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Near-Wall, Three-Dimensional Turbulence Measurements: A Challenge for Laser Velocimetry

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Abstract

In this paper, a new laser velocimeter approach is presented, which has distinct advantages in near-wall, two- and three-dimensional turbulence measurement applications. The approach does require placing a probe into the flow; but in return, there are some important benefits, such as, the direct measurement of the crossflow velocity, w, at a grazing incidence, and the ability to size optical components for the scale of the flow rather than the size of the facility. Promising results have been obtained with this approach for a two-dimensional turbulent boundary layer.

Introduction

Computational fluid dynamics has reached a level where the solution of the Reynolds-averaged, Navier-Stokes equations for complex three-dimensional flows is practical. In many applications for which these equations are solved, of primary interest is the effect of the fluid flow on a solid body (e.g., an aircraft or aircraft component). In these cases, the modeling of the turbulent Reynolds stresses in the near-wall region becomes a critical element in achieving accurate predictions of skin friction and heat transfer. For strong inviscid/viscous interactions, the near-wall modeling can also be important in predicting the mean pressure field. Unfortunately, the understanding of how these Reynolds stresses behave in the near-wall region under complex flow conditions and how they should be modeled is poor. This lack of understanding is due in part to the paucity of accurate near-wall turbulence data. Especially, lacking are near-wall data for flows that are highly three-dimensional and/or in some stage of separation.

Laser velocimetry, as a measurement technique, offers the potential for expanding this near-wall turbulent flow data base. However, solid surfaces and the measurement of the crossflow velocity component, w, present problems for laser velocimetry. In this paper, these problems are briefly discussed. Then a new laser velocimeter approach is presented, which offers several distinct advantages over conventional laser velocimetry in near-wall, two- and three-dimensional turbulence measurement applications. Finally, some preliminary results obtained in a turbulent boundary layer with this approach are presented.

Measurement problems

The primary shortcoming of laser velocimetry in near-wall applications is its susceptibility to diffuse reflections or scattering of laser light from solid surfaces. The diffusively reflected light that reaches the photodetector (as some of it must when measurements are attempted very near a solid surface) introduces noise into the signals which can cause measurement errors. The added noise can become so large that it overwhelms the low-level signals produced by micron-sized particles immersed in the fluid. In which case, meaningful measurements become virtually impossible.

The susceptibility of the technique to these diffuse reflections cannot be completely eliminated, but it can be minimized by reducing the intensity and the amount of diffusively reflected light, and by using good spatial filtering practices in collecting the particle-scattered light. Also, gross measurement errors can be avoided by using a signal processor capable of distinguishing between low and high signal-to-noise ratio (SNR) signals.

The intensity of the surface-scattered light can be reduced by having the laser beams at a grazing incidence to the measurement surface while the amount of scattered light can be reduced substantially by using a very smooth measurement surface (i.e., one that is smooth relative to the wavelength of light).

With regard to signal analysis, digitizing the signal bursts and than performing an FFT to determine the Doppler frequency would appear to be a better approach in near-wall applications than using a burst counter which measures the time between zero crossings. Studies[1] have shown that accurate frequency measurements can be made at lower SNR conditions with the FFT approach. But, perhaps more important is the ability with this approach to apply a very conservative SNR validation criterion, thereby eliminating the possibility of erroneous output. Erroneous output cannot be avoided with burst counters if SNR conditions become too low. This characteristic makes them ill-suited for near-wall measurements where scattered light from the wall is a problem.

In conventional laser velocimetry, two problems can arise in the measurement of the cross-flow velocity component, w. First, if the velocimeter system relies on a grazing incidence of the laser beams wherein the laser beams enter the flow from the side, sufficient sensitivity to the w component can be difficult to achieve. Direct measurements of u and v can easily be made in this case, but only a partial sensitivity to w is possible because the velocity component sensed in laser velocimetry is perpendicular to the optical axis. Often, only small sensitivities to w are possible because of limited optical access. The smaller the sensitivity, of course, the greater the uncertainty in the w measurement.

A second problem can arise when the overlap region of individual sensing volumes of a multivelocity component laser velocimeter is small in comparison to the individual sensing volumes. In this case, signals from particles outside the overlap region can cause "virtual particle" and "geometric bias" errors[2] if the data reduction assumes coincident multichannel measurements from the same particle. The "virtual particle" problem usually degrades the accuracy of the turbulent Reynolds stresses involving w.[3]

Besides the above problems, there is the issue of spatial resolution. Obviously, the closer to a surface that measurements are taken, the better the spatial resolution must be in the direction normal to the surface. For diffraction-limited performance, the $1/e^2$ sensing volume diameter is given by $d = 4\lambda/(\pi\theta_B)$ where λ is the wavelength of the laser light and θ_B is the farfield beam divergence angle. Accordingly, for a wavelength of 0.5 μm a farfield divergence angle of only 1° produces a beam just 36 μm in diameter. Thus, a small, cross-sectional dimension is achievable, but good quality optics are needed to ensure diffraction-limited performance.

The length of the sensing volume is usually determined by the light collection optical arrangement. The sensing volume can be quite long if a light collection angle near 0° or 180° is used.

Finally, there can be a problem of deteriorating performance with an increase in scale. One way to achieve better resolution of the near-wall region is to generate a larger scale flow. But in laser velocimetry, near-wall measurement capabilities degrade as the size of the test facility becomes larger because of practical limitations. One practical limitation, is that the scale of the flow usually does not increase in direct proportion to the size of the facility. Another limitation, is that the optical components as they become larger, become poorer quality, and diffraction-limited performance and light collection at the same F number become very expensive and difficult to achieve.

With the above factors in mind, a new measurement approach is proposed, which has major advantages if the goal is to achieve turbulence measurements of all three velocity components; u, v, and w very close to a solid surface. That is, close in terms of the appropriate nondimensional viscous length scale for turbulent boundary layers, $y^+ = yu_\tau/\nu$. u_τ is the friction velocity ($u_\tau = \sqrt{\tau_w/\rho}$), y is the distance from the surface, and ν is the kinematic viscosity.

New Approach

The simple basic idea follows. In some cases it may be better to introduce a laser probe into the flow, losing the advantage of nonintrusiveness, but gaining

1) a direct measurement of the crossflow velocity, w, with the laser beams at a grazing incidence

2) improved placement of the transmitting and receiving lenses, i.e., close to the measurement region of interest regardless of the size of the test facility—this facilitates the generation of small sensing volumes and the collection of light over a large solid angle

3) turbulence measurements (with the possible exception of $-\overline{w'u'}$) free of "virtual particle" or "geometric bias" errors

4) improved flexibility with regard to applications in different facilities

To achieve all of these advantages, all that is needed is the introduction of a probe into the flow that will turn laser beams 90°, while it negligibly influences the flow to be measured. This could be a probe with a mirror or a small corner cube, for example, mounted at its end.

A laser velocimeter arrangement which uses this beam-turning probe is sketched in figure 1a. In this sketch, the beam-turning probe is a straight probe with a mirror mounted at its end. The beam-turning probe could extend through the opposite wind tunnel wall or could be mounted to some form of probe-drive mechanism mounted within the wind tunnel test section. With this single probe, two orthogonal velocity components could be measured, for example, using a dual-color, four-beam matrix arrangement.

Another variation is shown in figure 1b where the beam-turning probe enters the flow from the measurement surface and a fiber-optic unit with transmitting lens is used to direct the laser beam from the laser table. The use of a fiber-optic head as shown would make system alignment easier. Also, in the case of a single-velocity component system, it could be rotated to change velocity-component sensitivity.

Today, the commercially available fiber-optic laser velocimeters are too large (at least 14 mm diameter) to be placed in many flows without causing significant flow disturbances. However, because in the present approach the fiber-optic head need only be used for light sending and not receiving, it may be possible for a fiber-optic head to be made small enough (say 6 mm in diameter) so it could be placed in the flow. In such a case, one could envision an arrangement like that shown in figure 1c.

Three component measurements would require pointing the probe and laser beams in two different directions. Referring to figure 1a, with the flow coming out of the paper, the Reynolds stresses $\overline{u'^2}$, $\overline{v'^2}$, and $-\overline{u'v'}$ can be measured. Then, with the laser beams redirected so the flow is left to right, in figure 1a the Reynolds stresses $\overline{w'^2}$, $\overline{v'^2}$, and $-\overline{w'v'}$ can be measured. A third direction would be needed for the final Reynolds stress, $-\overline{w'u'}$. Fortunately, for most three-dimensional flows this is the least important of the Reynolds stresses. For thin shear layers $-\overline{u'v'}$ and $-\overline{w'v'}$ are the most important Reynolds stresses.

A dual-probe configuration as sketched in figure 2 could be used for simultaneous measurements of u, v, and w. This arrangement would allow -w'u' to be computed for each particle.

The two primary disadvantages of the approach (besides possible probe disturbances) are the requirement of 90° light scattering, for which the scattered light levels are considerably reduced compared to forward scatter, and the requirement of an optically smooth transparent measurement surface. On the positive side, the 90° scattering allows for shorter sensing volumes and perhaps better isolation of the detector from background light. And, the use of an optically smooth surface considerably reduces the amount of light that is diffusively reflected.

Preliminary results

Some preliminary data have been obtained in a two-dimensional turbulent boundary layer using the approach described. These data are considered preliminary and thus, should not be used as a standard. They are presented solely for the purpose of providing a flavor for measurement potentials. Reasons for considering these data preliminary are the following:

1) The FFT data have not yet been interrogated to remove readings that could have resulted from coherent scattering from the surface. An examination of records indicates that there are some zero velocity readings present because of surface scattering.

2) The accuracy to which the distance to the surface can be measured has yet to be determined. When measurements are needed very close to a surface this becomes a critical issue.

A single-velocity component configuration like that illustrated in figure 3 was used to obtain the boundary-layer data. A Bragg cell driven at 40 MHz was used to produce two laser beams of equal intensity but of different frequency. To achieve a final frequency offset of about 2 MHz, which was more in line with the maximum Doppler frequency shift of 1 MHz, the photodetector output was electronically mixed. The lens characteristics and some physical dimensions are indicated in figure 3. Care was taken to ensure that the focus was at the beam crossover. The theoretical $1/e^2$ spot diameter at the crossover was 64 μm. (For the present flow, this corresponded to a $d^+ = du_\tau/\nu$ of 3.2.) Observations of the transient times of recorded signal bursts indicated that the actual spot diameter was close to that calculated. The angle, θ_D, between the two laser beams as they approached the crossover was close to 2°. This corresponds to a fringe spacing $X_f \cong \lambda/\theta_D$ of about 15 μm.

The optical components used were not necessarily the optima. For example, a transmitting lens with a focal length as short as 50 mm could have been used to produce a spot diameter half as large. And, a much smaller spatial filter at the collecting optical fiber could have been used. In the present study, a 0.6-mm diameter spatial filter was used. There also is some question as to what is the optimum grazing angle. For the u and v measurements, the grazing angle was 3.5° while in the w measurements this angle was 6°.

At present, only mean velocity and normal stresses ($\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$) have been measured with this system. Future measurements of $-\overline{u'v'}$ and $-\overline{w'v'}$ are planned by using multiple beam orientations. These orientations will be realized by rotating the Bragg cell about an axis coincident with the undiffracted laser beam passing through the Bragg cell.

The signal processing was performed with a commercially available digital signal processor which digitizes at a sample rate up to 40 MHz and then performs an FFT to determine the Doppler frequency. The ratio of the peak amplitude to secondary peaks in the spectra is used as the validation criteria. This ratio is selectable. The processor allows for permanent recording of the digitized signals; thus, the data can be reanalyzed for different validation criteria. A 256-point record length was used.

Only 1000 velocity samples were collected at each measurement location. This sample size equates to a 95% confidence interval of 4.5% for the standard deviations u', v', and w'.

The results presented in figures 4-6 were obtained in the lower tunnel wall boundary layer of the pilot channel of building 231 at NASA Ames Research Center. The fully turbulent boundary layer was about 20 mm thick. Re_θ was approximately 2000 and the free stream velocity, u_e was 15 m/sec. In figure 4, measured mean streamwise velocities, $\bar{u}$, are compared with results obtained with a 0.25-mm-high pitot tube. Also shown in this figure are $\bar{w}$ measurements. In this flow $\bar{w}$ should be zero. The small offset in the $\bar{w}$ results is likely due to a slight inclination of the fringes relative to the free stream direction. The offset in $\bar{w}$ was only 1% relative to u_e.

Notice in figure 4 that measurements inside of 0.15 mm were obtained with the laser velocimeter. In figure 5, the $\bar{u}$ results (in inner-layer scaling, $u^+ = \bar{u} / u_\tau$, with u_τ determined from a Clauser plot) are compared with the theory of van Driest.[4]

The normal stress data are compared with data obtained by other experimentors[5,6] in figure 6. These data were obtained in water flows where the free-stream velocity was nearly two orders of magnitude lower than that of the present study. In these water tunnel experiments, measurements were not reported closer than 0.2 mm, but data at lower values of y were realized because the boundary layers were considerably thicker. In the study of Karlsson and Johansson, u and v data were obtained down to a y^+ value of 1.5. (The complete data set has not been represented in figure 6.) The boundary layer was 130 mm thick. Karlsson and Johansson measured w, but with the incident laser beams normal to the measurement surface, so w measurements could not be obtained closer than 0.8 mm from the wall.

As noted earlier, there is some concern that the present data include some samples which are actually zero velocity surface readings. The associated signals, however, are known to have a lower SNR than those produced by particles in the flow. Thus, these erroneous readings can be removed from the data set by reanalyzing the results with a more stringent SNR criterion.

The results obtained to date are encouraging. It is believed that reliable turbulence measurements as close as 0.05 mm to the surface may be possible with the present approach if the spot diameter is made as small as practical.

Summary

In this paper, a new laser velocimeter approach intended specifically for near-wall measurements of the turbulent Reynolds stresses in two-and three-dimensional, boundary-layer type flows is described. In this approach, a beam-turning probe is used to provide the maximum sensitivity possible to the cross-stream velocity component, w, along with the best possible near-wall spatial resolution. With this optical configuration and FFT digital signal processing, substantial increases in near-wall measurement performance over hot-wire anemometry and conventional laser velocimetry should be obtainable.

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Meet the authors

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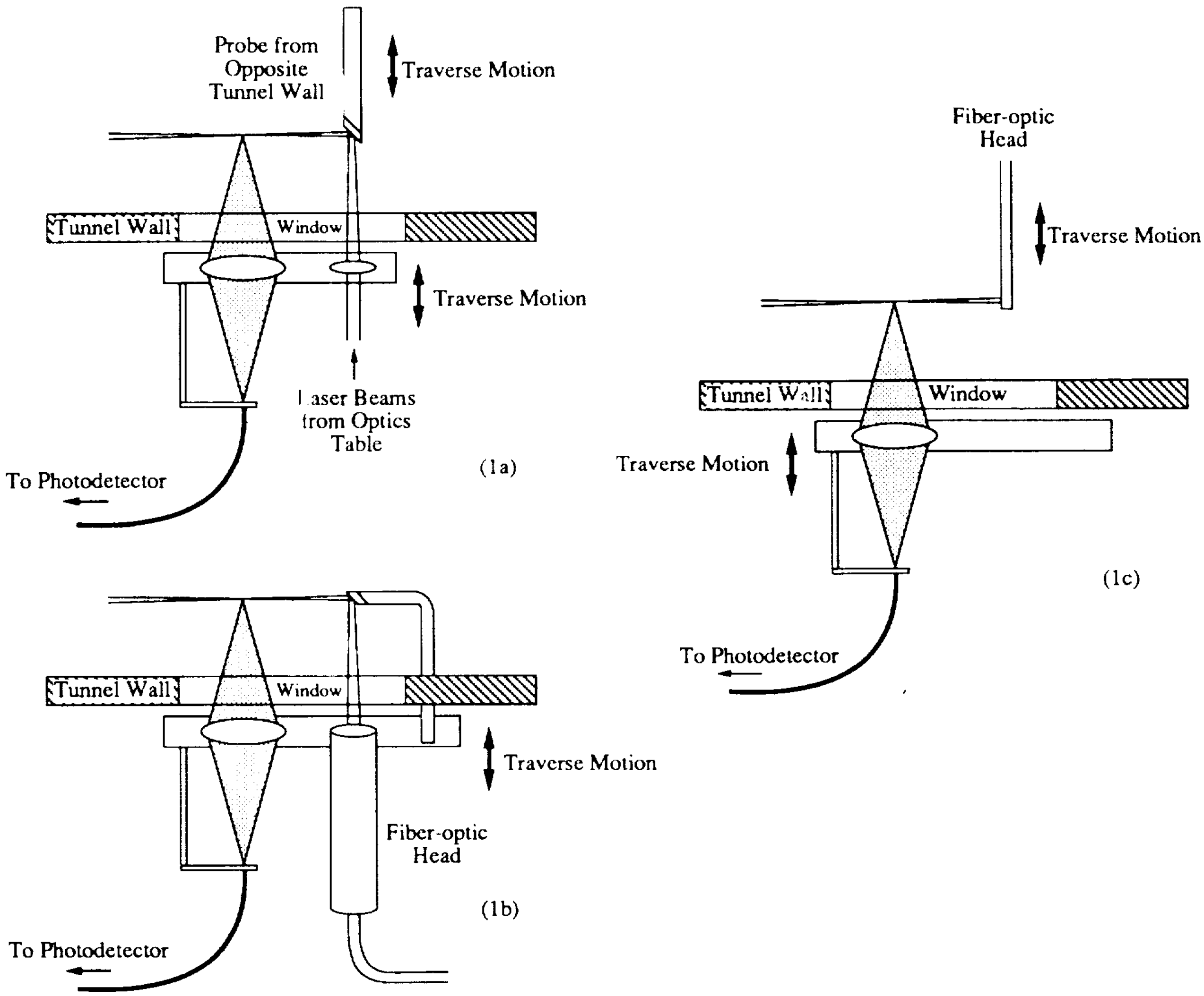

Figure 1. Schematic representations of miniature laser velocimeters for near-wall three-dimensional turbulence measurements: a) beam-turning probe from opposite tunnel wall or attached to probe-drive mechanism within test section, b) beam turning-probe from measurement wall and fiber-optic head outside tunnel and c) fiber-optic head inside tunnel.

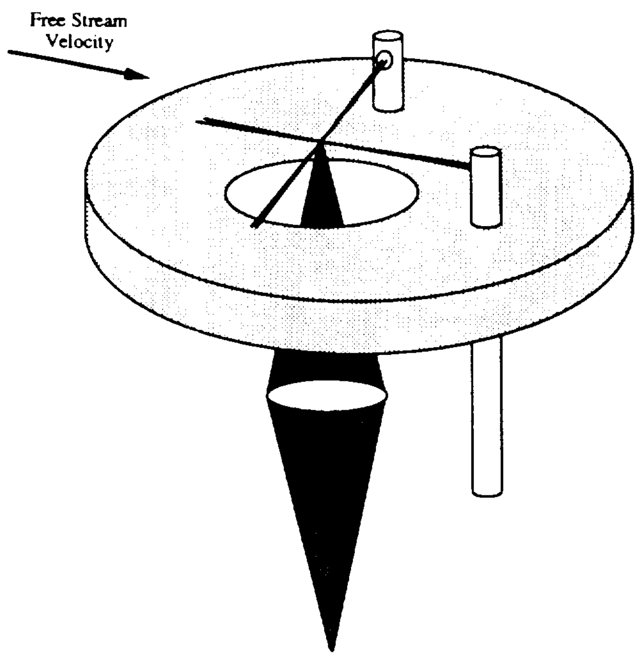

Figure 2. Miniature dual-probe laser velocimeter for near-wall simultaneous u, v and w measurements.

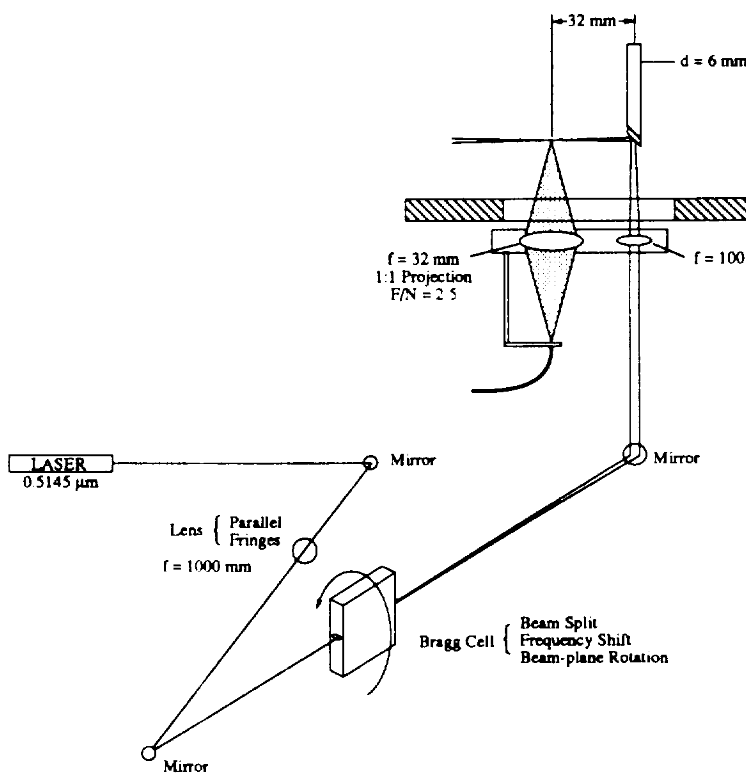

Figure 3. Schematic representation of optical layout for two-dimensional turbulent boundary layer measurements.

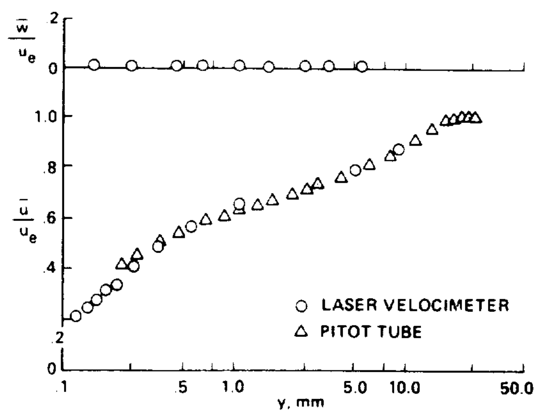

Figure 4. Two-dimensional turbulent boundary layer mean velocity results.

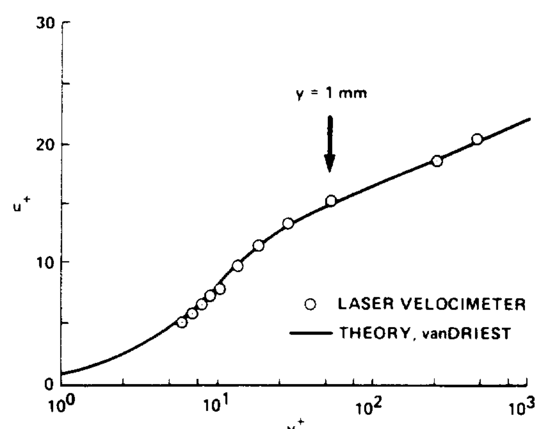

Figure 5. Comparison of streamwise velocity results with theory (inner-layer scaling used).

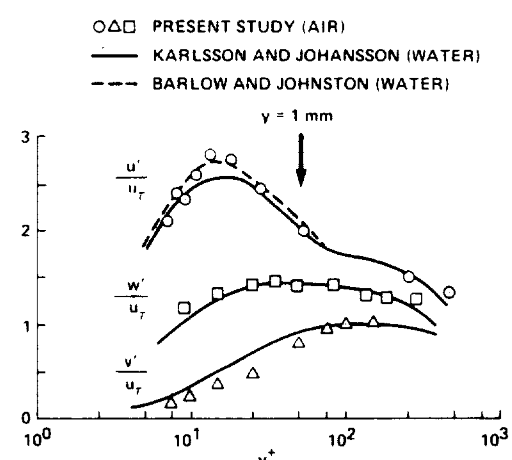

Figure 6. Comparison of Reynolds normal stresses with result form other studies (inner-layer scaling used).

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16. Abstract

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