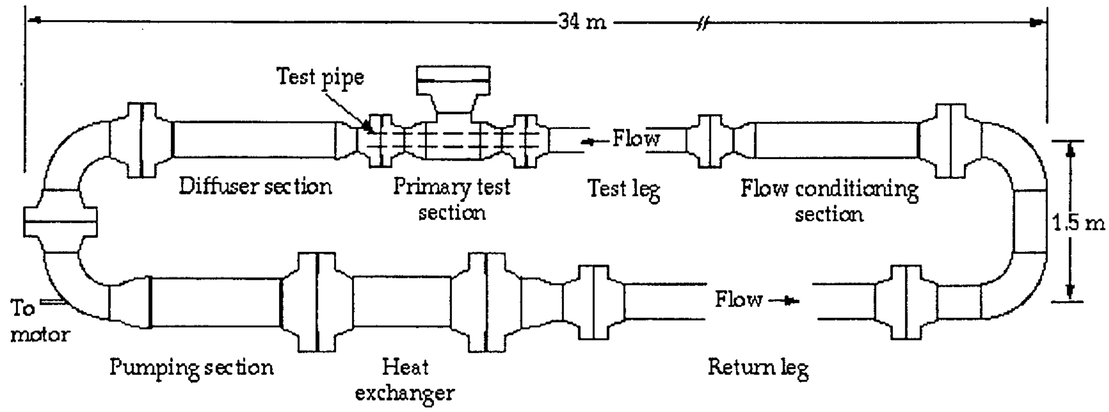

Figure 1: Princeton/DARPA/ONR Superpipe apparatus.

A wind tunnel to achieve high Reynolds numbers called the Princeton/ONR High Reynolds Number Testing Facility (HRTF) is also used to attain high Reynolds number. Like the Superpipe, it uses air at pressures up to 3,000psi as the working fluid (Figure 2). The primary purpose of the facility is to study the hydrodynamic forces, moments and flow-fields produced by advanced naval platforms up to length Reynolds numbers of 150 x 10^6. There are two working sections: each is 8ft long with an internal diameter of 18in. The facility will be equipped with a Magnetic Suspension Balance System (MSBS) to allow measurements free of the interference produced by the support systems usually employed in these applications. The MSBS is being designed, constructed and tested under the supervision of Colin Britcher of ODU.

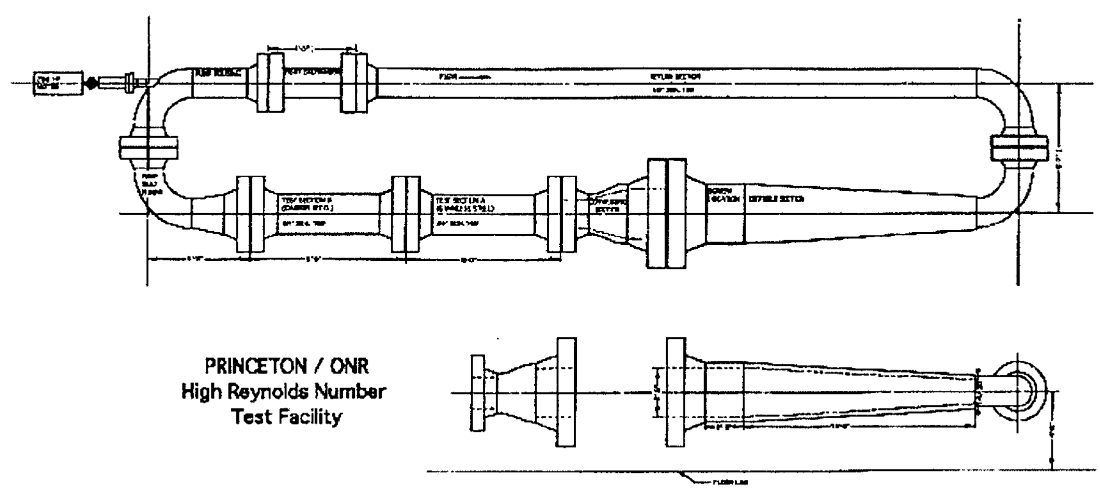

Figure 2: Princeton/ONR High Reynolds number Test Facility.

Progress

1. Honed rough pipe flow mean flow experiments

Mean flow measurements are reported by Shockling et al. (2006) and Allen et al. (2006). These experiments have shown that honed roughness has an inflectional transitional roughness behavior, similar to sand-grain roughness, and unlike the monotonic behavior expected according to Colebrook's transitional roughness function, on which the Moody Diagram is based (see Figure 3). In combination with the work of Schultz and Flack at the Naval Academy, we tentatively propose that inflectional roughness is much more common than previously known, and may well form the correct model for ship roughness. Measurements of the honed surface roughness function show that roughness begins to have an effect on the velocity profile when the equivalent sandgrain roughness exceeds about 3.5 (Figure 4). Outer flow similarity as proposed by Townsend was confirmed at all Reynolds numbers (Figure 5).

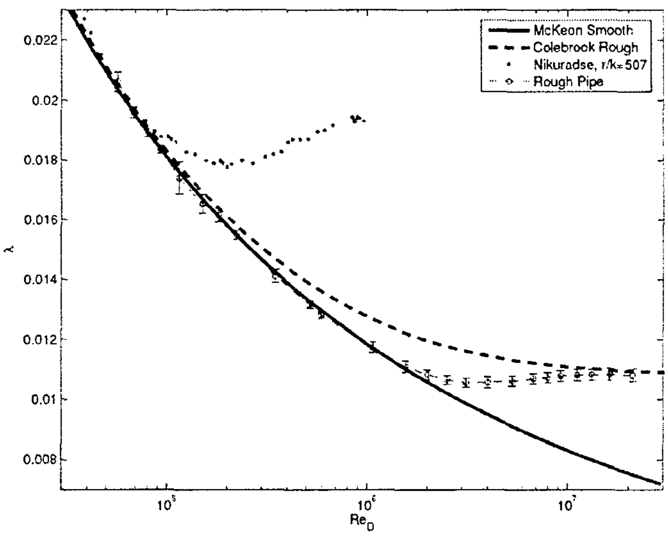

Figure 3: Friction factor for the present surface, compared with the rough-wall relations of Colebrook (1939) for the same equivalent sandgrain roughness, the smooth-wall relation of McKeon et al. (2005), and the results for the smallest sandgrain roughness used by Nikuradse (1933).

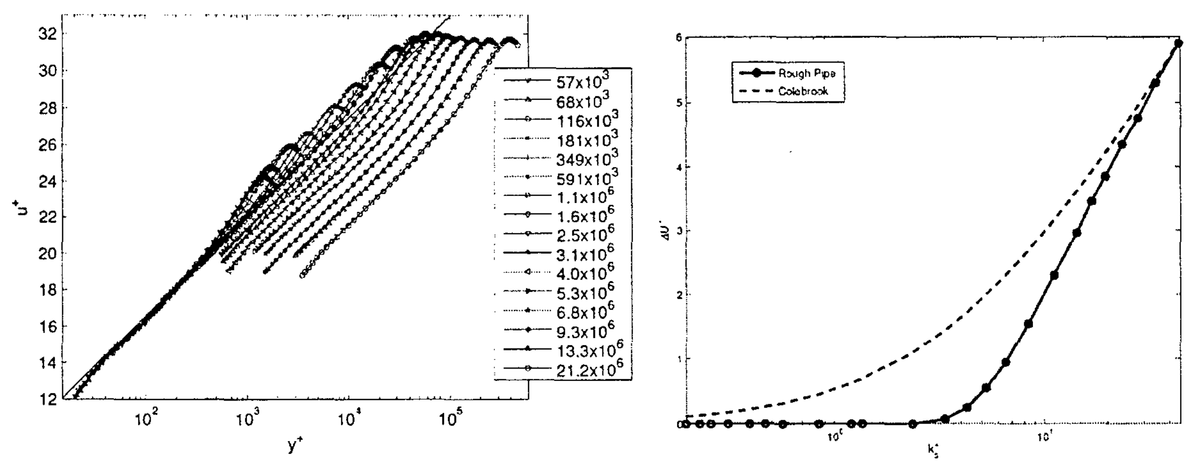

Figure 4: Left: Velocity profiles over the full Reynolds number range. Right: ------, Hama roughness function. - - - -, Colebrook roughness function with $k_s = 7.4 \times 10^{-6}$ m.

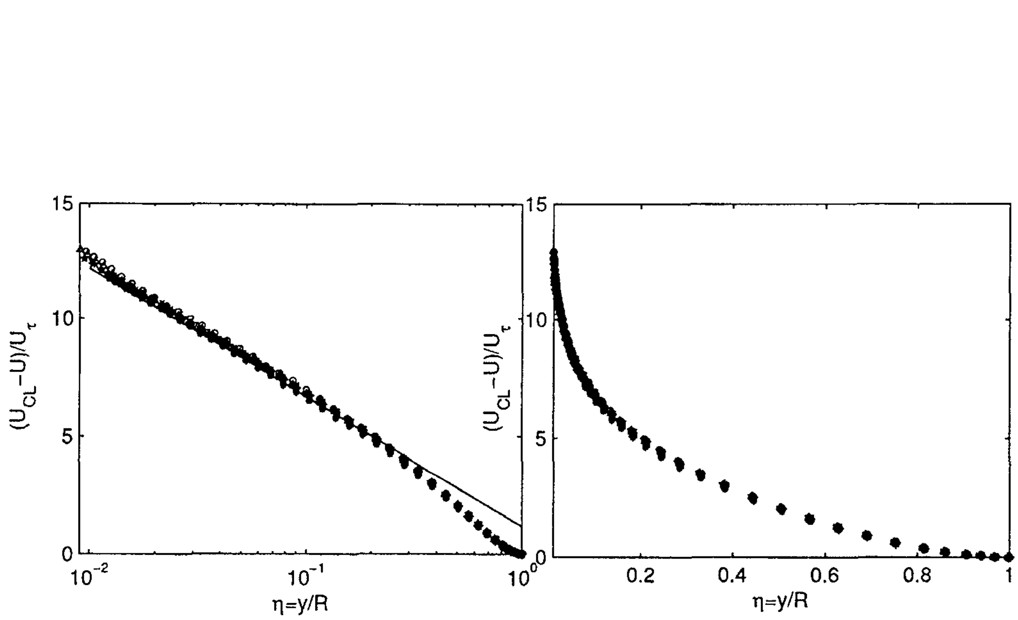

Figure 5: Outer scaling for 349 x 10^3 </= Re_D </= 21.2 x 10^6. Solid line: log law in outer layer variables.

2. Honed rough pipe flow turbulence experiments

The hot-wire measurements of the streamwise component of turbulence have been completed and are in press (Kunkel et al. 2007). Streamwise turbulence intensities, higher order moments, and spectra were compared with the corresponding results from a previous smooth wall pipe flow study in the same facility (Figures 6, 7 and 8). The hydrodynamically transitionally rough-wall turbulence intensities and higher-order moments agreed well with the smooth-wall results indicating that the roughness does not affect the time averaged statistics in the outer-region of the flow. The rough-wall one-dimensional streamwise spectra in the logarithmic region are also found to agree with the smooth-wall results indicating that the roughness does not affect the distribution of energy in the flow and implies that the it does not change the structure of the flow.

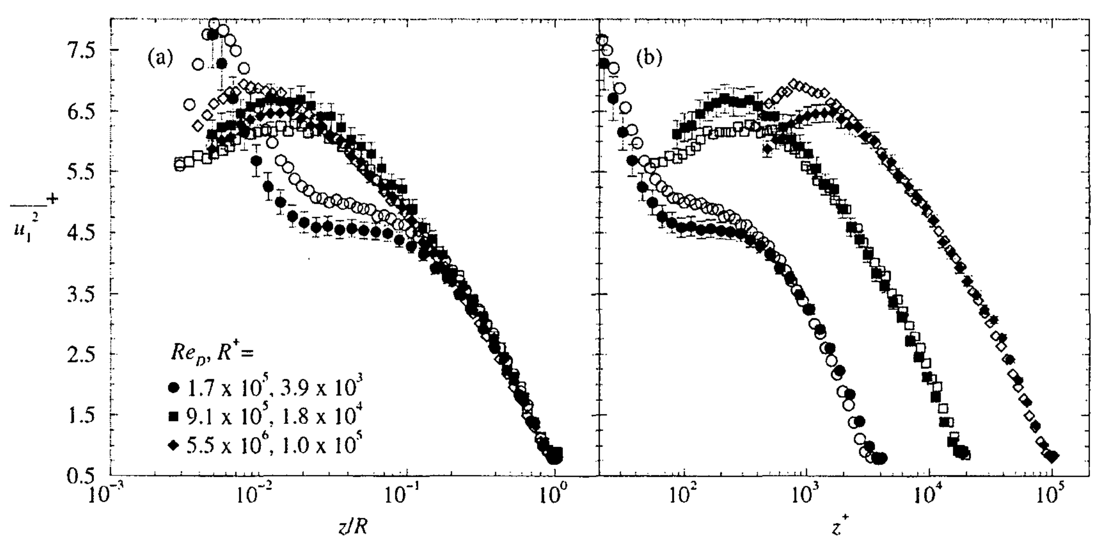

Figure 6: Streamwise turbulence intensities. Solid symbols are rough pipe data and hollow symbols are smooth pipe data reproduced from Morrison et al. (2004). (a) Outer layer scaling; (b) Inner layer scaling.

Overall these data support Townsend's Reynolds number similarity hypothesis in that the energycontaining motions are independent of roughness aside from the increased wall shear stress. The current measurements, while unique and insightful, are complicated by probe resolution problems at low wall-normal positions and high wave numbers. Future work will attempted to resolve these issues (see Kunkel et al. 2007) as well as measure the wall-normal velocity component of the flow. While other authors have found slight differences in the streamwise turbulence statistics, the wall-normal statistics were shown to be the most sensitive to wall roughness.

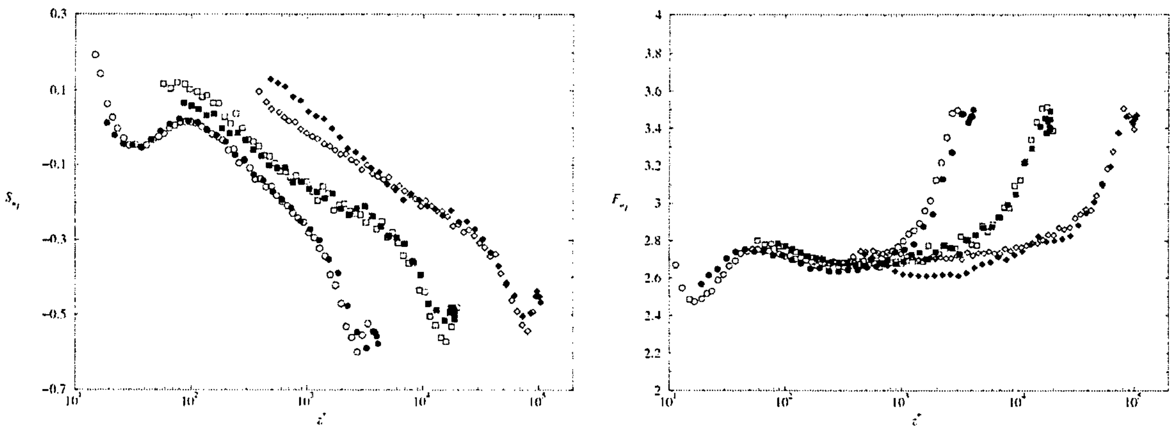

Figure 7: Smooth- and rough-wall pipe (a) skewness, (b) flatness. Symbols as in Figure 6.

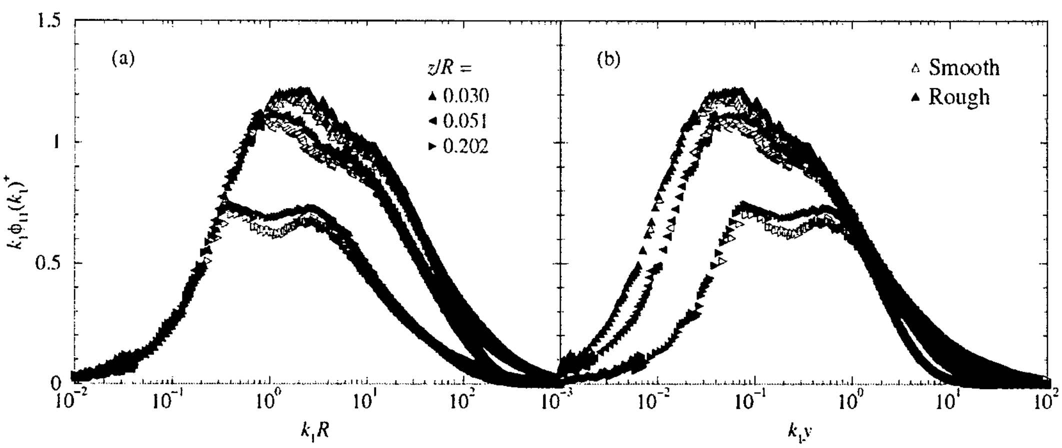

Figure 8: Rough and smooth pipe streamwise velocity spectra at Re_D, $R^+ = 5.5 \times 10^6$, 1.0×10^5. Solid symbols are rough pipe data and hollow symbols are smooth pipe data reproduced from Morrison et al. (2004). (a) Outer layer scaling; (b) Inner layer scaling.

3. Commercial steel rough pipe flow experiments

The honed pipe described above was replaced with a commercial, extruded steel pipe. The surface roughness was as delivered by the supplier, with $k_{rms} = 5$ μm. Results on friction factor and velocity profiles are shown in Figures 9 to 11. These are the first results ever obtained in commercial steel pipe under laboratory conditions. They show that commercial steel pipe has a friction factor behavior that lies between the Colebrook type roughness, and sand-grain type roughness, in that the departure from the smooth pipe is rather sudden, with little or no evidence for the "inflectional" behavior characteristic of sand-grain roughness (and honed surface roughness). In addition, the equivalent sand-grain roughness of commercial steel pipe is closer to $2.0k_{rms}$, rather than the commonly accepted value of $3.0k_{rms}$. The velocity profiles in the rough regime show the expected departure below the logarithmic law, and they also follow Townsend's outer-layer similarity (as did the honed pipe). The work has been submitted for publication (Langelandsvik et al. 2007)).

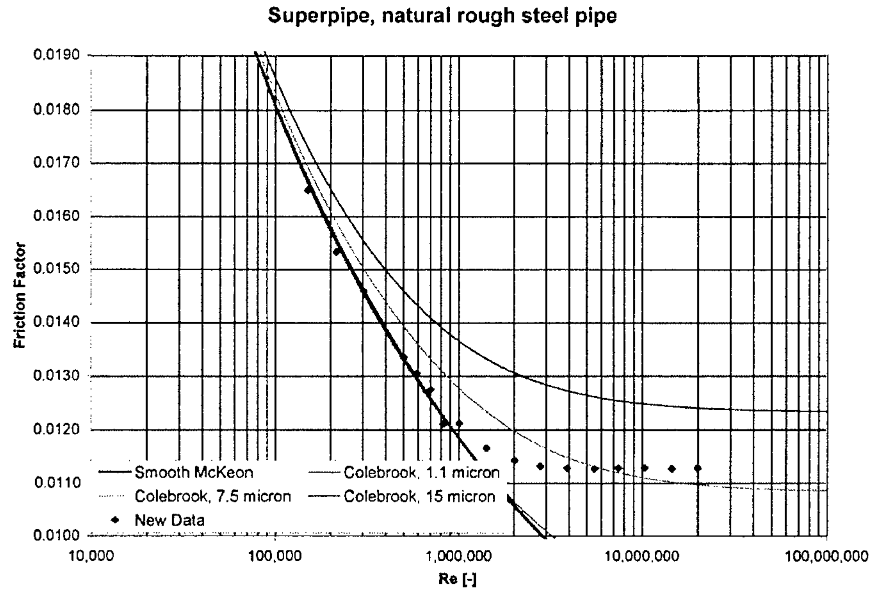

Figure 9: Friction factor for the commercial steel pipe surface, compared with the rough-wall relations of Colebrook (1939) for the same equivalent sand-grain roughness, and the smooth-wall relation of McKeon et al. (2005).

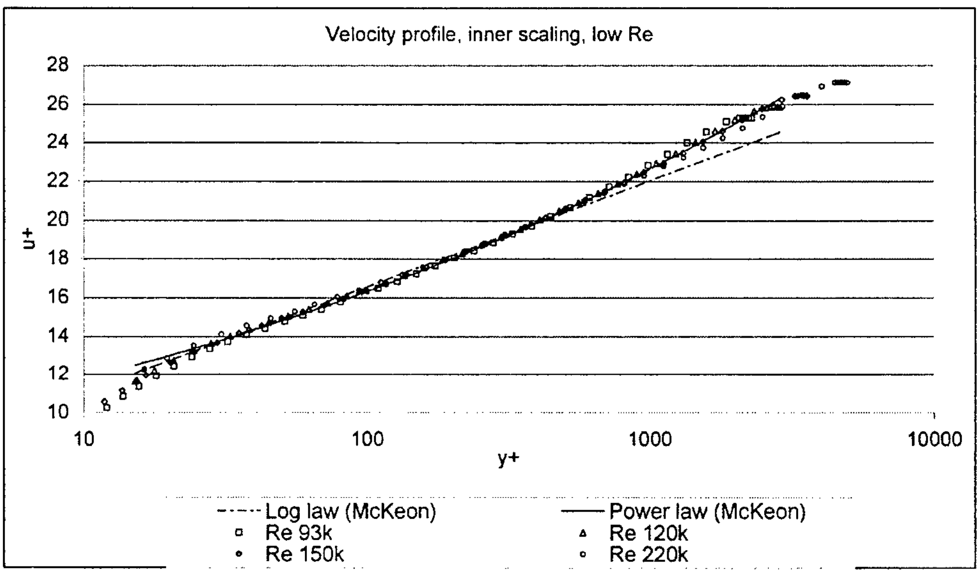

Figure 10: Velocity profiles in commercial steel pipe for Reynolds numbers up to 220 x 10^{-3}.

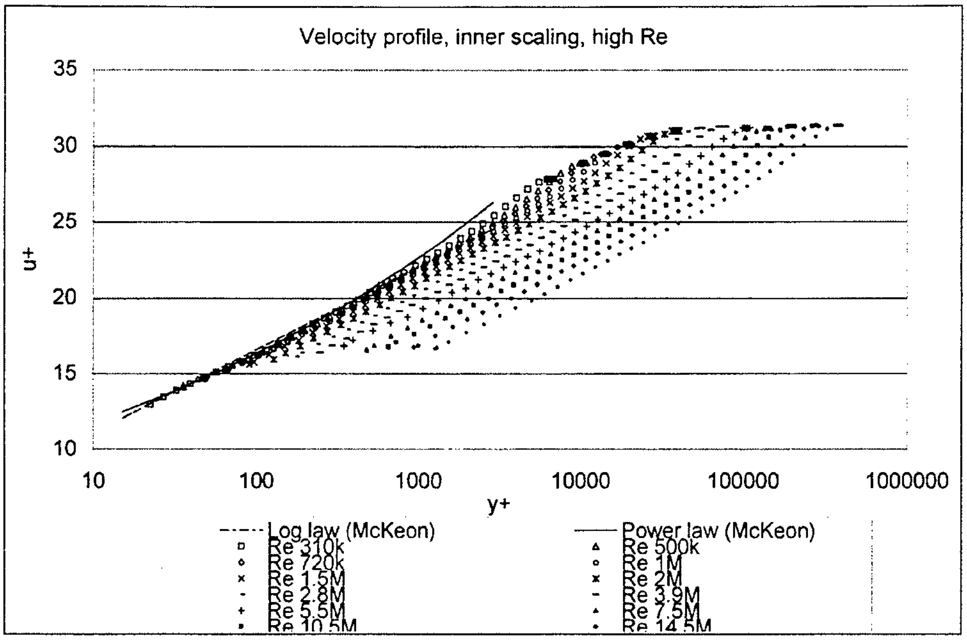

Figure 11: Velocity profiles in commercial steel pipe for Reynolds numbers up to 3 x 10^{-6}.

4. Boundary layer experiments

Additional tests have been performed on a flat plate boundary layer to establish the use of tunnel inserts to produce a zero pressure gradient environment (Figures 12 and 13). These experiments are preparatory to the HRTF experiments on the same plate. The mean velocity (Figure 13), turbulence intensity (Figure 14), and spectra (Figure 15) all demonstrate that the experimental arrangements used in the HRTF to study flat plate boundary layers are valid to an extraordinary degree.

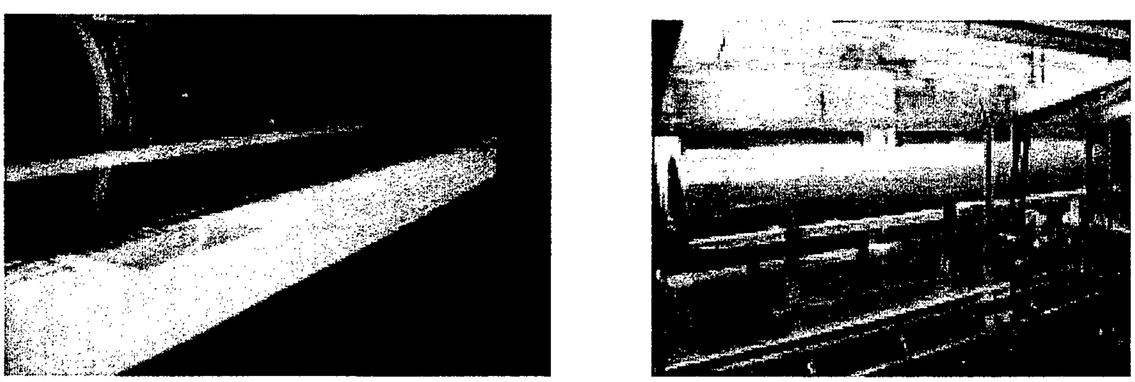

Figure 12: Boundary layer experiment on the flat plate. "Without lid" means in the empty tunnel (left). "With lid" means results on the flat plate with a semi-circular cover that includes an insert to produce a zero pressure gradient (right).

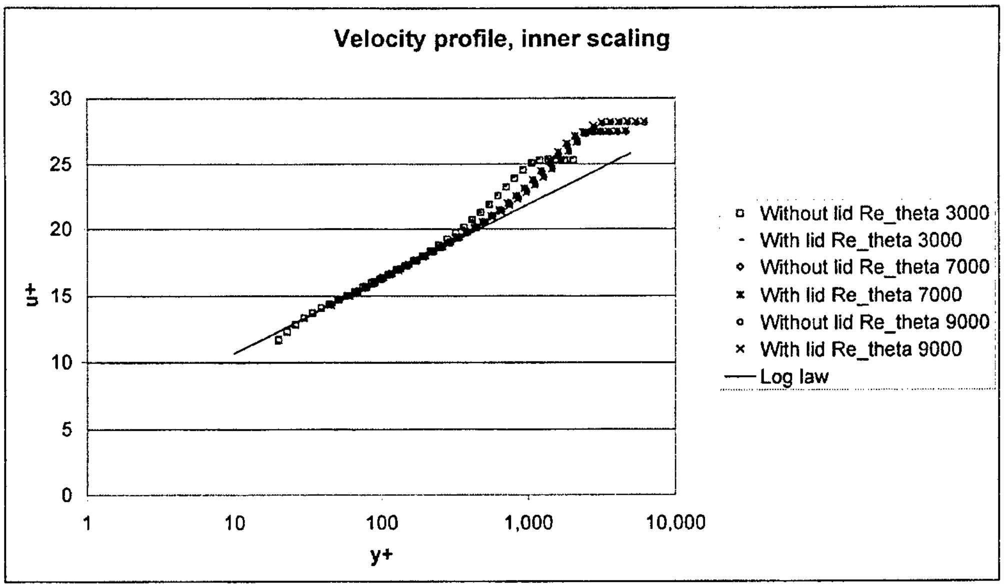

Figure 13: Boundary layer results on the flat plate. "Without lid" means in the empty tunnel. "With lid" means results on the flat plate with a semi-circular cover that includes an insert to produce a zero pressure gradient.

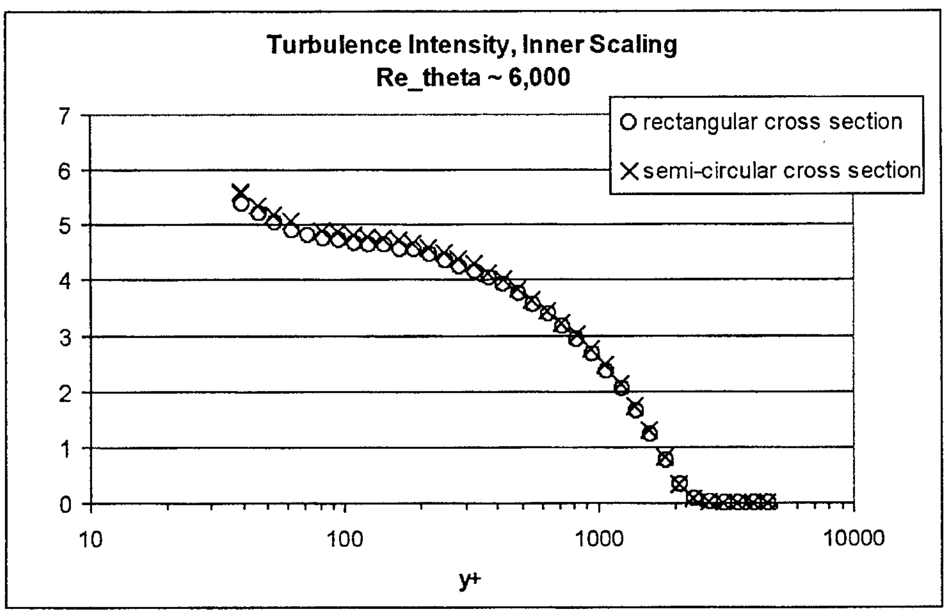

Figure 14: Turbulence intensity in boundary layer on the flat plate. "Rectangular cross-section" means in the empty tunnel. "Semi-circular cross-section" means results on the flat plate with a semi-circular cover that includes an insert to produce a zero pressure gradient.

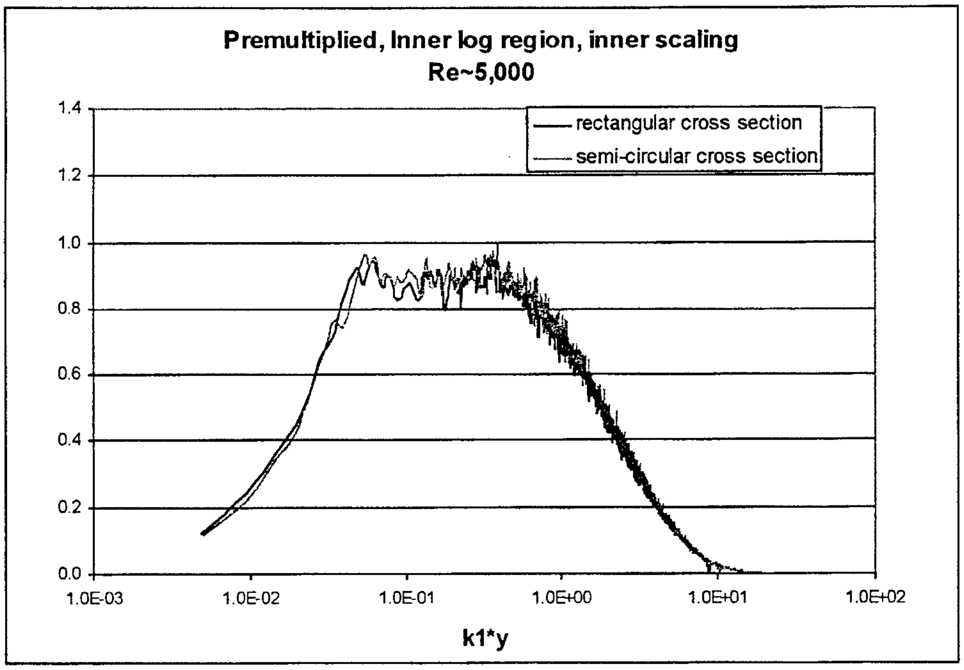

Figure 15: Spectra in turbulent boundary layer on the flat plate. "Rectangular cross-section" means in the empty tunnel. "Semi-circular cross-section" means results on the flat plate with a semi-circular cover that includes an insert to produce a zero pressure gradient.

5. SUBOFF wake experiments for the HRTF

The model has been completely pressure-tapped for static pressure measurements, and equipped with a Scanivalve system. The wake traversing system (2 degrees of translation, 2 degrees of rotation) has been completed and installed in the HRTF working section (Figures 16, 17 and 18). Additional screen and mesh have been installed to improve flow quality and reduce freestream turbulence level), as well as the model yaw motion system.

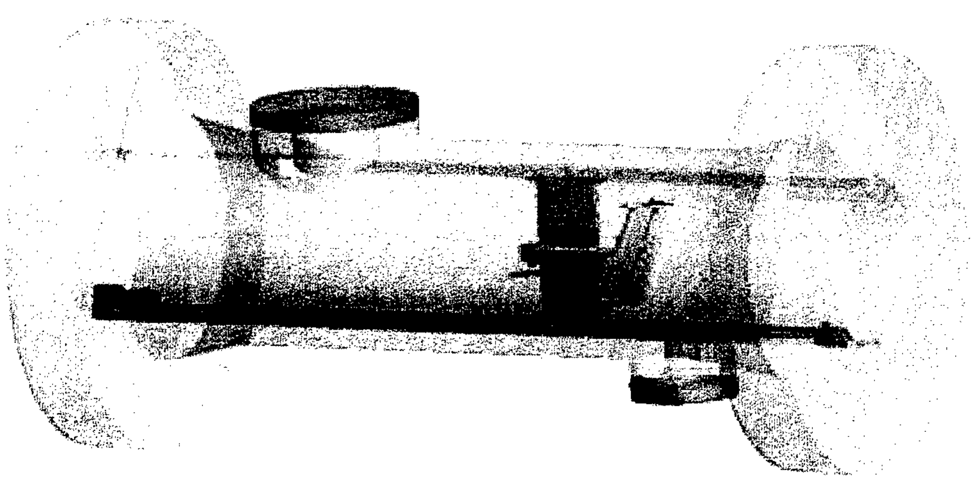

Figure 16: Traversing system as installed in the HRTF downstream of SUBOFF model.

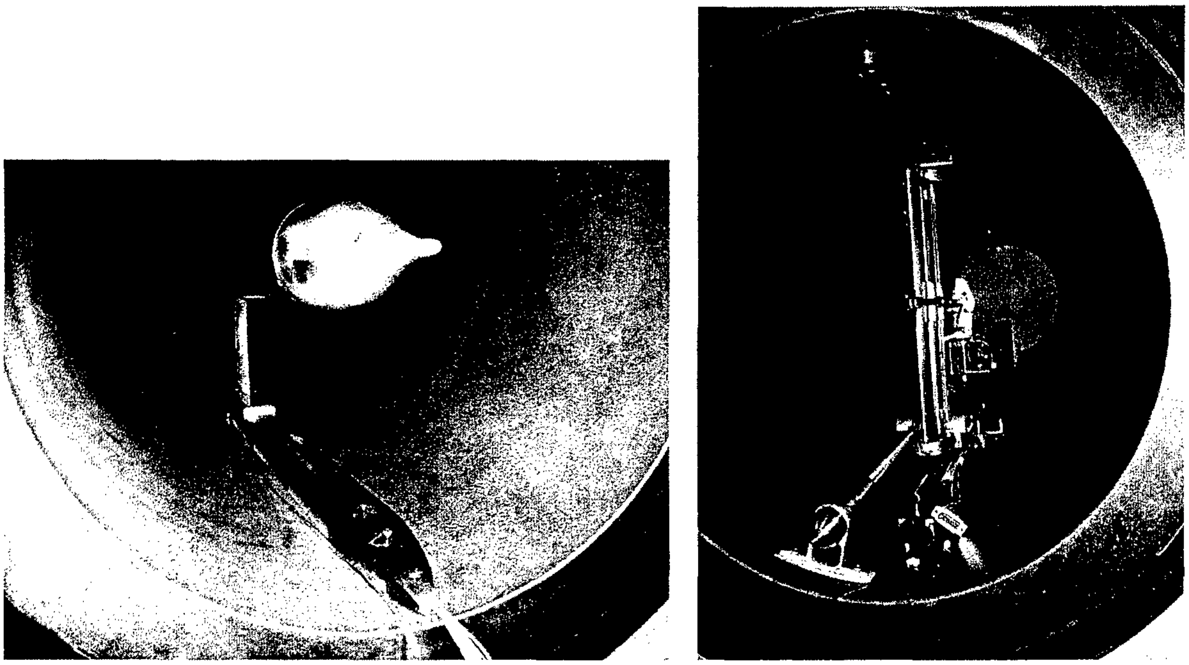

Figure 17: SUBOFF model (left) and traversing system (right) as installed in the HRTF.

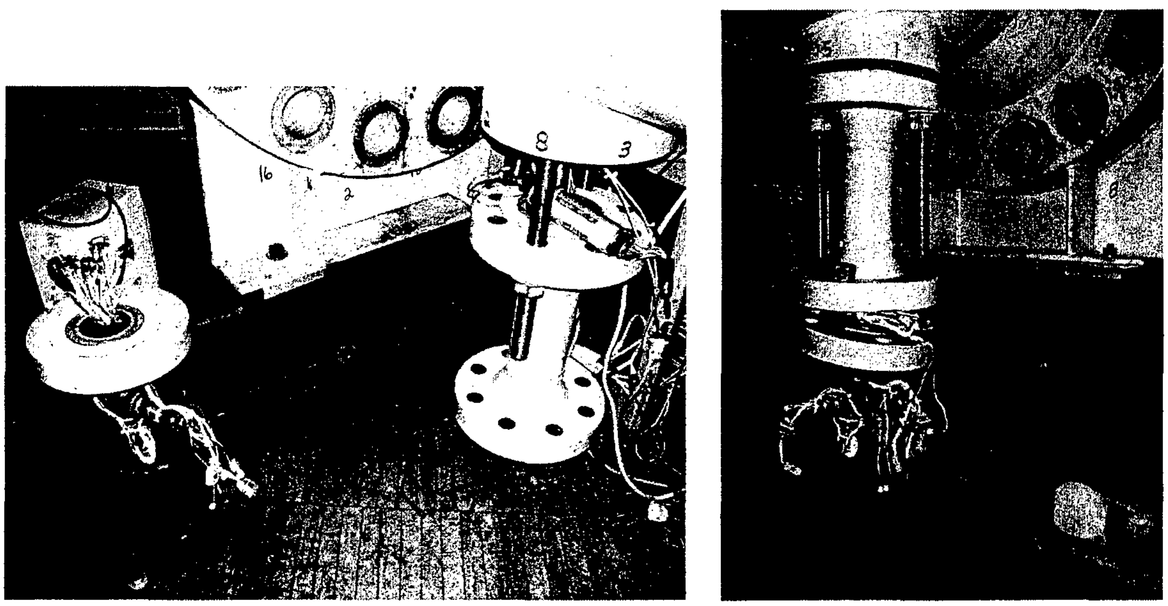

Figure 18: HRTF control, power, and pressure transducer port. Left: disassembled. Right: assembled.

Measurements were made in the wake of a DARPA SUBOFF model over a large range of Reynolds numbers based on model length, from 1.1 x 10^6 to 25 x 10^6, on the centerline of the wake for locations 3, 6, 9, 12, and 15 diameters downstream from the tail. The model was axisymmetric without appendages (fins) and it was supported by a streamlined support. That is a semi-infinite extension of the sail. The wake experimental results, obtained using Particle Image Velocimetry (PIV) and crossed hot-wires, provided qualitative and quantitative insight into the flow field created by an undersea platform. In addition, the pressure was measured at 45 different locations along the model for three different Reynolds numbers, 1.1×10^6, 12×10^6 and 25×10^6. Also, PIV measurements were conducted in the wake of the sail attached to a DARPA SUBOFF model at 9.36×10^5. Four different yaw angles, between 6 and 17 degrees were investigated yielding insights into the behavior of the junction/hull and sail tip vortices.

Mean flow and turbulence data obtained using crossed-wire anemometry for $Re = 25 \times 10^6$ are shown in figures 19, 20 and 21. For all Reynolds numbers studied, the mean velocity distribution attains self-similarity at distances between 3 and 6 diameters downstream for the side where the support is not located, and follows an exponential function as expected from similarity arguments. In contrast, the mean velocity distribution for the support side does not attain self-similarity, and displays significant effects of the support wake and support/body junction flows. In addition, none of the Reynolds stress distributions of the flow attain self similarity. For the higher Reynolds numbers studied the presence of the support introduces an asymmetry into the wake that results in the overall decrease of radial and axial turbulence intensities for the support side. Also for the higher Reynolds numbers, the axial turbulence intensity distribution is relatively symmetric while maintaining a maximum on the side without the support. The opposite is observed for $Re = 1.1 \times 10^6$. Furthermore, the values of the turbulent shear intensity, u'v', at $Re = 1.1 \times 10^6$ are higher on the support side, $r/D < 0$, for each x/D location measured. This trend is reversed for the two higher Reynolds number cases with the only exception of $x/D = 3$. Also, the coefficient of pressure distribution along the top meridian line of the model, $r/D > 0$, is generally lower for $Re = 1.1 \times 10^6$ than that for $Re = 12 \times 10^6$ and 25×10^6, which seem to have collapsed. The sail wake experiments demonstrated the significance of the sail tip vortex when the model is at a nonzero yaw angle. As the yaw angle is increased from 6 to 12 degrees the circulation of the sail tip vortex increases. As the yaw angle is further increased the boundary layer separates with an overall drop in circulation. A similar phenomenon is observed for the junction vortex with the exception that when the yaw angle is further increased to 17 degrees the circulation continues to increase at a slower rate. Also, the circulation values for the sail tip vortex are about an order of magnitude larger than those of the junction vortex.

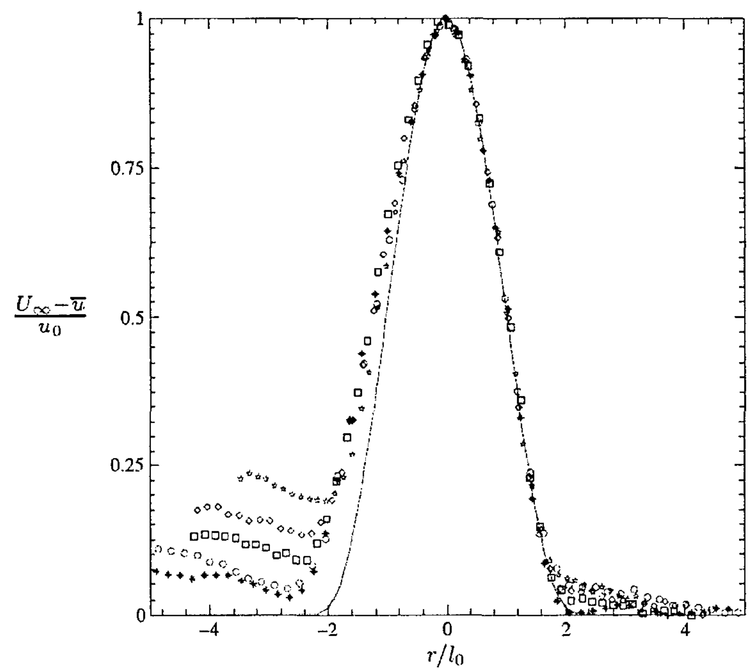

Figure 19: Mean flow results in similarity coordinates for $Re = 25 \times 10^6$.

The effects of the support on the wake development are similar to the effects introduced by the sail on a model wake (except for the absence of the tip flow). The presence of the support affects the flow differently for different Reynolds numbers emphasizing the importance of high Reynolds number studies to better understand naval platform flows.

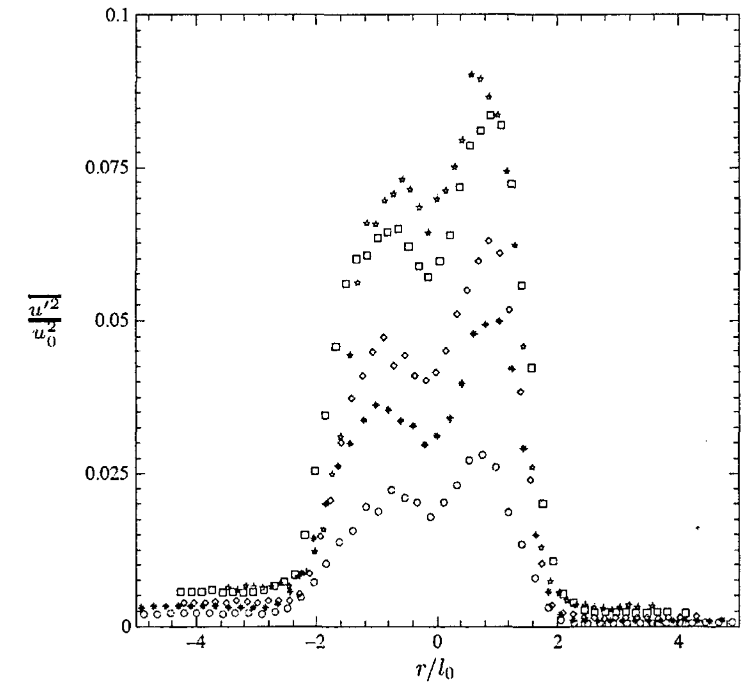

Figure 20: Streamwise turbulence results in similarity coordinates for Re = 25 x 10^6.

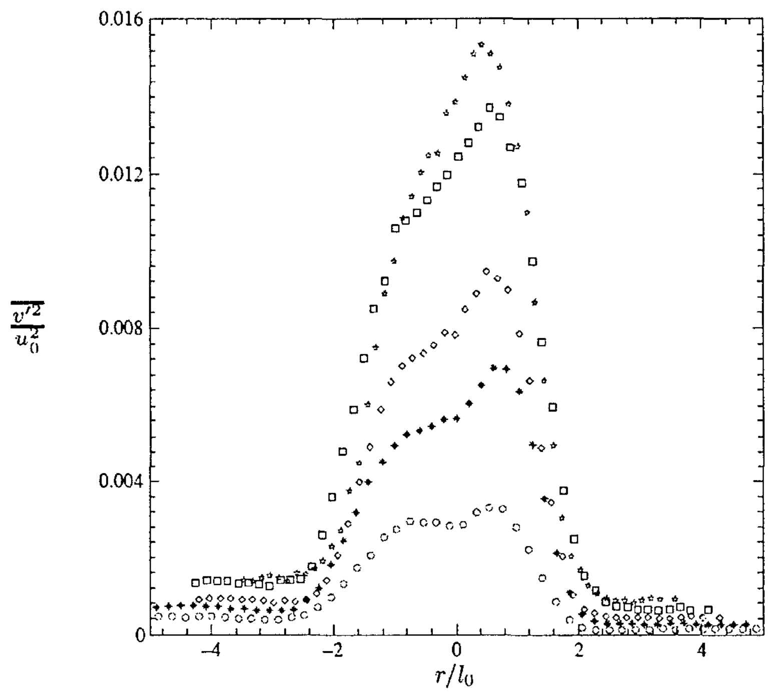

Figure 21: Streamwise turbulence results in similarity coordinates for Re = 25 x 10^6.

6. Magnetic Suspension Balance System (MSBS)

Work by Colin Britcher at ODU: 2 degree-of-freedom levitation has been achieved inside the test section; 5 degree-of-freedom levitation inside is imminent (Figure 22). Colin Britcher will report this progress separately.

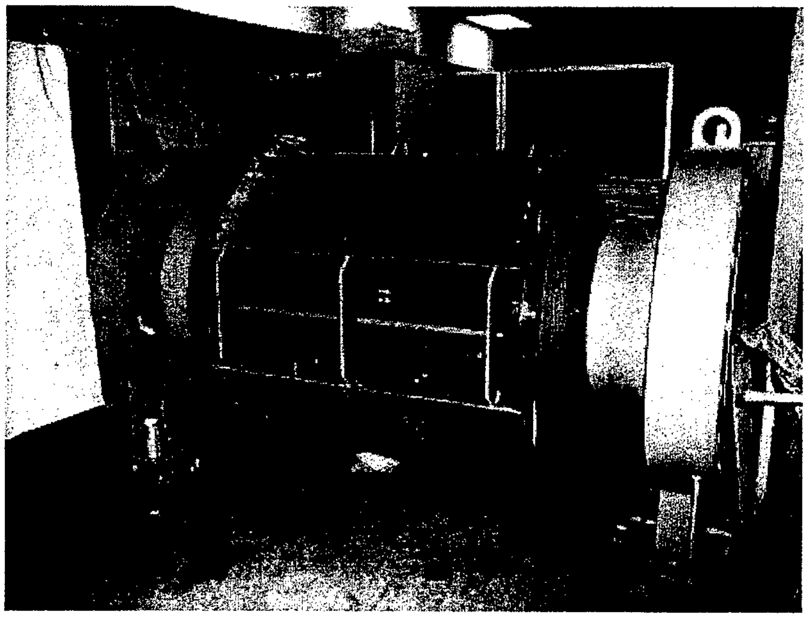

Figure 22: MSBS system as currently configures (presently located at NASA LaRC).

Technology Transfer

The Norwegian company Gassco has supported a graduate student (Leif Langelandsvik) for 6 months on studies of roughness in the Princeton Superpipe apparatus, in partial support of the ONR program. Gassco is continuing discussions on future collaborations.

References

Allen, J. J., Shockling, M. A. and Smits, A. J., "Evaluation of a universal transitional resistance diagram for pipes with honed surfaces." Physics of Fluids, Vol. 17, 121702, 2005.

Colebrook, C. F. "Turbulent flow in pipes, with particular reference to the transitional region between smooth and rough wall laws." J. Inst. Civ. Eng.} 11, 133-156, 1939.

Kunkel, G. J., Allen, J. J. and Smits, A. J. "Further support for Townsend's Reynolds number similarity hypothesis in high Reynolds number rough pipe flow." To appear Physics of Fluids.

Langelandsvik, L. I., Kunkel, G. J. and Smits, A. J., "Flow in a commercial steel pipe," Submitted Journal of Fluid Mechanics.

McKeon, B. J., Zagarola, M. V. and Smits, A. J., "A new friction factor relationship for turbulent pipe flow," Journal of Fluid Mechanics, Vol. 538, pp. 429-443, 2005.

Morrison, J. F., McKeon, B. J., Jiang, W. and Smits, A. J., "Scaling of the streamwise velocity components in turbulent pipe flow." Journal of Fluid Mechanics, Vol. 508, pp. 99-131, 2004.

Shockling, M. A., Allen, J. J. and Smits, A. J., "Effects of machined surface roughness on high-Reynolds-number turbulent pipe flow." Journal of Fluid Mechanics, Vol. 564, pp. 267-285, 2006.

Nikuradse, J. "Laws of flow in rough pipes. VDI Forschungsheft, 361, 1933. In translation, NACA TM 1292, 1950.

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Experimental methods for Pitot and hot-wire measurements

McKeon, B. J., Li, J. D., Jiang, W., Morrison, J. F. and Smits, A. J., "Pitot probe corrections in fully-developed turbulent pipe flow." Measurement Science and Technology, Vol. 14, 1449-1458, 2003.

Li, J., McKeon, B. J., Jiang, W., Morrison, J. F. and Smits, A. J., "The response of hot wires in high Reynolds-number turbulent pipe flow." Measurement Science and Technology, Vol. 15, pp. 789-798, 2004.

Zhao, R., Li, J. and Smits, A. J., "A new calibration method for crossed hot wires." Measurement Science and Technology, Vol. 15, pp. 1926-1931, 2004 .

Smits, A.J. and Zagarola, M.V., "Applications of Dense Gases to Model Testing for Aeronautical and Hydrodynamic Applications." Measurement Science and Technology, Vol. 16, pp. 1710-1715, 2005.

Zhao, R. and Smits, A. J., "Binormal cooling errors in crossed hot-wire measurements." Experiments in Fluids, Vol. 40 (2), pp. 212-217, 2006.

Mean velocity and friction factor results

B. J. McKeon, J. F. Morrison, W. Jiang, J. Li , A. J. Smits, "Revised Log-Law Constants For Fully-Developed Turbulent Pipe Flow, Reynolds Number Scaling in Turbulence, Ed. A. J. Smits, Kluwer, 2003.

McKeon, B. J., Li, J., Jiang, W., Morrison, J. F. and Smits, A. J., "Further Observations on the Mean Velocity in Fully-Developed Pipe Flow." Journal of Fluid Mechanics, Vol. 501, pp. 135-147, 2004.

McKeon, B. J., Swanson, C. J., Zagarola, M. V., Donnelly R. M. and Smits, A. J., "Friction factors for smooth pipe flow." Journal of Fluid Mechanics, Vol. 511, pp. 41-44, 2004.

McKeon, B. J., Zagarola, M. V. and Smits, A. J., "A new friction factor relationship for turbulent pipe flow," Journal of Fluid Mechanics, Vol. 538, pp. 429-443, 2005.

Allen, J. J., Shockling, M. A. and Smits, A. J., "Evaluation of a universal transitional resistance diagram for pipes with honed surfaces." Physics of Fluids, Vol. 17, 121702, 2005.

Shockling, M. A., Allen, J. J. and Smits, A. J., "Effects of machined surface roughness on high-Reynolds-number turbulent pipe flow." Journal of Fluid Mechanics, Vol. 564, pp. 267-285, 2006.

Langelandsvik, L. I., Kunkel, G. J. and Smits, A. J., "Flow in a commercial steel pipe," Submitted Journal of Fluid Mechanics.

Turbulence measurements

Zhao, R. and Smits, A.J., "Preliminary Crossed Hot-wire Measurement in High Reynolds Number Turbulent Pipe Flow," ASME International Mechanical Engineering Conference and Exposition, Washington, D.C., November 16-21, 2003.

Marusic, I, Kunkel, G. J., Zhao, R. and Smits, A. J., "Turbulence Intensity Similarity Formulations for Wall-Bounded Flows," Advances in Turbulence X, Proceedings of the Tenth European Turbulence Conference. H. I. Andersson and P.-A. Krogstad (Eds.) CIMNE, Barcelona 2004.

Morrison, J. F., McKeon, B. J., Jiang, W. and Smits, A. J., "Scaling of the streamwise velocity components in turbulent pipe flow." Journal of Fluid Mechanics, Vol. 508, pp. 99-131, 2004.

Marusic, I, Smits, A. J., Zhao, R. and Kunkel, G. J., "Turbulence Intensity Similarity Formulations for Wall-Bounded Flows," 10th EUROMECH European Turbulence Conference, H. I. Andersson and P.-A. Krogstad (Eds.) 29 June - 2 July 2004, Trondheim, Norway.

Zhao, R. and Smits, A. J., "Wall-normal turbulence statistics in high Reynolds number pipe flow," Journal of Fluid Mechanics, Vol. 576, pp. 457-473, 2007.

Allen, J., Shockling, M., Kunkel, G. J. and Smits, A. J. "Turbulent Flow in Smooth and Rough Pipes." Philosophical Transactions of the Royal Society A Mathematical, Physical and Engineering Sciences, Vol. 365 (1852) pp. 699-714, 2007.

•Pipe flow roughness

Allen, J.J., Shockling, M.A. and Smits, A.J. "Effects of a machined rough surface on high Reynolds number pipe flow," 15th Australasian Fluid Mechanics Conference, Sydney, Australia, 13-17 December 2004.

Smits A. J., Shockling, M. and Allen, J. "Turbulent Flow in Smooth and Rough Pipes," AIAA Paper 2005-4807, 35th AIAA Fluid Dynamics Conference, 6-9 June 2005, Toronto, Ontario, Canada.

Shockling, M. A., Allen, J. J. and Smits, A. J., "Effects of machined surface roughness on high-Reynolds-number turbulent pipe flow." Journal of Fluid Mechanics, Vol. 564, pp. 267-285, 2006.

Allen, J. J., Shockling, M. A. and Smits, A. J., "Evaluation of a universal transitional resistance diagram for pipes with honed surfaces." Physics of Fluids, Vol. 17, 121702, 2005.

Kunkel, G. J., Allen, J. J. and Smits, A. J. "Further support for Townsend's Reynolds number similarity hypothesis in high Reynolds number rough pipe flow." To appear Physics of Fluids.

Undersea Platform Flowfields

Jiménez, J. M. and. Smits, A. J "Wake Studies of a SUBOFF Model," Fourth International Symposium on Turbulence and Shear Flow Phenomena, Virginia, USA, June 27-29, 2005

Student Theses

Zhao, Rongrong "High Reynolds number turbulent pipe flow," PhD, Princeton 2005

Jiménez, Juan M. "High Reynolds Number Flows bout Bodies of Revolution," PhD, Princeton 2007.

Leif Langelandsvik "Optimized Pipeline Flow Modeling" Ph.D., Norwegian University of Science and Technology Trondheim, 2008.

Shockling, Michael "Turbulent flow in a rough pipe," MSE Princeton 2005

Richard L. Pepe "Turbulent Rough Pipe Flow at High Reynolds Number," MSE, Princeton 2007.

Adams,Mark "Design and implementation of one and two degree-of-freedom magnetic suspension and balance systems," MSE ODU 2005

Rosalind Echols "Turbulence measurements in a flat plate boundary layer" Senior Thesis 2005

Lily Fang, "Turbulence measurements in a rough pipe" Senior Thesis 2005

Stephen Farias "Flat plate boundary layer in a circular tunnel" Senior Thesis 2005

Technical Reports

Zhao, R. and Smits, A.J., "Preliminary Crossed Hot-wire Measurement in High Reynolds Number Turbulent Pipe Flow," ASME International Mechanical Engineering Conference and Exposition, Washington, D.C., November 16-21, 2003.

Marusic, I, Kunkel, G. J., Zhao, R. and Smits, A. J., "Turbulence Intensity Similarity Formulations for Wall-Bounded Flows," 10th EUROMECH European Turbulence Conference, 29 June - 2 July 2004, Trondheim, Norway.

Allen, J.J., Shockling, M.A. and Smits, A.J., "Effects of a machined rough surface on high Reynolds number pipe flow," 15th Australasian Fluid Mechanics Conference, Sydney, Australia, 13-17 December 2004.

Smits A. J., Shockling, M. and Allen, J. "Turbulent Flow in Smooth and Rough Pipes," AIAA Paper 2005-4807, 35th AIAA Fluid Dynamics Conference, 6-9 June 2005, Toronto, Ontario, Canada.

Jiménez, J. M. and. Smits, A. J "Wake Studies of a SUBOFF Model," Fourth International Symposium on Turbulence and Shear Flow Phenomena, Virginia, USA, June 27-29, 2005

Kunkel, G. J. and Smits, A. J., "Turbulence characteristics in high-Reynolds-number rough-wall pipe flow," AIAA Paper 2006-2884, 36th AIAA Fluid Dynamics Conference, San Francisco, CA, June 2006.