Characterization of length and velocity scales of free stream turbulence and investigation of their effects on surface heat transfer

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The main objective of this research is the characterization of the length and velocity scales of free stream turbulence and investigation of their effects on the length and velocity scales within the boundary layer and on surface heat transfer. An experimental and theoretical research has been carried out in order to achieve these goals. In the experimental arena, a new real-time hot wire technique is being developed using triple and quad wire probes. Both probes have been calibrated and qualified in a fully-developed turbulent channel flow. Reynolds stresses are calculated from the real-time data and compared with the previous data obtained with other means. Quadrant plots of fluctuating velocity components compare well with the numerical data.

These probes will later be used to measure vertical and transverse length scales for all the Reynolds stresses and velocity-temperature correlations, both in the free stream and within the boundary layer.

The surface heat transfer rates will also be measured. The relationship between the character of the free stream turbulence and the surface heat transfer will be explored. An existing wind tunnel capable of generating high levels of free stream turbulence with different length and velocity scales and with heat transfer measurement capability will be used for this purpose.

In the theoretical front, computational data generated from the full solutions of the Navier-Stokes equations for the case of fully-developed two-dimensional turbulent channel flow is being used to study the effect of large centerline structures on the events near the wall. This research is expected to lead into the determination of the relevant length and velocity scales that play a role in the processes near the wall. It will help in understanding of the free stream turbulence effects and will contribute in planning the experimental research.

1. Motivation and objectives

1.1. Introduction

Free stream turbulence is the turbulence in the approach stream. It is experienced in many applications. For example, nozzle guide vanes and the rotor blades in a gas turbine are exposed to the high levels of free stream turbulence.

The free stream turbulence has an important influence on the surface heat transfer. Under high levels of turbulence (10-20%), there is an appreciable increase in the heat transfer rate regardless of the character of the boundary layer.

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Some representative results in this area can be found in the studies by Kestin (1966), Kearney *et al.* (1970), Brown and Burton (1978), Bradshaw and Simonich (1978), and Blair (1983). A detailed review of this literature is given by Moffat and Maciejewski (1984). They conclude that the free stream turbulence levels up to 10% cause a proportional increase in heat transfer for constant velocity and accelerating turbulent boundary layers. It is indicated that large effects on the average values may result if the turbulence affects the location of the transition and if the heat transfer data are compared at constant x-Reynolds numbers.

One of the important observations from the literature in this area is that under the same levels of turbulence, different researchers found different enhancement of heat transfer rates. This leads to the speculation that not only the velocity scale but also the length scale of the turbulence is important. In fact, Moffat and Maciejewski (1984) relate to this fact and suggest that the effect of the length scale should be investigated.

Most of the studies that were discussed used, one way or another, grid generated turbulence in their experiments where the length and velocity scales are usually small. More recently, the flow fields of jets and wall jets have been used in order to simulate high free stream turbulence encountered in turbomachinery. Moffat and Maciejewski (1985) used a circular wall jet in order to obtain free stream turbulence intensities up to 48%. They measured Stanton numbers which are as much as 350% above the standard zero free stream turbulence correlations. Ames and Moffat (1990) have investigated the effects of free stream turbulence created by 2.5 inch diameter jet injection into a main flow in a plenum chamber followed by a wind tunnel test section on the heat transfer to a flat plate boundary layer. This study used autocorrelations to measure the length scales. In another recent study, MacMullin *et al.* (1989) investigated the effects of free stream turbulence from a circular wall jet on a flat plate boundary layer heat and momentum transfer with turbulence intensities 7-18%. They also observed increased Stanton numbers and skin friction coefficient with increasing turbulence intensities. They used autocorrelations for the determination of length scales. The influence of length scale on the Stanton numbers was not conclusive.

The present belief of the author is that the length scales in the vertical direction to the wall and in the transverse direction to the flow are more important in determining the scales within the boundary layer which affect the heat transfer. The measurement of these scales using autocorrelations will not give correct answers as indicated by Bradshaw (1971) in flows with high levels of turbulence. These length scales should be measured using space correlations.

There has been also several investigations on the effects of free stream turbulence on the stagnation region heat transfer and hydrodynamics. Some examples are: Sutera *et al.* (1963), Sutera (1965), Britter *et al.* (1979), Sadeh and Bauer (1981), and Vanfossen and Simoneau (1984). Since the boundary layer is thin in the stagnation region and the flow is accelerating, the effects of free stream turbulence can be seen more clearly. General observation obtained from these studies is that not only the level of the free stream turbulence and its length scale are important in understanding and predicting the heat transfer, but also its distortion as the flow approaches a stagnation point.

A detailed discussion on the free stream turbulence distortion for flows approaching stagnation and its effects on heat transfer can be found in Yavuzkurt and Tafti (1987) and Tafti (1989).

One can observe from these references that the free stream turbulence (especially at large scales and high intensities) is not isotropic. Therefore, in characterizing this phenomenon , the measurement of all velocity scales, i.e. Reynolds stresses and their corresponding length scales, is necessary. It is also important to measure these scales within the boundary layer in order to be able to determine the effects of the free stream scales on the boundary layer scales, which in turn determine the surface heat transfer rate. Interactions of temperature and velocity fluctuations also play an important role in the turbulent heat transfer. Therefore, measurement of velocity and temperature correlations and corresponding length scales is also necessary. For example, interactions of temperature fluctuations with the transverse fluctuating velocity component w' is believed to be an important mechanism; whereas, most of the data in the literature is concentrated upon the measurement of the streamwise component of the fluctuating velocity.

1.2. Objectives

The main objective of this research is to address two important but unresolved problems: The first is the measurement of vertical and transverse length scales via space correlations for all Reynolds stress components and velocity-temperature correlations, both in the free stream and within the boundary layer using the existing triple and quad-wire probes; the second is to relate the character of the free stream turbulence to the character of the turbulence within the boundary layer in order to determine the effect on surface heat transfer.

1.3. Theoretical speculations

There does not exist a complete theory about how the free stream turbulence affects the heat transfer and hydrodynamics within a boundary layer. However, there exists some educated guesses and speculations. Most work consists of experimental observations and some semi-empirical explanations of these observations. A few of these will be mentioned. Kestin (1966) tries to explain the phenomena using an oscillating free stream velocity and speculates that the effect of the free stream turbulence is similar to the secondary steady flow generated by oscillations. However, he acknowledges that the effect produced this way is an order of magnitude smaller than the effect created by the free stream turbulence. Another observation by Sutera *et al.* (1963) indicates that at the stagnation point, the axis of the vortices becomes stretched and certain wavelengths get amplified to affect the boundary layer. This study in general deals with the vorticity amplification near a stagnation point. However, it fails to explain how the free stream turbulence affects the boundary layer and the heat transfer at the stagnation point. Another common opinion is that the free stream turbulence changes the point of transition and thereby increases the heat transfer at a certain location. Again, this idea is not enough to explain all of the observed behavior, since the free stream turbulence also enhances the heat transfer in a full turbulent boundary layer. In order to address this problem, Moffat and Maciejewski (1985) argued that the turbulence should be treated as a separate property of the flow, measured by a set of attributes such as its intensity components, scale components, spectra, etc. The hypothesis is that whenever the free stream turbulence can disrupt the innermost region of the boundary layer, it will affect the heat transfer. Therefore, small and large scale turbulence may act by quite different means to affect surface heat transfer: small scale turbulence by diffusion and large scale by pressure and shear interactions in the near-wall region. There exists other investigations; however, there is almost no quantitative relationship between the enhancement of heat transfer and the character of the free stream turbulence. The ones which exist are not general enough. In fact, it is still not known what properties of free stream turbulence are the ones which are responsible for the observed behavior. Obviously, one is the velocity scale, but which one is unknown since several velocity scales exist (transverse, vertical, and axial).

In this study, all of the velocity and length scales will be investigated. Space correlations will be used for these measurements. As explained by Bradshaw (1971), as the Reynolds stress and intensity of turbulence increases, deviations from Taylor hypothesis will increase. Therefore, autocorrelations will not give correct length scales in flows with high turbulence intensity, which is exactly the case studied here.

In the author's opinion, interaction between the free stream turbulence and the boundary layer scales and thereby surface heat transfer should be related to the time scales of the free stream turbulence and the time scales of the structures within the boundary layer. Further, the length scales of the velocity fluctuations which interact with the temperature fluctuations could be different. It is most probable that conditional sampling will be needed in order to get the dominant length scales and relationship between them. There is also evidence (although not published yet) which leads this author to think that there might be two different events that are responsible for the action of high free stream turbulence. One is the large unsteady coherent structures like unsteady wake, the other is smaller scale but high frequency turbulent fluctuations. Therefore, two different length and velocity scales might be needed to characterize the free stream turbulence. During the experimental study, conditional sampling will be used to see if this speculation is correct.

2. Accomplishments

2.1. Experimental

The triple wire probe is used with a constant temperature anemometry system to obtain quadrant plots of fluctuating velocities in a fully developed turbulent channel flow at different Reynolds numbers. The data is reduced both digitally and also in an analog fashion using the "three dimensional turbulent flow analyzer" module developed earlier by the author. (Yavuzkurt *et al.* (1978,1980)). Plots of v' vs. u' and v' vs. w' are shown in figure 1. The fluctuating velocities are normalized with

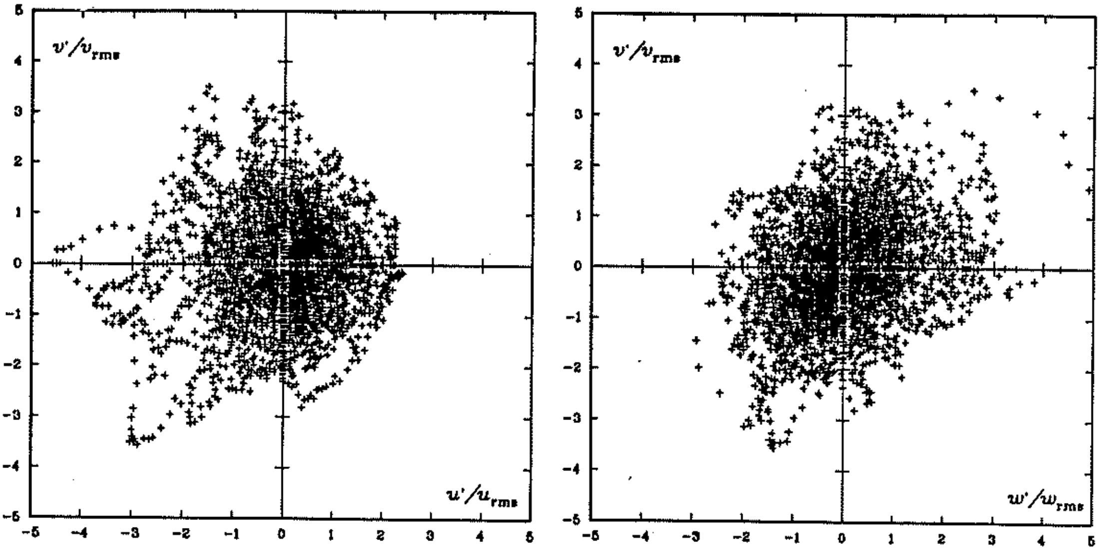

FIGURE 1. Quadrant plots of normalized fluctuating velocity components in the centerline of a fully developed channel flow (left: v' vs u', right: v' vs w'). Reynolds number based on channel half width and centerline velocity is 3300. Obtained using triple wire probe.

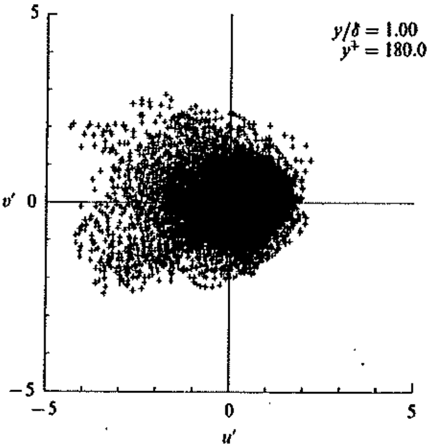

FIGURE 2. Quadrant plots of normalized fluctuating velocity components in the centerline of a fully developed channel flow. Reynolds number is 3300. Obtained from the numerical data of Kim *et al.* (1987).

their own rms values. They compare very well with the numerical results obtained by Kim *et al.* (1987), which are shown in the figure 2. The data was taken at the channel centerline at a Reynolds number based on the centerline velocity and channel half width of 3,300.

The data shown in figure 1 consists of 8,000 data points which were obtained at 5,000 hz. Therefore, the figure shows only about 1.6 seconds of real time data. The data loops which can be seen in the areas away from the figure center are the trajectory of large scales structures in the velocity space. They appear much more clearly in low Reynolds number flows such as this. The triple wire probe and the three-dimensional flow analyzer are also used to obtain the quadrant plots of u', v', and w' on an oscilloscope in real time at Reynolds numbers of 20,000 and 6,000 at different locations. The data is collected at different frequencies by using a low pass filter at 20, 200, 2,000, and 20,000 Hz. The output of the oscilloscope is recorded on a video tape along with the sound generated by the different fluctuating velocity components. The results show that most of the energy of u' is at low frequencies, whereas v' has higher frequency components. This is evident from the pictures and the sound generated by u' and v' under different cut-off frequencies. These measurements showed the capabilities of the triple wire probe and the measurement technique.

The quad wire which is much smaller than the triple wire probe is described in Frota (1982). This probe is shown in figure 3. It has a fourth wire for the measurements of the temperature. This allows the probe to be used in non-isothermal flows and also makes it possible to obtain the velocity-temperature fluctuations in real time. The probe measurement volume is much smaller than the triple wire due to its special construction (3mm vs 1mm). Its diameter being 2mm, it can get much closer to the wall. All the wires has a common prong at the center. The common grounding problems created by this have been solved by a new electronic circuitry. This probe and its circuitry which has not been used earlier is being checked thoroughly. The early results are encouraging. The quad wire has been successfully calibrated and checked in a fully developed channel flow. The shear stress profile obtained using this probe is shown in figure 4 at two different velocities. The comparison between the shear stress profiles obtained with this probe and the ones obtained from the channel pressure drop is excellent.

The quadrant plots of normalized velocity fluctuations u' and v' obtained with the quad wire probe are shown in figure 4 at a Reynolds number of 5,000 at the channel centerline and at a location $y/h = 0.57$ where h is the half channel width. They again compare very well with the previous results. These qualifications show that the quad wire probe with its electronic circuitry can be used for achieving the goals of this research.

2.2. Computational

The data of Kim *et al.* (1987) which is obtained from the full solutions of the Navier-Stokes equations for a fully developed turbulent channel flow is used to correlate the vertical component of the fluctuating velocity v' at the centerline with the temperature fluctuations t' at different planes parallel to the wall-specifically at

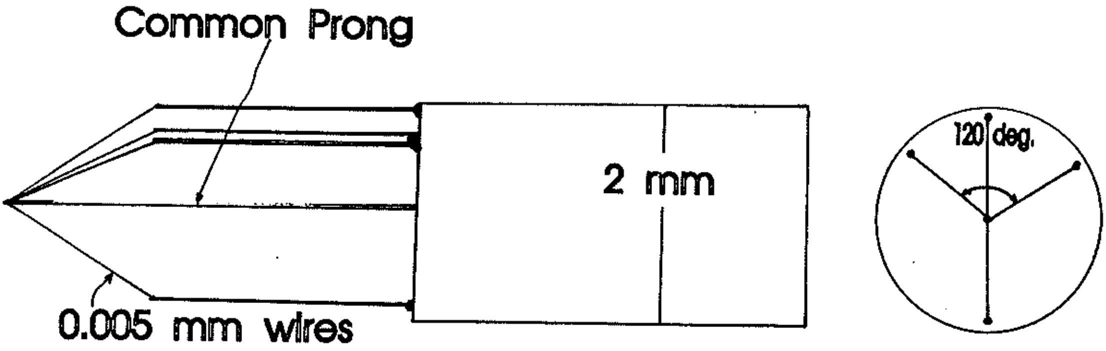

FIGURE 3. Quad wire probe.

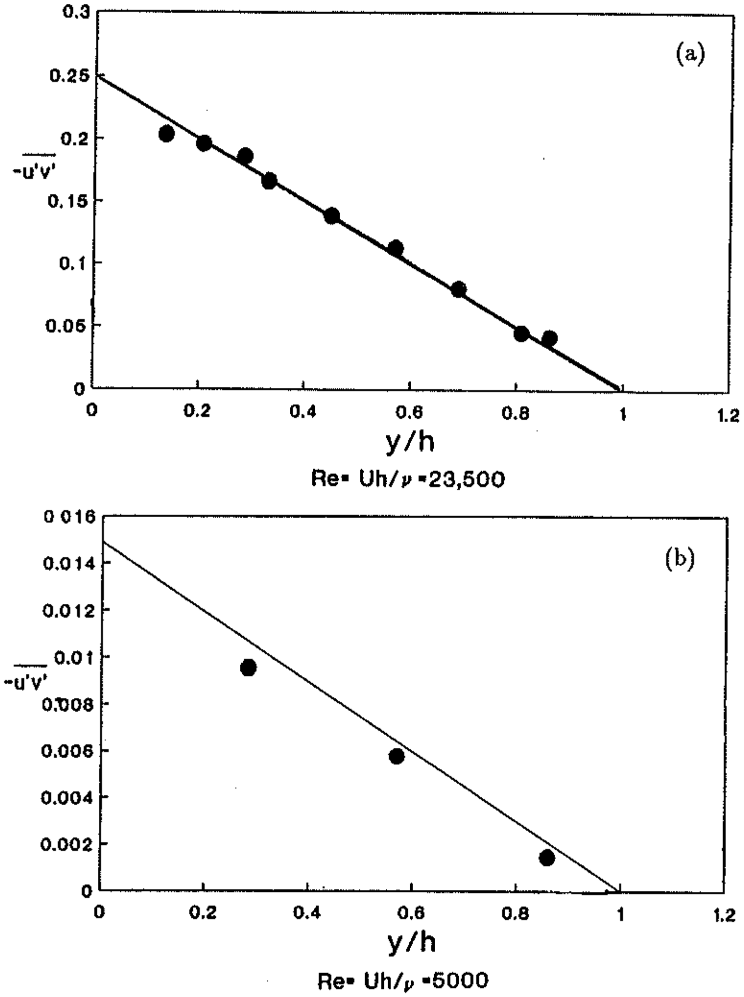

FIGURE 4. Shear stress profiles obtained with the quad wire probe (•) and the channel pressure drop (——) in a fully developed channel flow, a: Re = 23,500, b: Re = 5,000.

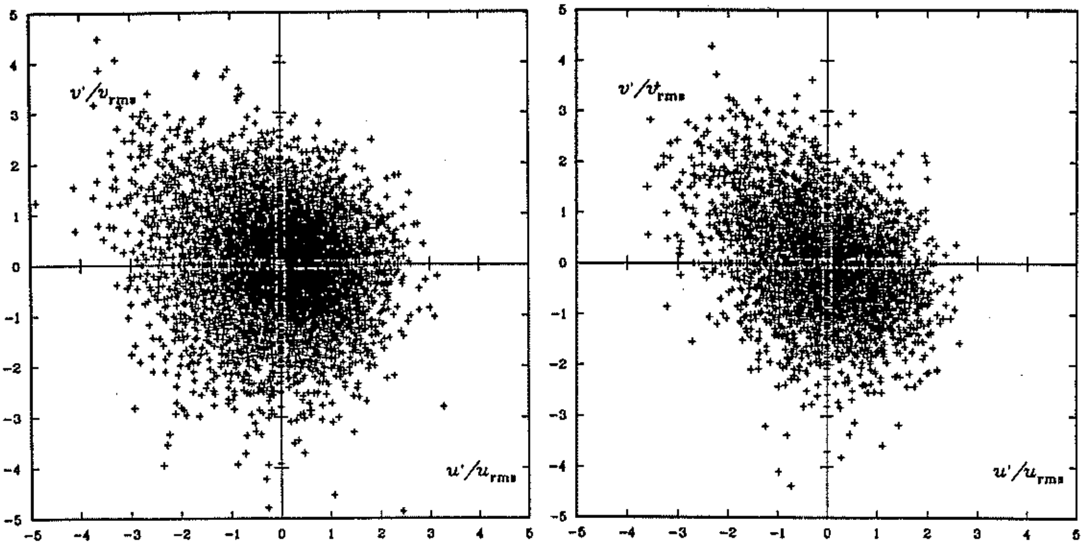

FIGURE 5. Quadrant plots of the velocity fluctuations u' and v' at the centerline (left) and at $y/h = 0.57$ (right) at a Reynolds number of 5,000 in a fully developed channel flow. Obtained with the quad wire probe.

locations $y+ = 180$ (centerline), 100, 60, 10- for different x and z separations. When the full set of wavelengths are used, no correlation is obtained between the centerline and $y+ = 10$ position as will be expected. However, when the filtered data is used, the value of the correlation coefficient is higher and results are more promising. Promising results are also obtained when negative v' is used for the correlations. The calculations using filtered data and different quantities for correlations are continuing. More computational data is needed for long time averaging and for more meaningful results.

3. Future plans

Future plans include using two quad wire probes in the high free stream turbulence rig to obtain the space correlations of the Reynolds stresses and velocity-temperature correlations leading to determination of the effective length and velocity scales of the free stream turbulence which affect the heat transfer as discussed in section 1.3. The computational research will continue in order to determine the proper velocity and length scales which exchange information between the centerline and the wall in a fully developed channel flow using the data of Kim *et al.* (1987). This will help in determining what type of a conditional sampling should be used in the experiments. It is hoped that the final output of this research will be better empirical correlations for the heat transfer with high levels of turbulence. It will also facilitate understanding of how the large scale structures far from a wall interact with the small scales near it.

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