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EXPERIMENTS IN HIGHLY SHEARED, NEARLY HOMOGENEOUS TURBULENCE

by

FENELLA DE SOUZA

A thesis submitted to the
School of Graduate Studies and Research
in partial fulfillment of the requirements
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MASTER OF APPLIED SCIENCE

Ottawa-Carleton Institute for Mechanical and Aeronautical Engineering

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Abstract

Nearly homogeneous, uniformly sheared, turbulent flow was generated in a high speed wind tunnel at shear rates ranging from 436 to 705 s^{-1} and Mach numbers below 0.2. The shear rates are substantially higher than those generated in the past, and comparable to those in the inner region of turbulent boundary layers. Measurements were obtained using a three-beam, two-component, laser-Doppler velocimetry (LDV) system in back-scatter mode. The system employs a 100mW Argon-Ion laser, which is connected to the measuring probe via fibre optics. Although the signal was filtered by the data acquisition system, additional computer programs were required to remove extraneous noise, which was defined as data samples beyond 2.5 standard deviations from the mean.

LDV measurements show that the turbulence structure attains a self-similar state with approximately constant dimensionless stresses and exponential kinetic energy growth. The main difference from realizations at lower shear rates (comparable to those in outer boundary layers) is a marked decrease in the dimensionless Reynolds shear stress, $-K_{12}$, which attained an average value of 0.11 over all present experiments, compared to the value 0.15 obtained previously in uniform shear flow and outer boundary layers. The Reynolds shear stress correlation coefficient averaged over all the present shear flows was 0.35, and was consistently lower than the value of 0.45 which has been found in outer boundary layers and uniform shear flows at lower shear rates.

It has been hypothesized that high shear rates are responsible for the decrease of turbulent shear stress, which is related to the production of turbulent kinetic energy. This finding is consistent with measurements in the inner boundary layer and with the observed change of structure of directly simulated, homogeneous shear flows at high shear rates. There were considerably larger discrepancies in the normal stress components of the stress tensor between different types of shear flow, particularly between uniform shear and boundary layer flow. It was concluded that although the partition of turbulent kinetic energy among its components most likely depends on the proximity of a wall, the rate of production of turbulence in shear flow depends mainly on the rate of mean shear, irrespectively of the shear generation mechanism.

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Nomenclature

a	speed of sound
d_m	maximum diameter of LDV measurement volume in the measurement plane
h	height of test section
h_m	height of LDV measurement volume
K_{ij}	dimensionless Reynolds stress tensor
k_s	flow generator constant
L_{11}	streamwise velocity integral lengthscale
M_c	convective Mach number
M_t	turbulent Mach number
P	kinetic energy production
p	turbulent pressure fluctuation
q	square root of twice the mean turbulent kinetic energy
$\frac{1}{2} \overline{q^2}$	mean turbulent kinetic energy
$\frac{1}{2} \overline{q_r^2}$	reference turbulent kinetic energy
R^*	dimensionless pipe radius

R_{12}	two-point spatial correlation
$R_{\lambda 1}$	turbulent Reynolds number based on u_1 and λ_{11}
S	magnitude of mean velocity gradient
S^*	dimensionless shear rate parameter in DNS studies
T_{TS}	time for mean flow to traverse wind tunnel test section
$\bar{U}_c$	streamwise mean velocity on test section centreline
$\bar{U}_i$	mean velocity
u_i	turbulent velocity fluctuation
u_i'	root-mean-squared turbulent velocity
u_τ	friction velocity
u^+	dimensionless mean velocity in inner boundary layer
x_i	coordinate axes; $i=1,2,3$
x_1	distance from flow separator
Δx_1	length of test section
y	perpendicular distance from wall
y^+	dimensionless distance from wall

Greek Symbols

δ	boundary layer thickness
δ_{ij}	Kronecker delta
ϵ	turbulent kinetic energy dissipation rate

η	Kolmogoroff microscale
κ	coefficient in exponential law for turbulent kinetic energy
λ_{11}	streamwise Taylor microscale
ν	kinematic viscosity of fluid
ρ	fluid density
τ	dimensionless flow development time or total strain
τ_s	characteristic straining time of the flow
τ_u	lifetime of energy containing eddies

Superscripts

+	non-dimensionalized by boundary layer wall variables
---	--

Subscripts

c	evaluated on test section centreline
e	due to factors other than shear, or "external" factors
m	measured
r	reference
rms	root-mean-squared
s	due to shear
T	tunnel conditions

Other Symbols

$\overline{(\quad)}$ overbar denotes average

Chapter 1

Introduction

1.1 The structure of turbulent shear flows

Turbulent fluid motion is an irregular condition of flow in which the various quantities, such as velocity, pressure, or temperature, show a random variation in time and space, so that statistically distinct average values can be discerned (Hinze 1975). Turbulent motion always occurs through instability of a corresponding laminar flow in which the Reynolds number has exceeded a certain critical value. Due to its highly diffusive nature, a turbulent flow is subject to rapid mixing and increased rates of momentum, mass and heat transfer. It is characterized by high levels of fluctuating vorticity and the mechanism of vortex stretching, which entail rotationality and three dimensionality. In any real fluid, viscosity causes the kinetic energy in a turbulent flow to be dissipated into heat, through the action of shear stresses. In the absence of a continuous external source of energy, turbulent motion will decay.

One such external source of energy is mean shear, which is the result of a nonuniform mean flow velocity. For example, turbulence can be generated and maintained in a fluid by

shear due to friction at fixed walls, as in flow through pipes or past solid bodies, or by shear between layers of fluids with different velocities, as in a jet or wake. The term "turbulent shear flow" is often used to designate both types of fluid motion, which can be classified respectively as "wall flows" and "free shear flows".

Various numerical and experimental studies have demonstrated that the motion of fluid in turbulent shear flows is not entirely random, but, in general, it also contains highly organized or "coherent" structures. Such structures are persistent features of turbulent boundary layers and other shear flows, and are believed to be related to turbulence production.

The structure of turbulence in shear flows depends on the geometrical features of the flow but there are indications that it also depends on the rate of mean shear. For example, distinct types of coherent structures have been identified in the different sublayers of the inner turbulent boundary layer. Within the viscous sublayer, the mean velocity gradient is very steep. Flow visualization has revealed regions of high and low velocity fluid ("streaks"), which are elongated downstream and alternating in the spanwise direction (Kline et al. 1967). Rapid lift-up of low speed streaks is called an ejection; the subsequently observed oscillations and violent break up of the flow into small scales, referred to as "bursting", is believed to be the main source of turbulence production (Kim, Kline & Reynolds 1971).

Outside the viscous sublayer, the shear rate decreases and the streaks become less discernable. It has been generally concluded that the dominant structures in this region are "horseshoe" or "hairpin" vortices, which apparently originate in the wall region and extend throughout a large part of the boundary layer. They are inclined at about 45 degrees with respect to the freestream direction, and become significantly stretched and elongated with increasing Reynolds number. Head and Bandyopadhyay (1981) determined that hairpin vortices are mostly found in the logarithmic layer, and are associated with high Reynolds shear stress. Chu and Falco (1988) concluded that hairpin vortices are related to streak formation and bursting, and thus to the turbulent production process.

1.2 Uniformly sheared turbulence

One method to study the relationship between shear rate and turbulence structure is to create a flow in which the effect of shear is essentially isolated. Consequently, the present study deals with the simplest type of shear flow: an unbounded flow with statistically homogeneous velocity fluctuations, maintained by a uniform mean velocity gradient. Such a flow is subject to the basic physical mechanisms of turbulence production, transport, and viscous dissipation, but it is free from the complicating interactions with rigid walls or nonturbulent streams and large-scale inhomogeneities associated with nonuniform shear (Tavoularis 1985). Measurements in uniformly sheared turbulence can be used to verify general turbulence theories and models, and also to understand structurally similar flows such as boundary layers.

There have been several attempts to generate nearly homogeneous turbulent shear flow in the laboratory. Experimental evidence generally indicates that uniformly sheared flow can reach an asymptotic state, where length scales, turbulent stresses, and turbulent kinetic energy grow exponentially with downstream distance, at a rate which depends on the mean shear. Details of these studies can be found in Chapter 2.

1.3 Motivation

The motivation for the present research arises from recent numerical studies which provide strong support for the theory that the structure of turbulent shear flow may depend primarily on the mean shear rate. Direct numerical simulation has revealed that the physical structure and statistical correlations observed in turbulent boundary layers can be reproduced in homogeneous shear flow at a similar shear rate.

Simulation of homogeneous flow at a shear rate typical of the logarithmic layer of wall-bounded turbulent shear revealed the presence of hairpin vortices (Rogers and Moin 1987). Higher shear rates produced streaky structures and statistical correlations similar to those

observed in the viscous sublayer, where the shear rate is comparable (Lee et al. 1990). The turbulent structures became increasingly elongated in the flow direction and narrow in the spanwise direction as the effective shear rate increased.

The above suggests that mean shear, rather than the presence of a solid boundary, may determine the structure of turbulent shear flow. In particular, the latter study indicates that the very near wall structure, where experimental measurement is often difficult, can be reproduced in a homogeneous shear flow at very high shear rate. This prompts the present study, and leads to the objectives outlined below.

1.4 Objectives

The primary objective of this thesis is to generate a nearly homogeneous uniformly sheared flow at a shear rate comparable to that which exists in the inner region of a turbulent boundary layer. Previous uniform shear experiments have been limited to fairly modest shear rates, up to 84 s^{-1} , whereas in a viscous sublayer the shear rate is more likely to exceed 500 s^{-1} .

It is proposed to obtain measurements of the turbulence structure via laser-Doppler velocimetry, in order to investigate the dependence of turbulence characteristics on the rate of uniform shear at high shear rates. The present study may also provide experimental validation of the recent direct numerical simulations of homogeneous shear flow and channel flow, which suggest that the structure of turbulence in the viscous sublayer may be reproduced in a free flow with high shear.

An essential objective of generating uniform high shear is to compare the results with turbulent boundary layer measurements from the literature, particularly those taken in the near-wall region. Consequently, it may be possible to understand better the structure of a turbulent boundary layer very close to the wall, where it is believed that most of the turbulence production

originates. A long-term goal is to understand fully the relationship between mean shear rate and flow structure in any turbulent shear flow.

1.5 Organization of thesis

In the next chapter, a comprehensive literature review of relevant work is presented. The governing equations and asymptotic laws for uniformly sheared turbulence are derived in Chapter 3. Chapter 4 describes the experimental apparatus, techniques and procedures. Measurements, presented in Chapter 5, are analyzed and discussed in Chapter 6. Conclusions which have been drawn from this study, along with recommendations for future work, are included in Chapter 7.

Chapter 2

Literature Review

2.1 General literature on turbulent flows

A clear and comprehensive introduction to the concept of turbulence can be found in the first chapter of the text book by Hinze (1975). The fundamental nature and properties of turbulent flow are presented by Bradshaw (1971), who also elaborates on measurement techniques.

Following a brief introduction to turbulence, Phillips (1969) describes the physical structure of turbulent shear flow in detail, focusing on wall turbulence. Observations of the evolution of near-wall turbulence structure and its relation to energy production and dissipation are very similar to results of more recent experimental and computational studies.

Phillips also provides a theoretical discussion of uniform shear flow, as an example of the simplest type of turbulent shear flow, and as a means to determine the relationship between mean shear and turbulence production. At that time, the uniform shear flow model was found

to be unsuccessful in accounting for the generation and development of Reynolds stress.

2.2 Homogeneous turbulent shear flow

An excellent theoretical and mathematical description of homogeneous turbulent shear flow is provided in Chapter 4 of Hinze (1975). The concept of homogeneous turbulence sheared by a uniform mean velocity gradient was introduced by von Karman (1937), out of the desire to study the relationship between shear stress and mean velocity gradient field without the complicating effects of boundaries.

It is important to note that any uniformly sheared flow can be only approximately homogeneous. Experimentally, boundary effects will always be present, although they can be ignored if the integral scales of the turbulent field are much smaller than the distance over which the mean shear is essentially constant. Theoretically, inconsistencies in the equations of motion have proved that a homogeneous shear flow cannot be stationary with respect to an inertial frame, and that a uniformly sheared flow cannot be perfectly homogeneous (Champagne et al. 1970).

2.2.1 Experimental realizations of nearly homogeneous shear flow

Corrsin (1963) was the first to propose a means of generating a nearly homogeneous shear flow in the laboratory. The experiment was performed by Rose (1966), who used a plane grid with parallel rods of uniform diameter but non-uniform spacing. Rose achieved a fairly uniform mean velocity gradient of about 13.7 s^{-1} , and nearly homogeneous transverse distributions of turbulent intensities and shear stress. However, the uneven rod spacing caused non-uniform transverse profiles of the integral length scales and Taylor microscales.

Transverse homogeneity was improved by using various combinations of uniform and non-uniform grids and honeycombs (Rose 1970; Hwang 1971; Mulhearn & Luxton 1970, 1975).

The most common and successful method employed a set of equal-width parallel channels with variable internal resistances (usually screens of various mesh size). Champagne, Harris & Corrsin (1970) achieved a mean shear rate of $d\bar{U}_1/dx_2 = 12.9 \text{ s}^{-1}$ in the first such experiment.

Some of the initial conclusions drawn from these earlier studies were that the Reynolds stress correlation coefficient approached an asymptotic value roughly equal to 0.45, the integral length scales and Taylor microscales increased monotonically, and the velocity correlation function and spectra reached approximately self-preserving forms.

A somewhat suspect finding was that the turbulent kinetic energy decreased from its initially imposed level to a seemingly asymptotic constant value, despite the growing integral scales. Champagne et al. (1970) attributed this paradoxical result to insufficiently long flow development time, which can also be interpreted as a too small value of total strain.

The above conjecture was confirmed by Harris, Graham & Corrsin (1977), who extended the experiment of Champagne et al. to larger values of the dimensionless downstream time or total strain by generating a larger mean velocity gradient, $d\bar{U}_1/dx_2 = 48 \text{ s}^{-1}$. The expression $\tau = (x_1/\bar{U}_c)d\bar{U}_1/dx_2$ was introduced to represent the total strain, where $\bar{U}_c$ is the value of $\bar{U}_1$ on the test section centreline. Harris et al. observed that the turbulent kinetic energy passed through a minimum and then increased monotonically. They also confirmed the continuous increase of the integral length scale, but found that the Taylor microscale increased more slowly than the integral length scale, if at all.

The wind tunnel used for the experiments of Rose (1966), Champagne et al. (1970) and Harris et al. (1977) was also used by Tavoularis and Corrsin (1981) to generate a flow with approximately uniform shear and transverse homogeneity. However, heated rods were added to the shear-turbulence generator used by Harris et al. in order to superimpose a uniform mean temperature gradient on the flow.

Using the technique of parallel channels with internal resistances, Tavoularis and Karnik

(1989) attained the highest to date uniform shear rate, $d\bar{U}_1/dx_2 = 84 \text{ s}^{-1}$, and consequently the largest values of total strain, τ . They concluded that uniformly sheared turbulence, given sufficient development time, attains an approximately self-preserving state, in which turbulent velocity and lengthscales follow well-defined laws of downstream evolution, and properly non-dimensionalized quantities, such as the dimensionless Reynolds stress ratios and the turbulent kinetic energy dissipation over production ratio, remain essentially constant. It was proposed that all such flows comprise a distinct class, for which self-similar solutions, which might be compatible with the available experimental results, exist for the asymptotic development stage.

The same paper actually divides uniformly sheared turbulent flows into two subclasses: flows with exponentially growing stresses, identified as "high-shear", and flows with roughly constant stresses as downstream distance increases, identified as "low-shear". Tavoularis and Karnik defined the flow generator constant, $k_s = (1/\bar{U}_c)d\bar{U}_1/dx_2$, as a measure of effective shear. They observed that in flows where $k_s > 3$, turbulent stresses grew exponentially at a rate which was linearly related to k_s , and the ratio of dissipation to production of kinetic energy reached a constant value of roughly 0.68. However, the "low-shear" flows exhibited roughly equal rates of production and dissipation. In both cases, the energy dissipation to production ratio appeared to be independent of the mean strain rate.

In the above wind tunnel experiments, each flow generator channel was fed by a common air supply. As a result, adjustment of the resistance in any one channel affected the flow in all the others. As a solution to this difficulty, Rohr et al. (1988) produced a uniform shear flow using a ten-layer, closed loop, water channel. Each layer had its own separate pump and feeding system, greatly facilitating flow control, and permitting them to isolate the effect of changing the mean shear while keeping the other parameters of the flow nearly constant. A less versatile but simpler alternative is to place a fixed blockage, such as a perforated plate with varying porosity, ahead of the flow separator channels. This technique is proposed in the present study, and will be elaborated in Chapter 4.

2.2.2 Computational simulation of homogeneous shear flow

Direct numerical simulation of the three-dimensional, time-dependent Navier-Stokes equations is another technique used to investigate the structure of homogeneous shear flow. This computational method has been applied, among others, by Rogers and Moin (1987), and Lee, Kim and Moin (1990), who discovered structures similar to those observed in the inner region of turbulent boundary layers, as outlined in Chapter 1.

The high shear results of Lee et al. are of particular interest to the present study. Similarly to uniform shear experiments, the simulation revealed that the turbulent kinetic energy initially underwent a transient period of adjustment, followed by a period of monotonic growth. Statistical quantities, such as the Reynolds stresses, as well as instantaneous velocity fields, compared remarkably well with those in the sublayer of a simulated turbulent channel flow at the same dimensionless shear rate. Statistical agreement with experimentally generated homogeneous shear flow remains to be verified.

An alternative theoretical/numerical technique is rapid distortion theory (RDT), discussed, for example, by Hunt & Carruthers (1990). Several authors have shown that many features of turbulent wakes, pipe flows and boundary layers can be described by applying RDT to homogeneous turbulence subjected to a uniform shear.

2.2.3 Compressibility effects

In the future, it is hoped to extend experimental work in the field of homogeneous shear flow to include compressibility. Recent studies have indicated that the main effect of compressibility on shear flow turbulence is an inhibition of the growth rate of turbulent kinetic energy.

Direct numerical simulation of compressible homogeneous shear flow was recently used to provide insight into compressibility effects on turbulence. Blaisdell et al. (1991) and Sarkar

et al. (1991) simulated flows with initial turbulent Mach numbers $M_{t,0}$ between 0.3 and 0.6, where $M_t = \sqrt{q^2}/\bar{a}$, and $\bar{a}$ is the mean speed of sound. They attribute the reduced turbulence growth rate to two factors: an increase in the compressible or dilatational dissipation rate due to the divergence of the velocity, and the pressure-dilatation correlation, which acts to transfer energy between internal (potential) and kinetic forms. Through visualization of the simulated flow field, Blaisdell et al. discovered the presence of eddy shocklets. These structures are believed to be important contributors to the increased dissipation rate, as substantiated by Lele et al. (1992).

Zeman (1992) evaluated a mathematical model for compressible homogeneous shear flow. The modelled turbulence is shown to approach an asymptotic, self-similar state in which the turbulent energy growth is exponential. However, the growth rate is significantly lower than that in incompressible flow, due to an elevated dissipation rate and the transfer of kinetic energy to pressure fluctuations. This result and others are shown to be in excellent agreement with the DNS studies mentioned above.

In support of numerical and analytical results, Samimy et al. (1992) provide experimental evidence for the reduction in turbulence growth rate due to compressibility in free shear flows. The measurements also indicate a significant drop in the normalized Reynolds shear stress and the lateral turbulence fluctuations.

A parameter to correlate compressibility effects in turbulent shear layers was identified by Bogdanoff (1983). This parameter was called the convective Mach number, M_c , by Papamoschou and Roshko (1988). In physical terms, M_c is the Mach number in a coordinate system convecting with the velocity of the dominant waves and structures of the shear layer. Several experimental investigations and numerical simulations have shown that the onset of compressibility effects occurs typically at $M_c \geq 0.5$.

2.3 Application to turbulent boundary layers

A main application of homogeneous shear flow is to serve as a simplified model and lead to a better understanding of more practical shear flows, such as turbulent boundary layers. In an exhaustive review of turbulent boundary layer structure and dynamics, Robinson (1991) notes that the majority of turbulence production in the entire boundary layer occurs in the inner region, particularly in the buffer layer between the viscous and logarithmic layers. Kinetic energy is produced during intermittent, violent outward ejections of low-speed fluid from the wall, and during intrushes of high-speed fluid at a shallow angle towards the wall. As a result, there is enormous interest in the structure of the inner turbulent boundary layer. A number of studies report inner layer measurements, although relatively few provide data in the viscous region very close to the wall. Some of these studies will be discussed in the following section.

2.3.1 Near-wall measurements in turbulent boundary layers

Although some similarity between homogeneous shear flows and the inner region of turbulent wall flows has been demonstrated numerically, the issue can be resolved conclusively only by experimental comparison. Measurements reported in the following studies will be used for this purpose.

Lu and Willmarth (1973), using a cross-wire probe, performed conditionally sampled measurements of the structure of the Reynolds stress across a turbulent boundary layer. Their findings indicated that the two largest contributors to Reynolds stress, and thus to kinetic energy, were bursts of low speed fluid ejected from the wall, and sweeps of high speed fluid towards the wall. They also found that the Reynolds stress correlation coefficient, $-\overline{u_1 u_2} / u_1' u_2'$, was nearly constant throughout the boundary layer and assumed a mean value of 0.44. This value agreed very well with the results of earlier studies, which ranged from 0.4 to 0.5, with an average of 0.45, in flows over flat plates, as well as through pipes and channels. However, the average reported by Lu and Willmarth was taken over just six data points, among which only two were measured in the inner layer, $y/\delta < 0.1$ (y and δ represent respectively the

perpendicular distance from the wall and the boundary layer thickness). There were no measurements within the viscous sublayer.

More recent measurements indicate that the correlation coefficient decreases very close to the wall. Chevrin, Petrie & Deutsch (1992) employed two laser-Doppler velocimetry systems to investigate the structure of the Reynolds stress in the near-wall region of a fully developed turbulent pipe flow. The use of glycerine as the working fluid permitted detailed measurements inside the viscous sublayer, by creating a relatively thick boundary layer. A two-component LDV and a one-component fibre-optics LDV were combined to measure the two-point spatial correlation, R_{12} , between the streamwise and radial velocities in a radial plane of the pipe. The use of LDV systems permitted small spatial separations without probe interference. Single-point statistics, obtained from both single-point and two-point measurements, extended over the region from y^* of 2 to 64. In all boundary layer studies discussed in this section, $y^* = yu_\tau/\nu$, where ν is the kinematic viscosity of the fluid and u_τ^2 is defined as the wall shear stress divided by the fluid density.

The LDV data of Chevrin et al. (1992) compared favourably with the split-film results of Herzog (1986), carried out earlier in the same facility. Excellent agreement was also demonstrated with Laufer's (1954) hot-wire measurements in a fully developed turbulent pipe flow, and with Eckelmann's (1974) hot-film results in a fully developed turbulent channel flow. Eckelmann used single and X-probes in an oil channel with a thick viscous sublayer, which permitted measurements in the range $0.8 \leq y^* \leq 300$. Measurements as close to the wall as at $y^* \approx 0.1$ were obtained with a hot-film wall element. The Reynolds stress data of Eckelmann and Chevrin et al. were shown to be consistent with the relation

$$-\frac{\overline{u_1 u_2}}{u_\tau^2} = \left[1 - \frac{y^*}{R^*} \right] - \frac{du^*}{dy^*} \quad (2.1)$$

which was first developed by Laufer (1954) from the equations of motion for a turbulent pipe flow. In equation (2.1), R^* is the pipe radius divided by ν/u_τ , and u^* is the mean

velocity divided by u_τ . The same relation was subsequently applied to a turbulent channel flow (Tennekes & Lumley 1972).

All the data clearly show that very near to the wall, the Reynolds shear stress, $\overline{u_1 u_2}$, approaches zero much faster than the product of the rms normal velocities, which are in the denominator of the correlation coefficient. Similar behaviour of the Reynolds stress correlation coefficient may therefore be expected in uniform shear flow at a comparably high shear rate. This supposition will be verified during the presentation and analysis of results in later chapters.

Chapter 3

Theory

3.1 Turbulent kinetic energy equation

The turbulent kinetic energy equation for the special case of nearly homogeneous uniform shear flow will now be developed. Here and throughout this study, x_1 , x_2 , and x_3 denote the streamwise, transverse or cross-shear, and spanwise directions respectively.

Consider a two-dimensional, steady rectilinear mean velocity of the form:

$$\begin{aligned}\bar{U}_1(x_2) &= \bar{U}_c + \left[\frac{d\bar{U}_1}{dx_2} \right] x_2 \\ \bar{U}_2 &= \bar{U}_3 = 0\end{aligned}\tag{3.1}$$

where the subscript c denotes conditions along the wind tunnel centreline. For uniform shear,

$$\frac{d\bar{U}_1}{dx_2} = \text{constant} \quad (3.2)$$

It is assumed that the flow is statistically stationary in a laboratory frame, with Reynolds stresses and pressure-velocity covariances which are uniform in the transverse (x_2-x_3) plane. The mean continuity equation is

$$\frac{\partial \bar{U}_1}{\partial x_1} = 0 \quad (3.3)$$

and the turbulent kinetic energy equation reduces to:

$$\begin{aligned} \bar{U}_1 \frac{\partial \left[\frac{1}{2} \overline{q^2} \right]}{\partial x_1} \approx & \\ & - \overline{u_1 u_2} \frac{d\bar{U}_1}{dx_2} - \frac{\partial}{\partial x_1} \left[\frac{1}{2} \overline{u_1 u_i u_i} \right] - \frac{1}{\rho} \frac{\partial}{\partial x_1} (\overline{u_1 p}) \\ & + \nu \frac{\partial^2}{\partial x_1^2} \left[\frac{1}{2} \overline{q^2} + \overline{u_1^2} \right] - \nu \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \end{aligned} \quad (3.4)$$

where $\overline{q^2}(x_1) = \overline{u_i u_i}$.

Experiments at low shear rates (Harris et al. 1977; Tavoularis and Corrsin 1981) have shown that the turbulent transport and viscous transport terms are typically less than 3% of the mean convection term. Since the turbulence would be increasingly dominated by mean shear as the shear rate increases, these two quantities are expected to be even less significant in the present flows, and may justifiably be neglected. Thus the turbulent kinetic energy equation can be further reduced to:

$$\bar{U}_1 \frac{d \left[\frac{1}{2} \overline{q^2} \right]}{dx_1} \approx - \overline{u_1 u_2} \frac{d\bar{U}_1}{dx_2} - \nu \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \quad (3.5)$$

The first term on the right hand side of the equation represents energy production,

$$P = -\overline{u_1 u_2} \frac{d\overline{U}_1}{dx_2} \quad (3.6)$$

while the second term is the mean turbulent kinetic energy dissipation rate:

$$\epsilon = \nu \overline{\frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j}} \quad (3.7)$$

3.2 Exponential growth law for the turbulent kinetic energy

Tavoularis (1985) has derived solutions to the kinetic energy equation for the asymptotic development state of the flow, where it is assumed that the turbulent structure evolves in a self-similar manner, and the various dimensionless structural parameters remain constant. A number of experimental studies have confirmed that the dimensionless Reynolds stress tensor, defined as:

$$K_{ij} = \frac{\overline{u_i u_j}}{\overline{q^2}} \quad (3.8)$$

does indeed have constant components, which do not vary appreciably among the various available experiments.

Along the centreline of the tunnel, where $\overline{U}_1 = \overline{U}_c$, (3.5) can be expressed as:

$$\frac{\overline{U}_c}{2} \frac{d(\overline{q^2})}{dx_1} \approx -K_{12} \overline{q^2} \frac{d\overline{U}_1}{dx_2} - \epsilon \quad (3.9)$$

The above can be arranged as follows:

$$\frac{d\overline{q^2}}{dx_1} = \left[\frac{-2K_{12}}{U_c} \frac{d\overline{U}_1}{dx_2} \left(1 - \frac{\epsilon}{P} \right) \right] \overline{q^2} \quad (3.10)$$

so that the turbulent kinetic energy equation is seen to have the simple exponential solution:

$$\overline{q^2} = \overline{q_r^2} e^{\left[\frac{-2K_{12}}{U_c} \frac{d\overline{U}_1}{dx_2} \left(1 - \frac{\epsilon}{P} \right) \right] (x_1 - x_r)} \quad (3.11)$$

where $\overline{q_r^2}$ is a reference value of the turbulent kinetic energy at a location $x_1 = x_r$ within the asymptotic region.

3.3 Some important scaling parameters

In an unbounded uniformly sheared flow, the sole externally imposed parameter is the value of the mean shear, which represents both the mean vorticity and the mean strain rate (Tavoularis and Karnik 1989). The inverse of the shear rate constitutes the timescale of mean shear or deformation, and can be described as the characteristic "straining" time:

$$\tau_s = \left[\frac{d\overline{U}_1}{dx_2} \right]^{-1} \quad (3.12)$$

The idealized concept of unbounded, transversely homogeneous shear flow precludes the existence of an external lengthscale or a velocity scale, thus preventing further non-dimensionalization. In laboratory approximations of such flows, however, it has been demonstrated (Rohr et al. 1988) that the centreline velocity is an appropriate scale for non-dimensionalizing the Reynolds stresses. This led Tavoularis and Karnik (1989) to define the flow generator constant,

$$k_s = \frac{1}{U_c} \frac{d\bar{U}_1}{dx_2} \quad (3.13)$$

as a scaling parameter whose value might have a qualitative effect on the turbulence structure.

As mentioned in Chapter 2, Harris et al. (1977) introduced the parameter

$$\tau = \frac{1}{U_c} \frac{d\bar{U}_1}{dx_2} (x_1 - x_r) \quad (3.14)$$

as a measure of total strain in a uniformly sheared flow, where the subscript r denotes some reference value. τ also represents the dimensionless time or distance downstream of a given reference point. Recalling the flow generator constant, the total dimensionless strain imposed upon the turbulence at a particular distance from the origin can be expressed simply as $\tau = k_s x_1$. In the present study, x_1 is measured from the exit of the shear generator. By substituting into equation 11, the exponential relation for the growth of kinetic energy becomes:

$$\bar{q}^2 = \bar{q}_r^2 e^{\left[-2K_{12} \left(1 - \frac{\epsilon}{P} \right) \right] \tau} \quad (3.15)$$

It appears logical to plot the downstream development of the turbulence characteristics in a uniform shear flow versus the total strain, τ .

The coefficient in the exponential law is defined as:

$$\kappa = -2 K_{12} \left[1 - \frac{\epsilon}{P} \right] \quad (3.16)$$

and will be determined experimentally from a least squares exponential fit of the turbulent kinetic energy plotted versus the total strain:

$$\bar{q}^2 = \bar{q}_r^2 e^{\kappa \tau} \quad (3.17)$$

Since K_{12} is a measurable quantity, the ratio of kinetic energy dissipation over production can also be determined from the data.

Another commonly used timescale is formed by the ratio of turbulent kinetic energy to dissipation rate,

$$\tau_u = \frac{\overline{q^2}}{\epsilon} \quad (3.18)$$

and represents the typical "lifetime" of the energy containing eddies, sometimes referred to as the eddy "turnover" time. This quantity can easily be calculated from the experimental data by using the value of ϵ/P , and noting that the rate of turbulence production can be expressed as:

$$P = -K_{12} \frac{d\overline{U}_1}{dx_2} \overline{q^2} \quad (3.19)$$

An alternative form of effective shear rate is obtained by using τ_u to non-dimensionalize the velocity gradient. The resulting parameter signifies the ratio of eddy "turnover" time to the timescale of mean deformation:

$$\left[\frac{d\overline{U}_1}{dx_2} \right] \frac{\overline{q^2}}{\epsilon} = \frac{\tau_u}{\tau_s} \quad (3.20)$$

In the direct numerical simulation study by Lee et al. (1990), this parameter was found to correctly indicate the dependence of turbulence structure on mean shear, both in a channel flow and in homogeneous shear flows. In Chapter 6, τ_u/τ_s will be used to compare the present uniform shear flow measurements with DNS results, as well as with experimental data from the near-wall region of turbulent boundary layers.

Chapter 4

Experimental Facility and Procedures

4.1 Facilities

4.1.1 The wind tunnel

All experiments were conducted in the 127 x 127 mm pilot wind tunnel at the High Speed Aerodynamics Laboratory (HSAL) of the National Research Council's Institute of Aerospace Research (IAR). This facility is a pressurized, continuous flow blowdown wind tunnel, capable of running in the subsonic, transonic and supersonic flow regimes, with the aid of interchangeable test sections. The pilot tunnel is a 1/12 scale aerodynamic model of the IAR 1.5 x 1.5 m (5 x 5 ft.) trisonic blowdown wind tunnel. A schematic drawing is shown in figure 1.

The pilot tunnel is supplied with compressed air at up to 21 atm from the 1 430 m³ storage tanks connected to the 1.5 m facility, which provides the means for continuous running. The air temperature in the settling chamber is stabilized via thermal matrices and is typically

about 21° C. During a run, air passes along pipes from the reservoir to an automatic pressure control valve, which maintains the settling chamber pressure at a constant, pre-selected value. From the settling chamber, the air passes through a number of turbulence reduction screens, a nozzle with a contraction ratio 10:1, and the test section. It then exhausts to the atmosphere via the variable geometry supersonic/subsonic diffuser, which is a two-dimensional duct with fixed top and bottom walls and articulated sidewalls.

For the present study, all measurements were made in the supersonic test section, which has a 127 mm square cross-section. Without the supersonic nozzle blocks on the side walls, subsonic flow in the range of approximately Mach 0.05 to 1.0 can be generated over a length of roughly 1 m. The shear generator was inserted between the contraction section and the entrance to the test section.

Since the desired stagnation pressure does not exceed 207 kPa (30 psia) for the shear flow tests, the wind tunnel operates most steadily, that is, with the least stagnation pressure fluctuation, when the air pressure in the storage tanks is at approximately 700 kPa or less. This permits the automatic pressure control valve to be more widely open than it would have been if the supply pressure were higher, which reduces the sensitivity of the feedback signal to small fluctuations. Control of the test section static pressure and, thus, the Mach number is achieved by manually adjusting the width of the variable geometry diffuser throat.

A rectangular cut-out in the test section ceiling enables the installation of either an eight-probe pitot rake, used for preliminary shear profile measurements, or a 31.75 mm thick glass window which measures 127 mm wide and about 254 mm long. The upstream edge of this opening is approximately 635 mm from the entrance of the test section, as sketched in figure 1.

An opening of similar size and location on the test section floor can accommodate a second window, permitting LDV measurements in forward scatter mode. However, this would require the simultaneous displacement of the laser source above the test section, and the photodetector below. Instead, the optical probe was used as both the light source and detector

in back-scatter mode, which simplified data collection and required only one window. A matte black plate was installed on the test section floor in order to reduce reflection of the laser beam.

4.1.2 The shear generator

The shear generator is housed in an aluminum frame which is bolted between the wind tunnel test section and the contraction section. A flow separator module is inserted into the frame to divide the flow into ten, 12.7 mm high, parallel channels. Up to two screens can be stretched across each channel in order to adjust the flow blockage locally. The main blockage is created by a 3.175 mm thick perforated aluminum plate which fits as a cover on the upstream face of the aluminum frame, locking the flow separator into place. The shear generator can be seen in figure 2.

The flow separator module is made of nine 0.792 mm (22 gauge) stainless steel plates which are held parallel between two 3.175 mm thick mild steel side plates. Both side plates have nine equidistant grooves into which the wide end of the T-shaped separator plates are epoxied. To obtain transverse uniformity of scales and to further straighten the flow, the separator plates extend 120.65 mm in the flow direction. At their narrow end, which protrudes 63.5 mm into the test section, the separator plates are supported between two 1.588 mm (1/16") thick grooved mild steel plates, in order to minimize vibrations, particularly at higher speeds. Aluminum blocks are placed between the plates at their wide end in order to reduce the width of each channel to that of the wind tunnel test section. A combination of blocks and screws can be used to clamp up to two screens or wires across each channel. If necessary, any channel can be completely blocked by a solid aluminum plug.

Each perforated cover plate is designed to fit against the separator plates, leaving no gap, while locking the entire separator module in place. Three different perforated plates were manufactured, each with ten 12.7 mm high rows of varying solidity. A large rectangular area cut out of the top of all three plates leaves the top two rows completely open, and the third row

blocked by a thin strip of material along the bottom of the channel. Slots were machined out of the fourth and fifth channel. Blockage of the bottom five channels was achieved by drilling eleven equally spaced holes of a given diameter across each channel.

The varying solidity, or fraction of blocked area, of cover plates #1 and #2 was selected empirically, roughly based on the results of Karnik and Tavoularis (1987). Initial velocity profile measurements using the first two cover plates suggested that a linear velocity profile might be obtained if the solidity of each channel varies roughly linearly from the top to the bottom of the shear generator. Cover plate #3 was designed in order to verify this hypothesis. Details and drawings of the shear generator components may be found in Appendix A.

4.2 Instrumentation

4.2.1 Pitot tube rake

An eight-probe Pitot tube rake, shown in figure 3, was used to obtain a preliminary velocity profile measurement of the shear flow. This permitted an assessment of the perforated plates, and indicated where fine tuning of the shear generator was required. The eight Pitot tubes were aligned with flow direction on the centreline of the test section, and spaced 12.7 mm apart in the vertical direction so that a reading could be taken at the centre of each flow channel, excluding the top and bottom channels. The protruding end of each tube measured 0.711 mm ID, 1.079 mm OD, and was located approximately 741 mm downstream of the test section entrance.

4.2.2 Laser-Doppler velocimetry system

Turbulence measurements such as root mean squared fluctuations, Reynolds stress tensors and velocity correlations were measured via laser-Doppler velocimetry (LDV). The system employs a three-beam, 100 mW Argon-Ion laser, connected to the measuring probe via fibre

optics, and can measure up to two velocity components simultaneously in either forward or back-scatter mode. Separation of the two components of velocity is achieved by colour, using the green (514.5 nm wavelength) and blue (488 nm) line of the Ar-ion spectrum. The system includes a frequency shifter, which permits the detection of reversing flow. Details on the physical and optical parameters of the laser system can be found in Appendix B.

The optical head of the laser was mounted on a two-dimensional manual traversing table over the glass window on the test section ceiling. This permitted accurate displacement of the measuring volume in the vertical and spanwise directions. Axial positions were located along rails fixed to the test section, onto which the traversing table could be mounted at any one of ten different downstream locations, spaced exactly 25.4 mm apart. The laser set-up is shown in figure 4.

The LDV system can measure simultaneously only the two components of velocity which are normal to the axis of the optical probe. Since windows can be installed on the test section ceiling or floor only, the axis of the incident beams is vertical, and hence it is not possible to measure the vertical component. However, because the shear generator is perfectly symmetric and can be rotated by 90 degrees, it is possible to measure all three velocity components in the sheared flow, two components at a time.

The streamwise (U_1), and spanwise (U_3) components can be measured when the shear generator is installed so that the direction of shear is vertical, and the streamwise and transverse (U_2) components can be measured when the shear generator is rotated by 90 degrees so that the shear is horizontal. This method may introduce some uncertainty in the measurements of turbulent kinetic energy, which will be discussed in the analysis of the results in Chapter 6.

4.2.3 Seeding system and particles

In order to obtain a signal from the laser-Doppler velocimeter, a suitable concentration

of tracer particles must be present in the flow. If such particles do not occur naturally, as for example in tap water, the flow must be seeded with an appropriate material.

In general, seeding particles must be small enough to follow the flow which is being measured, but large enough to scatter sufficiently the incident laser light. To help meet these requirements, the density of the seeding material should be as close as possible to that of the flow medium, and the refractive index should be as high as possible. Ideally, the seeding substance should be non-toxic and non-corrosive.

For the present measurements, a six-jet atomizer (TSI model 9306) was used to generate a spray of fine droplets of fairly uniform diameter from a liquid (figure 5). The atomizer was supplied with compressed air at 620 kPa. The seeding particles were introduced into the wind tunnel settling chamber immediately upstream of the contraction section via a 17.5 mm ID aluminum tube. The tube was connected to the atomizer by a short length of 25.4 mm ID flexible tubing reinforced with fibre netting.

The outlet of the aluminum tube was tailored to guide the seeding particles entering the flow into the freestream direction, as shown in figure 6. This was done by plugging the end of the tube and machining a side opening with a ball-nosed cutter. The height of the seeding tube outlet in the settling chamber could be manually adjusted, although it was most convenient and effective to keep the tube outlet fixed at the centre of the settling chamber, on the test section centreline axis.

Three different liquids were selected as possible seeding materials: olive oil, polyethylene glycol 400 and propylene glycol. All three have relatively low densities, high refractive indices and produce small mean particle size when atomized. Their relevant properties are listed below in table 1.

Table 1 Properties of selected seeding materials					
material	specific density	refractive index	vapour pressure	mean particle size (μm)	particle output conc. (parts/cc)
polyethylene glycol	1.11	1.45	very low	≈ 0.6	1.2×10^6
olive oil	0.913	1.47	very low	< 0.6	4.0×10^6
propylene glycol	1.04	1.43	101.3 kPa at 188°C	≈ 0.6	2×10^5

The first liquid to be tested, olive oil, was chosen for its very low vapour pressure, which leads to a high particle output concentration, its wide availability, low cost and low toxicity. The particle concentration was so high, however, that the test section window fogged up within minutes, obscuring the laser beams and preventing further data collection. Even during a single data profile, using olive oil required frequent cleaning of the test section walls and window. This necessitated removing the test section window, and/or disconnecting the test section from the tunnel, both of which are very time consuming.

As an alternative, polyethylene glycol 400, which has a lower particle output concentration, low toxicity and is water soluble, was tested. Cleaning was required slightly less often and was easier due to water solubility, however it was still required too often for practical purposes.

Finally, propylene glycol was selected as the best material for the present experiments. Its high vapour pressure results in a lower particle output concentration and greatly reduces fogging of the test section. Although the data rate was lower than that using the previous materials, total testing time decreased significantly due to reduced need for frequent cleaning. In addition, propylene glycol is water soluble, it is the least toxic of the three substances, and it has a lower specific density than polyethylene glycol.

The formation of fog on the test section window and walls was the main problem

encountered in seeding the flow. Fogging occurred as a result of the relatively small test section, but mostly because many of the particles were trapped upstream of the variable geometry diffuser throat, which was reduced to a very small cross sectional area in order to attain the Mach number required for the present tests.

The test section window was observed to fog up more rapidly when the shear was oriented horizontally, particularly on the high velocity side of the tunnel. For the vertical shear measurements, therefore, the shear generator was installed so that the high velocity region was towards the floor of the test section, in order to keep the window as clean as possible.

4.2.4 Data acquisition and processing

4.2.4.1 Preliminary measurements

All preliminary shear profile measurements using the pitot tube rake were acquired using the HSAL pilot tunnel acquisition system and programs. The pitot tubes were connected to eight ± 69 kPa (10 psi) differential transducers. These total pressures were referenced to the flow static pressure, measured from a tap on the test section roof located approximately 754 mm downstream of the test section entrance.

The resulting eight dynamic pressure signals, the tunnel total and static pressure measured by a piezoelectric (Digiquartz) transducer, and the ambient pressure were acquired simultaneously using the program VALUE on a VAX workstation. To obtain a reasonable average, between three and five data scans of all nine channels were taken during each run, with each scan consisting of 100 data points per channel. A schematic diagram of the data acquisition set-up is shown in figure 7.

After each run, the program VALUE created a data file in ASCII form, containing the pre- and post-tare of each channel and the uncorrected readings for each scan. These files were transferred to a personal computer and imported into LOTUS-123 for processing.

4.2.4.2 Turbulence measurements

The DANTEC FLOWare software, run on an IBM 386 PC, provided the means for all data acquisition and much of the initial data processing using the laser-Doppler velocimeter. A number of computer programs, provided in Appendix C, were written for further processing and calculation of turbulence statistics. Data was also imported into graphical software programs such as LOTUS-123 and Easyplot for viewing, curve-fitting and plotting.

4.3 Experimental procedure

4.3.1 Measurements with the Pitot tube rake

4.3.1.1 Pitot tube rake response in the empty tunnel

Prior to the measurement of the velocity profile obtained with the shear generator, a profile was taken by the rake in the empty wind tunnel with the downstream throat set for Mach 0.1, in order to detect the nature of any possible error introduced by the pitot tubes or transducers. For each probe the measured velocity was non-dimensionalized using the tunnel velocity. The latter was calculated from the tunnel dynamic pressure, measured by a piezoelectric (Digiquartz) transducer, and was assumed to be uniform throughout the tunnel. It was found that the velocity calculated from the rake and the static tap dynamic pressure varied only slightly in the transverse direction, as can be seen in figure 8, from 98 to 102% of the tunnel velocity.

In an attempt to determine the rake response under various conditions, empty tunnel profiles were taken at seven values of tunnel velocity, which were set by adjustment of the downstream throat. At each velocity, or throat configuration, the tunnel total pressure was varied between 165 and 207 kPa (24 and 30 psi), in steps of approximately 14 kPa (2 psi).

Attempts to generate flow at Mach 0.05 were unsuccessful because the throat was almost

completely closed, causing large fluctuations in the tunnel static pressure. This, coupled with the usual unsteadiness in the tunnel total pressure which occurs when the air supply pressure is above 700 kPa, resulted in highly fluctuating and virtually meaningless dynamic pressures.

With the wind tunnel throat set for Mach 0.1, unsteady total pressure caused the actual Mach number to fluctuate between 0.073 and 0.121. The Mach number became more stable as time passed, which happened to coincide with the increase in total pressure. This is why deviations in rake velocities from the tunnel velocity were fairly large at low total pressure, but gradually decreased with increasing total pressure. It is likely that deviations were a result of sensitivity to fluctuations in the total pressure, rather than to the value of total pressure.

The above hypothesis was confirmed from the rake profiles at higher Mach numbers, where deviations of rake velocity from tunnel velocity showed no particular dependence on total pressure or Mach number. In fact, although the total pressure at different Mach numbers, and the Mach numbers themselves were both increased and decreased with time, the deviations from tunnel velocity became progressively smaller with time, excluding the effect of very slight uniform drift of all the transducers. This coincided with the increasing stability of the tunnel total pressure with time. In addition, the transverse uniformity of the eight measured velocities gradually increased with time, and it appeared that the outputs of all tubes would eventually have collapsed onto a single value in the absence of transducer drift.

The empty tunnel rake profiles, as well as the sequence in time of Mach numbers and total pressures, are shown in figure 9. At steady tunnel conditions, the measured velocity varies by approximately $\pm 1\%$ of the actual tunnel velocity. The above results indicate that the Pitot tube rake can provide fairly accurate measurements, if care is taken to obtain a steady tunnel total pressure. This can be achieved by running the wind tunnel when the pressure in the air reservoir is below 700 kPa, and by waiting a sufficient amount of time for the flow to stabilize.

4.3.1.2 Preliminary measurement of shear flow velocity profiles

The first velocity profile measurements via the eight-probe Pitot tube rake were made using perforated cover plates #1 and #2 in the shear generator, with no additional blockage. The adjustable downstream throat was set so as to obtain Mach 0.1 in the empty wind tunnel. The resulting centreline speed $\bar{U}_c$ with the shear generator installed was 35.5 m/s using cover plate #1 and 32.1 m/s using cover plate #2. The velocity profiles obtained using both cover plates were fairly linear, as can be seen in figure 10. According to the empty tunnel profiles, the measured velocity should be within about one percent of the actual velocity.

During preliminary tests, the top two plates of the flow separator module were bent during a run at $\bar{U}_c = 47.2$ m/s, a speed achieved by setting the empty tunnel Mach number to 0.15. The epoxy bond between the top few separator plates and the supporting side plates also began to fail, although the velocity profile remained fairly linear and constant, as figure 10 depicts. The failure was possibly the result of an error in manufacturing. The separator plates were designed to be 0.792 mm stainless steel, but 0.559 mm stainless steel was used instead.

The flow separator module was rebuilt according to the design for use in all subsequent tests. Due to the potential fragility of the shear generator at high speeds, however, it was decided to limit the empty tunnel Mach number to 0.1.

With the downstream diffuser throat set for a freestream Mach number of 0.1, eight more preliminary runs were performed, beginning with a velocity profile with no shear generator installed. The first three shear profiles were measured with cover plates #1, #2 and #3 in the shear generator. The subsequent three runs were identical to the previous ones, but with the bottom (lowest velocity) channel blocked in an attempt to reduce the flow rate in the low velocity region of the profile. Spanwise uniformity of the flow was measured by rotating the shear generator by 90 degrees while leaving the pitot rake vertical. Only cover plate #3 was used for this run.

Based on fairly satisfactory results, which are presented in more detail in the following chapter, it was decided to begin detailed turbulence measurements of the uniform shear flow obtained with the shear generator in configurations similar to those tested preliminarily.

4.3.2 Turbulence measurements using the LDV system

Prior to LDV measurements, the optical probe was carefully aligned using a high precision gauge block, so that the 488 nm (blue) beam measured the streamwise component and the 514.5 nm (green) beam measured the horizontal component. The exact coordinates of the point of intersection of the blue, green and reference beams, which constitutes the probe measurement volume, were then determined within approximately 0.3 mm. The measurement volume is ellipsoidal, with its major axis parallel to that of the optical probe. Its extent can be described by its height, h_m , and its maximum diameter in the plane of measurement, d_m . The intersection of the blue and reference beams form the U_1 measurement volume, which has the dimensions $h_m = 1.1725$ mm and $d_m = 0.0736$ mm. Similarly, the intersection of the green and reference beams form a measurement volume of dimensions $h_m = 1.2362$ mm and $d_m = 0.0776$ mm for the second velocity component.

4.3.2.1 Flow uniformity in empty tunnel

Five different uniformly sheared flows were created by varying the configuration of the shear generator and the mean tunnel velocity. For each case, the variable diffuser throat was adjusted for the desired Mach number before installing the shear generator, and an empty tunnel run was performed to measure the baseline velocity. Throughout these and all subsequent tests, the wind tunnel total pressure was set to 165 kPa (24 psi). At the first two Mach numbers, a horizontal profile was taken at $x_1/h = 6.0$ on the centre plane of the test section. Measurements were taken at three positions ($x_1/h = 5.2, 6.0$ and 6.8) along the axial centreline of the test section for all but the second flow case.

Mean velocity profiles in the empty tunnel, shown in figure 11, appear to be fairly

uniform. However, scatter in the turbulent fluctuations, plotted in figure 12, suggests either some fluctuations in the empty tunnel or noise in the data acquisition system. The large discrepancies seem to be random, as there is no apparent relationship linking the magnitudes of the fluctuations with either the mean tunnel velocity or the location of measurement. Inspection of the time series of the fluctuating velocity in the empty tunnel (figure 13), as well as in the shear flow (Appendix C), indicated the presence of large random spikes. These spikes were sometimes upwards of the mean velocity, but were far more often downwards, indicating a "drop out" in the LDV signal. The biased distribution of spurious noise is also evident in the shear flow velocity histograms, some of which appear in Appendix C. There appears to be little explanation for the high velocity spikes. However, according to DANTEC staff (private communication), "drop out" in the LDV signal would likely be caused by droplets of the seeding liquid attached to and obscuring the test section window.

There appears to be no correlation between the noise in the streamwise and spanwise components. This is confirmed by the fact that the covariance and correlation coefficient of the streamwise and spanwise velocity, plotted in figure 14, was almost always close to zero, despite the large variations in the individual velocity components. Therefore, random noise should not affect significantly the measurement of covariances in the sheared flow. Following evaluation of the various correction procedures, it was concluded that random noise could be eliminated by rejecting individual data samples which lie further than 2.5 standard deviations from the mean. Computer programs written to perform this task are presented in Appendix C. The corrected empty tunnel data are included in figures 11, 12 and 14.

Although it is possible to correct for random noise in the data signal, other sources of error exist. One such source is the turbulence inherent to the wind tunnel. Ideally, the flow should be laminar throughout the test section in the absence of obstructions. In reality, there is always a certain level of turbulence in the empty tunnel, which can be caused, for example, by pressure or temperature fluctuations in the air supply, by irregularities on the inside surface of the nozzle or test section, and by the wake of the tube used for seeding the flow. The turbulent fluctuations generated by these, often uncontrollable, "external" factors, may also be

present during the shear flow measurements, and may therefore affect the results. The "free" tunnel turbulence will be strongly distorted by the shear generator, so that it is impossible to separate it from the turbulence produced by the uniform shear. The following analysis constitutes an attempt to estimate upper bounds for the various errors in the measured velocity statistics.

Any turbulent fluctuation measured in the shear flow, u_{im} , can be separated into two components: the fluctuation produced by the uniform shear, u_{is} , plus the fluctuation due to other, or external, factors, u_{ie} . These relations are shown in equation (4.1).

$$\begin{aligned} u_{1m} &= u_{1s} + u_{1e} \\ u_{2m} &= u_{2s} + u_{2e} \end{aligned} \quad (4.1)$$

The mean-squared velocity fluctuations and dominant covariance can then be expressed as:

$$\begin{aligned} \overline{u_{1m}^2} &= \overline{u_{1s}^2} + \overline{u_{1e}^2} + 2\overline{u_{1s}u_{1e}} \\ \overline{u_{2m}^2} &= \overline{u_{2s}^2} + \overline{u_{2e}^2} + 2\overline{u_{2s}u_{2e}} \\ \overline{(u_1u_2)_m} &= \overline{(u_1u_2)_s} + \overline{u_{1s}u_{2e}} + \overline{u_{2s}u_{1e}} + \overline{(u_1u_2)_e} \end{aligned} \quad (4.2)$$

In general, the fluctuations due to external factors is uncorrelated with the shear flow turbulence. Therefore, the cross covariances of the shear turbulence and external fluctuations are assumed negligible:

$$\overline{u_{1s}u_{1e}} \approx \overline{u_{2s}u_{2e}} \approx \overline{u_{1s}u_{2e}} \approx \overline{u_{2s}u_{1e}} \approx 0 \quad (4.3)$$

The measured rms fluctuations and covariance then take the forms:

$$\begin{aligned}
\left(\overline{u_{1m}^2}\right)^{\frac{1}{2}} &= \left(\overline{u_{1s}^2} + \overline{u_{1e}^2}\right)^{\frac{1}{2}} \\
\left(\overline{u_{2m}^2}\right)^{\frac{1}{2}} &= \left(\overline{u_{2s}^2} + \overline{u_{2e}^2}\right)^{\frac{1}{2}} \\
\overline{(u_1 u_2)_m} &= \overline{(u_1 u_2)_s} + \overline{(u_1 u_2)_e}
\end{aligned} \tag{4.4}$$

There was no direct way to measure the turbulence caused by external factors in the sheared flow. However, since the turbulence intensities in the empty tunnel were measured at the baseline velocity of each shear flow, the maximum reduction in correlation could be estimated for all experiments. This method assumed that, for a given tunnel velocity, the turbulence measured at selected locations in the empty tunnel was produced throughout the corresponding shear flow, which obviously represents the worst possible situation.

The empty tunnel rms fluctuations and turbulence intensities, corrected for random noise, are listed in table 2. They were used as the "external" quantities in (4.5), in order to calculate an upper bound for the Reynolds stress correlation coefficient measured in each shear flow. These values were determined by using the measurements presented in Chapter 5, and are listed in Chapter 6.

$$\left| \frac{\overline{u_1 u_2}}{\overline{u_1' u_2'}} \right| \leq \frac{\overline{(u_1 u_2)_m}}{\left(\overline{u_{1m}^2} - \overline{u_{1e}^2}\right)^{\frac{1}{2}} \left(\overline{u_{2m}^2} - \overline{u_{2e}^2}\right)^{\frac{1}{2}}} \tag{4.5}$$

Note that the covariance of external turbulence is not subtracted from the numerator of (4.5). One reason is that this covariance was relatively small in the empty tunnel, as shown in figure 14, and therefore could be assumed to behave similarly in the shear flow. In addition, subtracting this small quantity would tend to reduce the value of the right hand side of (4.5). Since (4.5) represents an upper bound, the covariance of external turbulence could be safely neglected.

Table 2 RMS turbulent fluctuations in empty tunnel				
Flow case	$\bar{U}_1$ (m/s)	u_1' (m/s)	u_2' (m/s)	$u_1'/\bar{U}_1$
1	35.8	2.11	1.12	0.059
2	37.8	2.22	1.15	0.059
3	45.6	2.29	1.39	0.050
4	40.4	1.32	1.05	0.033
5	55.8	2.48	1.44	0.044

4.3.2.2 Measurements in uniformly sheared flow

4.3.2.2.1 Set-up of wind tunnel and shear generator

The first set of measurements was obtained with plate #1 in the shear generator and the empty tunnel centreline speed set to 36 m/s. Next, the empty tunnel speed was increased slightly to 38 m/s and plate #2 was installed. In an attempt to reduce the curvature observed in the low speed region of the preliminary profile, channel 2 of the flow separator was blocked instead of channel 1. For the third shear flow, the empty tunnel speed was set to 46 m/s and plate #3 was used while blocking channel 1. A second test of plate #2 followed, with the tunnel speed reduced to 40 m/s in order to accommodate the high speed end of the steep plate #2 profile. Since blocking channel 2 caused waviness in the low speed portion of the second shear flow profile, only the first channel of the flow separator was blocked for this case. For the last shear flow, the empty tunnel speed was increased to 55 m/s and plate #1 was installed. Although this was approximately the speed at which the first flow separator began to fail, the improved model suffered no damage, and could likely withstand even higher speeds.

4.3.2.2.2 Data collection

In general, six continuous data collection runs were performed for each shear flow. These consisted of a streamwise (x_1 direction), a transverse (x_2 direction) and a spanwise (x_3 direction) profile, with the shear generator oriented vertically and horizontally. The data was stored temporarily on the 40 megabyte hard disk drive of the personal computer used for data acquisition, and then transferred to 2 megabyte flexible disks.

The transverse profile run was comprised of profiles at three downstream locations. At each streamwise position, data points were taken at intervals of 5 mm, to establish the shear rate as accurately as possible. The data acquisition system was instructed to stop after collecting 500 valid samples, but the time limit at each point was set to 20 sec because of the large number of measurement points (73 with vertical shear orientation) required for the run. Due to low data rates, the time limit was sometimes reached before the required number of samples was collected. This often occurred when the shear was oriented horizontally, due to fog on the test section window. Therefore, the horizontal shear profiles were relied upon less to determine the shear rate, and as a result data points were sometimes spaced at larger intervals. With the shear generator oriented vertically, enough samples were collected to obtain an acceptable mean velocity profile.

During a spanwise profile run in both shear generator orientations, data profiles were taken at two and sometimes three streamwise stations, with measurement points at intervals of typically 10 mm. The data acquisition parameters were the same as those for the transverse profiles.

The most important data runs were those to measure the downstream development of the turbulence. For both horizontal and vertical shear orientations, ten measurement points were taken along the centreline of the test section, from $x_1/h = 5.2$ to $x_1/h = 6.8$, at intervals of 25.4 mm. For the first shear flow using plate #1, the time limit was set to 60 sec at each point. The measurements were repeated in a different order to ensure that no time effects were

present. Although the measurements appeared independent of time, they exhibited significant scatter. For subsequent tests, therefore, data acquisition at each point was halted only after 1000 valid samples were collected.

In addition to the above, measurements of downstream development in the last shear flow (generated by plate #1 at an empty tunnel speed of 55 m/s) were also taken approximately halfway between the centreline and the wall, on the low velocity side of the test section. The purpose of this was to increase the flow generator constant, k_f , and thus the flow development time, by centering the shear flow measurements around a lower mean velocity. Due to a very low data rate at this location, however, only 400-500 samples were collected at each point.

4.3.2.2.3 Final data processing

It is again emphasized that the most crucial measurements in the present study are those of downstream turbulence development. Therefore, these data were filtered to remove random noise which persisted despite hardware and software signal level validation in the LDV system. This procedure was not performed for the transverse and spanwise profile measurements of flow uniformity, due to the large number of data points that it would have been necessary to process (up to 73 points for transverse profile data runs).

For transverse and spanwise profile runs, the mean and rms fluctuation of velocity at each measurement point were calculated by FLOWare. This data was then imported into LOTUS-123, where it was non-dimensionalized and prepared for input into Easyplot. Plotting, as well as straight line fits of mean velocity profiles to determine the shear rate, $d\bar{U}_1/dx_2$, were performed with Easyplot for each flow case.

Mean and rms values for downstream development runs were calculated independently by the program "stat", which read exported FLOWare files containing all the velocity samples collected at each measurement point. To eliminate noise, the program rejected data samples further than 2.5 standard deviations from the mean. It then converted the data to non-

dimensional form, and created an output file to be read into Easyplot for graphical presentation. Easyplot was also used to perform a least squares fit to the turbulent kinetic energy, in order to determine its exponential growth rate.

The program "turb" read the output files from "stat", and computed averages for the constant coefficients K_y and the Reynolds stress correlation, using only values within two standard deviations from the mean. Using the equations of Chapter 3, as well as the previously determined velocity gradient and kinetic energy growth rate for each case, the program "turb" calculated turbulence statistics, such as the ratio of dissipation to production, and the dimensionless effective shear rate.

The final results are presented in tabular and graphical form in the following chapter. Source listings of the computer programs, "stat.f" and "turb.f", can be found in Appendix C.

Chapter 5

Measurements and Presentation of Results

5.1 Mean velocity profiles with the Pitot tube rake

The results of the preliminary mean velocity measurements introduced in section 4.3.1.2 are now presented. Velocity profiles obtained using plates #1, #2 and #3 in the shear generator (after the flow separator was rebuilt according to the original design) are shown in figure 15. The greatest deviation from linearity occurs in the low velocity region of the shear flow, where the blockage is greatest. This is particularly evident in the plate #2 profile. As an initial remedy, velocity profiles were measured once again with each plate, while completely blocking the bottom (highest blockage) channel of the shear generator.

Figure 16 indicates that blocking the bottom channel does not improve the linearity of the profile, but increases the shear rate significantly. The flow with the most linear profile, but also the lowest shear rate, is produced by plate #1 with no additional blockage. Both shears generated by plate #2 appear to be uniform over approximately 60% of the test section. The latter flow is preferred due to higher shear, although considerable deviation from linearity in the

low velocity region of the profile is still apparent. Plate #3 was designed so that the solidity of each channel would vary linearly across the shear generator with the bottom channel blocked. This configuration seems to yield the best combination of uniformity and high rate of shear.

Spanwise variation of velocity appears to be well within $\pm 10\%$ of the average value, although it was only measured for plate #3 (figure 17). Further measurements of spanwise and transverse flow uniformity were performed via LDV, and are presented in the section 5.2.2.

5.2 Turbulence measurements via LDV

5.2.1 Uniformity and rate of shear

Profiles of the streamwise mean velocity along the transverse (x_2) direction are plotted at three downstream locations in figures 18 to 22, for each of the five shear flows. Similar to the preliminary Pitot rake measurements, plate #1 produced the most linear velocity profile, but the lowest shear rate.

Blocking the second to last channel in an attempt to further reduce the flow in the low velocity region of the plate #2 profile seems to have caused slight waviness in this area, as shown in figure 19. The profile improved when plate #2 was tested again with the bottom channel of the shear generator blocked. In fact, the low velocity region appeared to be more linear than it was in the preliminary tests, as seen in figure 21.

The highest shear rates were obtained using plates #2 and #3, while blocking the bottom channel of the shear generator. These configurations generated fairly uniform shear as well. The relatively larger scatter in the low velocity region of figure 21 was the result of an insufficient data rate, as the very high shear directed most of the seeding particles towards the high velocity region of the flow. High shear also necessitated extremely low velocity close to one wall. Therefore, these measurements were in the low end of the velocity range detectable

by the LDV system, which may have reduced their accuracy.

The flow with the highest centreline velocity was generated using plate #1 (figure 22). The velocity gradient appears constant throughout most of the flow, but seems to level off in the high speed region. This was not actually the case, but was due to the fact that these high velocity readings were beyond the range of the LDV system. Based on the first shear flow of plate #1, it can be assumed that the shear is uniform throughout the test section.

Table 3 lists the five cases of uniformly sheared flows generated in the present study, with the corresponding shear rates, mean centreline velocities and flow generator constants. Case #6 refers to the same shear flow as in case #5, but for which measurements of downstream development were taken at $x_2/h = 0.236$, rather than on the centreline of the test section. During the course of the experiments, variation of the mean centreline velocity for each case was usually very small and rarely exceeded 1 m/s.

Table 3 Summary of uniform shear flows				
Case	Description	$\bar{U}_c$ (m/s)	$d\bar{U}_1/dx_2$ (s ⁻¹)	k_s (m ⁻¹)
1	Plate 1	35.1	436	12.4
2	Plate 2 (ch.2 blkd)	34.1	665	19.5
3	Plate 3 (ch.1 blkd)	44.6	705	15.8
4	Plate 2 (ch.1 blkd)	38.8	705	18.2
5	Plate 1	54.7	646	11.8
6	Plate 1 ($x_2/h=0.236$)	35.2	646	18.3

5.2.2 Homogeneity of flow

Measurements to assess the degree of homogeneity of the shear flow in the plane perpendicular to the streamwise direction are now reported. The cross-section $x_1/h = 6.0$, located exactly midway along the streamwise range of data collection, was found to be representative of the entire measurement region.

Figures 23 and 24 depict the transverse (x_2) and spanwise (x_3) variation of the three mean velocity components for each flow case. The cross-shear (U_2) and spanwise (U_3) mean velocity components appear fairly constant and close to zero in the profiles of figure 23. There is slightly more scatter in the spanwise profiles of these components (figure 24), particularly in shear flow cases #2, #3 and #4.

The distribution of streamwise mean velocity (U_1) across the test section span seems to be most uniform in shear flow cases #1 and #5, which were generated with plate #1. The plate #2 flows exhibit the most variation in freestream velocity along the spanwise axis. In the central portion of the test section, however, this variation is limited to approximately $\pm 4\%$ and $\pm 8\%$ of the centreline value, for cases #2 and #4 respectively.

Transverse and spanwise variations of the rms velocity fluctuations at $x_1/h = 6.0$ are plotted for all shear flow cases in figures 25 to 27. Profiles of all three rms components along the x_2 axis are shown in figure 25, while x_3 profiles are presented in figure 26.

Although the relative magnitudes of the turbulent fluctuations throughout most of the test section appear to be consistent with previous measurements in shear flows, namely in the order $u_1' > u_3' > u_2'$, there is significant variation in the data. The greatest variation seems to occur in the streamwise component across the shear, which may indicate that the flow is not completely developed at this point of the test section. The streamwise fluctuation is least uniform across the shear flows generated with plate #2. The rms fluctuations appear to be more uniform across the span of the test section, as shown in figure 26, although a small degree of

scatter is also present in these measurements.

In order to provide an indication of downstream evolution, figure 27 depicts the transverse variation of the streamwise fluctuation at three downstream locations. The results appear to contain too much scatter to identify any definite trends.

Finally, the transverse variation of the Reynolds stress correlation coefficient is plotted at three downstream locations for all shear flows in figure 28. Although deviations are present, the profiles appear fairly uniform near the centre of the test section. Again, the validity of any other conclusions drawn from these results would be limited due to the high scatter.

It is important to note that compared to the downstream development runs, much fewer data samples were collected during the transverse and spanwise runs, due to the large number of measurement points and the limited time. In addition, as explained in the previous chapter, data from these runs were not post-processed to remove extraneous noise. The effect of random noise is often cancelled out in a large group of samples, but it becomes significant at measurement points where very few data samples are collected, such as those in the low velocity region where fewer seeding particles were present. Therefore, some of the scatter in the figures, especially that which appears as random spikes, is possibly caused by insufficient data sampling as well as by spurious noise. As the figures show, rms velocity fluctuations are affected more by these factors than are the mean velocities, as the former require a larger sampling size in order to yield a good statistical average.

In summary, the shear flows produced with plate #1 possess the highest degree of homogeneity in the x_2 - x_3 plane, as well as the most uniform shear. The plate #2 flows are the least homogeneous. Considering the factors discussed in the previous paragraph, it can be concluded that the uniformity of shear, the homogeneity of the turbulence intensities and the two-dimensionality of the mean velocity for the range of flows generated are adequate for the present purposes.

5.2.3 Downstream turbulence development

The streamwise development of the four dominant Reynolds stresses and the turbulent kinetic energy are plotted in figure 29. Semilogarithmic coordinates were used to facilitate identification and determination of exponential growth rates. Values which have been reported in the literature to remain essentially constant along the streamwise axis, such as the Reynolds stress correlation coefficient and the ratios of Reynolds stress over kinetic energy, are plotted on linear axes in figure 30.

The most important feature of figure 29 is the roughly linear region of positive slope on all the plots, indicating asymptotic exponential growth of the Reynolds stresses and turbulent kinetic energy. For each shear flow case, the rates of growth of all the stresses away from the origin were roughly the same. The ordering of the Reynolds stresses was always $\overline{u_1^2} > \overline{u_3^2} > \overline{u_2^2} > |\overline{u_1 u_2}|$.

On average, the non-dimensional Reynolds stresses plotted in figure 30 do not change appreciably with downstream distance. The graphs reveal a slightly wider variation of the Reynolds stress correlation coefficient, from within 12% of the mean value for case #6, to as much as 39% of the mean for case #2. However, the general trend for this quantity appears constant as well.

The relatively low degree of scatter in the data can be attributed to the large sample size at each measurement point (typically 1000 samples), in support of the discussion of the previous section. For further accuracy, the results presented in figures 29 and 30 were filtered to remove extraneous noise, which amounted to less than 1.4% of all data, using the procedure outlined in Chapter 4. Unfiltered data from the streamwise profiles can be found in Appendix C for comparison with the above. Appendix C also includes examples of varying the window of data acceptance (ie. the number of standard deviations beyond which to reject samples), and selected plots of shear flow velocity time series and histograms depicting random noise in the signal.

5.2.4 Effect of rotating the shear generator by 90°

As discussed in section 4.2.2, the LDV system is only capable of measuring two velocity components at a time. Therefore, in order to obtain all three components, the shear generator was rotated by 90°. Since the streamwise velocity component was measured in both orientations of shear, vertical and horizontal, the variation introduced by this procedure can be evaluated.

Figures 31 to 33 permit comparison between the streamwise component measured in horizontal and vertical orientation of the shear flow of case #3. In figure 31, mean and rms values, obtained during measurement of downstream turbulence development, are plotted on a streamwise profile along the centreline of the test section. Figure 32 illustrates the variation of streamwise mean and rms velocity with orientation of shear, measured along a cross-shear profile. Spanwise profiles are shown in figure 33.

As expected, agreement is best in the downstream development runs, due to the large number of data samples collected in order to obtain a good statistical average at each point. With this in mind, it can be concluded that the procedure of rotating the shear generator to obtain measurements in three dimensions, although not ideal, yields acceptable results.

5.3 Turbulence statistics

The non-dimensional Reynolds stresses and other turbulence characteristics for each shear flow are presented in Tables 4 and 5. For comparison, values obtained from data which were not filtered to remove samples beyond 2.5 standard deviations from the mean are included in parentheses. Experimental uniform shear data from the literature (TC: Tavoularis & Corrsin 1981; TK: Tavoularis and Karnik 1989; HT: Holloway and Tavoularis 1992) are also included for comparison. Previous data from flows whose structure was complicated by the presence of grids downstream of the shear generator are omitted. Analysis and discussion of the results presented here follow in Chapter 6.

Table 4 Non-dimensional Reynolds stresses						
Case	$d\bar{U}_1/dx_2$ (s ⁻¹)	k_s (m ⁻¹)	K_{11}	K_{22}	K_{33}	$-K_{12}$
1	436	12.4	0.50 (0.54)	0.20 (0.18)	0.30 (0.28)	0.093 (0.091)
2	665	19.5	0.54 (0.57)	0.19 (0.18)	0.27 (0.25)	0.105 (0.107)
3	705	15.8	0.47 (0.53)	0.23 (0.20)	0.30 (0.27)	0.106 (0.105)
4	705	18.2	0.55 (0.59)	0.20 (0.19)	0.25 (0.22)	0.121 (0.117)
5	646	11.8	0.44 (0.52)	0.23 (0.20)	0.33 (0.28)	0.109 (0.100)
6	646	18.3	0.55 (0.59)	0.20 (0.18)	0.25 (0.23)	0.120 (0.119)
A (TK)	84	6.56	0.55	0.20	0.25	0.165
B (TK)	60	6.56	0.56	0.20	0.24	0.165
C (TK)	43.5	7.21	0.59	0.19	0.22	0.165
TC	46.8	3.77	0.53	0.19	0.28	0.14
PA (HT)	65	6.7	0.498	0.202	0.300	0.135
NA (HT)	64	6.3	0.495	0.201	0.304	0.143

Table 5 Turbulence characteristics					
Case	$-\overline{u_1 u_2} / u_1' u_2'$	κ	ϵ / P	$\tau_u = \overline{q^2} / \epsilon$ [s]	τ_u / τ_s
1	0.303 (0.288)	0.095 (0.083)	0.491 (0.549)	0.0500 (0.0457)	21.8 (19.9)
2	0.362 (0.388)	0.084 (0.082)	0.603 (0.617)	0.0237 (0.0228)	15.7 (15.2)
3	0.329 (0.333)	0.070 (0.072)	0.667 (0.654)	0.0201 (0.0207)	14.2 (14.6)
4	0.364 (0.354)	0.074 (0.080)	0.694 (0.658)	0.0168 (0.0185)	11.9 (13.0)
5	0.340 (0.320)	0.107 (0.065)	0.509 (0.676)	0.0278 (0.0228)	18.0 (14.7)
6	0.377 (0.386)	0.071 (0.095)	0.707 (0.599)	0.0182 (0.0217)	11.7 (14.0)
A (TK)	0.49	0.090	0.72	0.10	8.4
B (TK)	0.49	0.095	0.72	0.14	8.4
C (TK)	0.49	0.091	0.73	0.19	8.3
TC	0.44	0.122	0.57	0.27	12.5
PA (HT)	0.426	0.098	0.64	0.18	11.57
NA (HT)	0.453	0.083	0.71	0.15	9.86

Chapter 6

Analysis and Discussion of Results

6.1 Compressibility effects

The studies reviewed in section 2.2.3 indicate that compressibility has very pronounced effects on the turbulence growth rate and Reynolds stresses in simulated homogeneous shear flow. In experimental turbulent shear layers, effects such as these were present only when the convective Mach number, M_c , exceeded approximately 0.5. This parameter was defined for two-stream turbulent shear layers, but an upper bound for its value can be estimated for the present uniform shear flows, in order to determine whether compressibility may have had an effect on the results.

The compressible Mach number of a two-stream turbulent shear layer was defined by Papamoschou and Roshko (1988) as follows:

$$M_c = \frac{\bar{U}_1 - \bar{U}_c}{a_1} \quad (6.1)$$

In this expression, $\bar{U}_c$ is the velocity of the dominant waves and structures in the shear layer, and is defined as:

$$\bar{U}_c = \frac{a_2 \bar{U}_1 + a_1 \bar{U}_2}{a_1 + a_2} \quad (6.2)$$

where the subscripts 1 and 2 denote each stream, and a is the speed of sound.

For the present experiments, the flow between any two adjacent channels at the exit of the flow separator can be treated as a two-stream shear layer. The maximum value of M_c for any shear layer can obviously not exceed the highest Mach number in the uniform shear flow, which occurs in the top (lowest blockage) flow separator channel. An upper bound for the velocity in the top channel can be estimated by assuming that the shear rate is constant right up to the wall, thus ignoring boundary effects.

The highest possible velocity would have occurred in shear flow case #5, and would have resulted in a Mach number of less than 0.3 in the top flow separator channel. Therefore, the convective Mach number cannot exceed 0.3 for any shear layer at the exit of the flow separator. In reality, M_c is a great deal lower than this value. Following this analysis, it can be inferred that there were no compressibility effects throughout any of the shear flows of the present study.

6.2 Evolution of turbulence structure in uniform shear flow

6.2.1 The development of turbulent stresses and kinetic energy

An asymptotic region of exponential growth of the four dominant Reynolds stresses and the turbulent kinetic energy is evident in the graphs of figure 29. Visually, figure 29 compares fairly well with recent uniform shear results (see Tavoularis and Karnik 1989), in terms of the

slopes and relative magnitudes of the normal and shear stresses plotted in semi-logarithmic coordinates.

The ordering of the magnitudes of the stresses is similar to that which has been observed in other flows with a fixed dominant mean shear direction. The streamwise normal stress dominates because it receives energy directly from the mean shear, while the other two normal stresses are maintained by means of their coupling to the streamwise stress through pressure-velocity correlations (Champagne et al. 1970).

The least-squares fitted values of κ , listed for each shear flow case in table 5, are compatible with the growth rates of turbulent kinetic energy measured in past experiments (TC; TK; HT), and exhibit roughly the same degree of scatter. Tavoularis and Karnik (1989) compiled a summary of uniform shear flow measurements, in which all other growth rates reported also compared favourably with the present values of κ .

A number of studies (Rohr et al. 1988; Tavoularis and Karnik 1989) indicate that plots of the ratios $\overline{u_i u_i} / \overline{U_c}^2$, corresponding to the same flow generating apparatus but different $\overline{U_c}$, essentially collapse when plotted versus the total strain. Recalling that the constant k_s is representative of a given flow-generating apparatus, figure 34 confirms this theory. The present flows can be divided into three visibly distinct groups, each corresponding to a unique value or range of the flow generator constant: $11.8 < k_s < 12.5$, $k_s = 15.8$, and $18 < k_s < 20$. Shear flow cases #1 and #5 belong to the low- k_s group. Initially, it may seem that the flows are grouped according to physical apparatus, since cases #1 and #5 were generated with plate #1. However, cases #2, #4 and #6 form the high- k_s group, which includes a plate #1 flow as well as both plate #2 flows. Case #3 was alone in its group.

The low- and high- k_s groups are plotted separately in figure 35. A least-squares fit of the turbulent kinetic energy data revealed that $\kappa=0.103$ for $11.8 < k_s < 12.5$, while $\kappa=0.078$ for the higher range. These values are essentially the average growth rates of the individual shear flows in each group. Oddly, the turbulent kinetic energy growth rate is slightly

higher in the lower- k_s flows, although both values of κ are within the range of growth rates reported for flows identified as "high shear" by Tavoularis and Karnik (1989). It is more likely that the difference in κ is an artifact of non-systematic scatter than an indication of an inverse relationship between κ and k_s . Figure 36 seems to support this hypothesis, although more measurements would be required for complete certainty. The growth rate, averaged over all of the present and previous results (TC; TK; HT) plotted in the figure, is $\kappa=0.090\pm0.013$. The number which indicates the certainty of the measurement, in this case 0.013, represents the mean absolute deviation from the reported average. Note that the data sets of both TK and HT have been averaged as a single point for the sake of clarity.

6.2.2 The dimensionless Reynolds stress tensor

Figure 30 shows that, in each shear flow case, the values of K_{ij} in the downstream part of the tunnel were practically constant. The evolution of the Reynolds stress tensor is plotted for all the flow cases together in figure 37. At first glance, there appears to be a growing trend towards anisotropy with downstream distance, which suggests that the flows may not have been fully developed. However, careful examination of figure 37 reveals that the level of anisotropy differs mainly between distinct shear flows, rather than within a given flow, and may therefore be related to the flow generator constant k_s . Regardless, differences between the fully developed values of the Reynolds stress tensor for the different flow cases were not extremely large. The average over all present experiments is as follows.

$$K_{ij} = \begin{bmatrix} 0.51\pm0.04 & -0.11\pm0.01 & 0 \\ -0.11\pm0.01 & 0.21\pm0.02 & 0 \\ 0 & 0 & 0.28\pm0.03 \end{bmatrix} \quad (6.3)$$

The diagonal components of (6.3) are in excellent agreement with the average values obtained by Tavoularis and Karnik, which were $K_{11} = 0.51\pm0.04$, $K_{22} = 0.22\pm0.02$, and $K_{33} = 0.27\pm0.03$. Table 4 indicates that the normal stresses compare favourably with earlier measurements (TC), as well as with more recent data (HT).

Measurements of the dominant shear stress term $-K_{12}$ were consistently lower than values reported in the literature. Previous averages of $-K_{12}$ were 0.14 (TC; HT), and 0.16 (TK). The authors agree that the latter value was suspiciously high; $-K_{12} = 0.14$ is commonly accepted for the uniform shear flows generated in past experiments. The 20% drop in $-K_{12}$ is most obviously attributed to very high shear, as this is the major distinguishing characteristic of the present shear flows. In fact, the average rate of shear is approximately an order of magnitude higher than has been realized in the past, and more importantly, the corresponding flow generator constant is between two and three times the highest value previously attained. It is hypothesized that these conditions are sufficient to cause a significant change in flow structure, particularly in the more sensitive quantities such as shear stress.

A similar phenomenon has also been observed in the inner region of turbulent boundary layers with increasing proximity to the wall. The present measurements suggest that high shear, and not necessarily the damping of normal velocity fluctuations at the wall, may be responsible for the decrease in Reynolds shear stress relative to the turbulent kinetic energy. Consequently, the uniform shear flow model may be capable of reproducing near wall turbulence structure. Supporting evidence will be presented and discussed in sections 6.3 and 6.4.

The trend towards anisotropy of the Reynolds stress tensor is easily identified when the components are plotted versus the flow generator constant k_s (figure 38). Similar to previous experimental findings (TK), it appears that anisotropy of the diagonal components of K_{ij} increases with the value of k_s . With increased shear, more of the kinetic energy is concentrated in the streamwise direction, further amplifying K_{11} , while detracting from the remaining normal stress components. Direct numerical simulation of homogeneous shear (Lee et al. 1990) has shown that high shear rate enhances the streamwise fluctuating motions to such an extent that a highly anisotropic turbulence state develops asymptotically as total shear increases. The following expression, which is an invariant under rotations of the coordinate system, is a measure of anisotropy:

$$m^2 = m_{11}^2 + m_{22}^2 + m_{33}^2 + 2m_{12}^2 \quad (6.4)$$

where $m_{ij} = K_{ij} - \delta_{ij}/3$ is the Reynolds stress anisotropy tensor. Considering only the present set of experiments, this quantity, plotted in figure 39, shows a clear increase with increasing k_s . However, because in the present study $-K_{12}$ was lower than that in previous experiments, there was no significant variation in the total anisotropy, m^2 , despite the increase in normal stress anisotropy.

6.2.3 The ratio of turbulent kinetic energy dissipation over production

The ratio of turbulent kinetic energy dissipation over production rate is plotted versus the flow generator constant k_s in figure 40, for all present and some previous uniform shear flows (TC; TK; HT). Although the few data points are somewhat scattered, ϵ/P appears to be fairly constant over the k_s range of cases #1 to #6, with an average of $\epsilon/P = 0.61 \pm 0.08$. This value is slightly lower than recent measurements (TK; HT), although the degree of scatter is comparable. Tavoularis and Karnik reported an average of 0.68 ± 0.06 for flows with $k_s > 3$, identified as "high shear". However, it should be noted that the authors used their measurements of $-K_{12}$ to compute ϵ/P , and thus this value also is suspected to be high.

As in the studies mentioned above (TC; TK; HT), the dissipation over production ratio was estimated from equation (3.16), based on the balance of the production and convection terms in the turbulent kinetic energy equation (3.5). Along with the establishment that the growth rate κ is essentially independent of the flow generator constant k_s , equation (3.16) indicates that the ratio ϵ/P may be solely dependent on, and decreases with, the magnitude of K_{12} . Equation (3.19) demonstrates that a decrease of shear stress relative to kinetic energy, which appears to be related to strong shear, counteracts the effect of the shear rate term itself on turbulence production. However since the magnitude of K_{12} is small compared to that of the mean shear rate, the former term plays a much less significant role in the equation. In fact, equation (3.16) suggests that the inhibition of the shear stress component $-K_{12}$ appears to be the mechanism through which strong shear enhances the net rate of increase of turbulent kinetic

energy.

Ideally, the turbulent kinetic energy dissipation would be evaluated directly by measuring the quantities on the right hand side of equation 3.7. However this is virtually impossible due to the inability of conventional instrumentation techniques, such as LDV or hot wires, to resolve the fine structure of the flow. Measurement of the spatial derivatives in equation 3.7 requires resolution of the order of the Kolmogoroff microscale. At turbulent Reynolds numbers as high as those generated in the present experiments, the anticipated values of the Kolmogoroff microscale are far too small to be resolved by even the most sophisticated techniques. This is supported by a rough estimation of the various lengthscales in the present flows, which is presented in section 6.2.6.

6.2.4 Timescales and dimensionless shear rate parameter

The indication of the "lifetime" of energy containing eddies in Table 5 suggests that the present eddies exist for much shorter periods of time, as the values of τ_u are roughly an order of magnitude smaller than their measurements in previous studies. In other words, there is an extremely rapid "turnover" of energy containing eddies as compared to that in the lower-shear flows. The small values of τ_u imply that turbulence requires considerably less time to develop in highly sheared flows, characterized by larger values of the flow generator constant k_s , which is consistent with the faster flow development with downstream distance. In figure 41, τ_u is plotted versus k_s for all available uniform shear data (some data has been averaged) in order to demonstrate this point graphically.

It is logical to compare τ_u with the time it takes the mean flow to traverse the wind tunnel test section, $T_{TS} = \Delta x_1 / \bar{U}_c$, where Δx_1 is the length of the test section. Values of the ratio T_{TS}/τ_u are listed in table 6.

Table 6 Comparison of timescales			
Case	τ_u [s]	T_{TS} [s]	T_{TS}/τ_u
1	0.0500	0.0285	0.57
2	0.0237	0.0293	1.24
3	0.0201	0.0224	1.11
4	0.0168	0.0258	1.54
5	0.0278	0.0183	0.66
6	0.0182	0.0284	1.56

With the exception of cases #1 and #5, the available flow development time was always slightly greater than the typical eddy lifetime. Ideally, T_{TS} should be several times larger than τ_u , in order to ensure ample development time for the turbulence. If it had been possible to measure further downstream, therefore, the data likely would have displayed improved transverse homogeneity and less scatter. Nevertheless, the fact that $T_{TS}/\tau_u = O(1)$ for all flow cases indicates that the turbulence development time was just sufficient. Not surprisingly, the ratio T_{TS}/τ_u was greatest for the flows with high values of k_s , and smallest for the low- k_s flows.

Values of the ratio of eddy lifetime over the straining time, τ_u/τ_s , are a great deal higher than in earlier uniform shear flows, as shown in table 5. Tavoularis and Karnik reported an average of about 6.5 and 9.0 for flows classified respectively as "low shear" and "high shear", whereas the present results range from approximately 12 to 22. This dimensionless parameter has been used as an effective shear rate, as well as the primary indicator of the type of turbulence structures in numerically simulated shear flows. Unlike the flow generator constant, it is not restricted to uniform shear flows, and is thus an excellent means for comparison between a variety of turbulent flows, including both homogeneous and non-homogeneous shear flows. In fact, this parameter can be expressed solely in terms of internal

flow quantities as follows:

$$\frac{\tau_u}{\tau_s} = \left[\frac{d\bar{U}_1}{dx_2} \right] \frac{\bar{q}^2}{\epsilon} = \frac{1}{(\epsilon/P)(-K_{12})} \quad (6.5)$$

Oddly, in the present as well as past uniform shear experiments (TC; TK; HT), there seems to be no monotonic relationship between the flow generator constant k_s and the non-dimensional shear rate, τ_u/τ_s , as shown in figure 42. However, the average over the range $11 < k_s < 20$, corresponding to the present shear flows, is $\tau_u/\tau_s = 16 \pm 3$. This is considerably higher than the average of $\tau_u/\tau_s = 10 \pm 2$ over the previous uniform shear flows listed in table 5, which fall into the range $3 < k_s < 8$. It is not clear whether the large scatter is due to experimental errors or some other factor.

6.2.5 The Reynolds stress correlation coefficient

The most significant result of the present study is probably the consistently low values of the Reynolds stress correlation coefficient,

$$-\frac{\overline{u_1 u_2}}{\overline{u_1' u_2'}} = \frac{-K_{12}}{\sqrt{K_{11} K_{22}}} \quad (6.6)$$

relative to values in previous uniform shear and boundary layer measurements. In the past, the coefficient has assumed an average value of 0.44 in uniform shear (TC; HT), as well as throughout most of the boundary layer (Lu and Willmarth 1973). By contrast, the average value in the six uniform shear flows at very high shear rates is 0.35 ± 0.02 . Since it has been postulated that strong shear causes a reduction in the dimensionless shear stress $-K_{12}$, it follows that it is also responsible for lower values of the Reynolds stress correlation coefficient.

Figure 43 depicts the relation between the Reynolds stress correlation coefficient and the flow generator constant k_s , for recent uniform shear results. The data of Tavoularis and

Karnik (1989) may be too high, reflecting possible overestimation of $-K_{12}$, as discussed in section 6.2.2.

It may be noted that the Reynolds stress correlation coefficients of cases #1 to #6 in table 5 are not always recovered from the K_{ij} values of table 4. Differences may have arisen from the averaging process, in which different outlying points may have been rejected for each value calculated, but these are likely to be insignificant. The most probable reason for discrepancies is that the value of the streamwise normal stress $\overline{u_1^2}/\overline{U_c^2}$, used in the computation of K_{ij} , was an average of data obtained in both horizontal and vertical shear. By contrast, the Reynolds stress correlation was calculated entirely from horizontal shear data, in order to obtain the greatest possible accuracy. On average, however, the coefficients calculated from the components of K_{ij} in table 4 are within approximately 3% of the values reported in table 5.

In section 6.3, the correlation coefficient in high uniform shear is compared to near-wall turbulent boundary layer measurements. Prior to this, it must be ascertained that the reduced correlation is indeed characteristic of highly sheared flow, and not due to turbulence inherent to the wind tunnel. Equation (4.5) was used to calculate an upper bound for the Reynolds stress correlation coefficient in each shear flow, according to the procedure outlined in section 4.3.2.1. These values appear in table 7. They clearly show that even in the absence of wind tunnel turbulence, the measured correlation coefficients would be consistently lower than those reported in the literature.

Table 7 Reynolds stress correlation coefficient		
Case	measured value	upper bound for true value
1	0.303	0.383
2	0.362	0.366
3	0.329	0.362
4	0.364	0.368
5	0.340	0.414
6	0.377	0.400

6.2.6 Rough estimation of lengthscales

Rough estimations for the streamwise integral lengthscale, the Taylor microscale and the Kolmogoroff microscale are now presented. Due to the limited resolution of the LDV system and the relatively low data acquisition rate, direct methods cannot be employed to measure these quantities. Therefore, the following results represent an indication of order of magnitude of the lengthscales only.

The streamwise integral lengthscale L_{11} is usually measured by integrating the corresponding autocorrelation coefficient to its first zero and using Taylor's "frozen flow" approximation (TK). This quantity can be estimated, however, by noting that the timescale characteristic of large eddies, L_{11}/q , and the "lifetime" of energy containing eddies (also called the timescale of dissipation), $\overline{q^2}/\epsilon$, are of the same order of magnitude in most fully turbulent flows (Sreenivasan 1984). In fact, it has been shown that the ratio of the two timescales is essentially independent of the turbulent Reynolds number at sufficiently high values of the latter in flows behind biplane, square-mesh grids. In previous uniform shear flow studies, relatively large values of the turbulent Reynolds number suggest that this ratio should remain fairly constant as well. Using previous data (TC; TK; HT), it was found that, on average, the characteristic timescale of large eddies is approximately 4 times the timescale of dissipation.

Therefore, the streamwise integral lengthscale can be approximated from the following:

$$L_{11} = 4 \frac{q^3}{\epsilon} \quad (6.7)$$

The above expression implies exponential growth of the streamwise integral lengthscale, at exactly half the growth rate of the turbulent kinetic energy. Using this growth rate, therefore, a reference value for the streamwise integral lengthscale at the exit of the shear generator, L_{110} , can be defined by extrapolating upstream to the origin. However, this method does not take into account the developmental region of the shear flow, for which the growth rate of L_{11} is determined by a multitude of factors and is not exponential. As a result, the extrapolated value of L_{110} may be significantly larger or smaller than the true value, which is limited in size by the channel width of the flow separator, but should be of approximately the same order of magnitude. The estimated values for the present flows are listed in table 8. Extrapolated values using the actual asymptotic growth rate of the measured integral lengthscales from previous studies are also presented for comparison.

The streamwise Taylor microscale is usually measured as

$$\lambda_{11} = \left[\frac{\overline{u_1^2}}{(\partial u_1 / \partial x_1)^2} \right]^{\frac{1}{2}} \quad (6.8)$$

where the streamwise derivative is estimated from the time derivative using Taylor's "frozen flow" approximation. In the present experiments, however, the low rate of data acquisition prevented any reasonable evaluation of the time derivative. Instead, a very rough approximation can be made using the quasi-isotropic relation:

$$\epsilon = \frac{B \nu \overline{q^2}}{\lambda_{11}^2} \quad (6.9)$$

The constant B, which is equal to 15 in isotropic turbulence, was evaluated by averaging the data from previous uniform shear flows (TC; TK; HT). This resulted in a value of $B \approx 12$. The ratio of the streamwise Taylor microscale to the streamwise integral lengthscale at a given

dimensionless downstream distance is approximated for the present uniform shear flows in table 8, and is compared to measured values from previous studies. The turbulent Reynolds number, $R_{\lambda 1}$, which is based on the streamwise Taylor microscale and the streamwise rms velocity fluctuation, is also listed in table 8.

The Kolmogoroff microscale is given by:

$$\eta = \left[\frac{\nu^3}{\epsilon} \right]^{\frac{1}{4}} \quad (6.10)$$

As explained in section 6.2.3, the dissipation rate could not be measured directly from equation 3.7, due primarily to the fact that only one measurement probe was used and the data rate was too low to approximate the spatial derivatives by temporal ones. As a result, the dissipation rate was estimated from the balance of the production and convection terms in the turbulent kinetic energy equation, that is, using equation 3.16. The resulting approximate ratio of the Kolmogoroff microscale to the streamwise integral lengthscale is also shown in table 8.

Table 8 Estimated lengthscales							
Experiment		τ	channel width [mm]	L_{110} [mm]	λ_{11}/L_{11}	η/L_{11}	$R_{\lambda 1}$
Present	1	9	12.7	43	0.035	.0005	1012
	2	12	12.7	31	0.031	.0004	1189
	3	13	12.7	30	0.032	.0004	1089
	4	12	12.7	25	0.035	.0005	1056
	5	10	12.7	33	0.031	.0004	1088
	6	15	12.7	25	0.033	.0005	1132
TC		13	30.7	24	0.102	0.003	266
A (TK)		20	25.4	12	0.129	0.003	310

Table 8 shows that the initial value of the streamwise integral lengthscale is approximately of the same order of magnitude as the flow separator channel width. The fact that it is greater than the channel width, which represents an upper bound for this value, reflects the very rough nature of the approximation, and also that the evolution of the integral lengthscale upstream of the asymptotic region of flow development was ignored in the extrapolation process. It may be expected, based on grid turbulence data, that the initial growth of length scales would be faster than that in uniformly sheared flow.

The ratios of the microscales to the integral lengthscales in Table 8 indicates that the turbulence structure is roughly an order of magnitude finer than it was in previous experiments. This is to be expected, due to the significantly higher centreline velocities, mean shear rates and hence rates of turbulence production and dissipation. The fact that the fine scales of the present flows are much smaller is also justified by the fact that the turbulent Reynolds numbers are nearly an order of magnitude larger than previous values. Another important conclusion that can be drawn from the approximated microscales is that it would not have been possible to measure the dissipation rate directly, even if the data rate was sufficiently increased. The results show that the required resolution, which is of the order of the Kolmogoroff microscale, is much less than 0.1 mm, while the resolution of the LDV system is of the order of 1 mm.

6.3 Comparison with near-wall boundary layer structure

6.3.1 Effective shear-rate parameter

It will now be verified whether the turbulence statistics of uniformly sheared flow are similar to those measured in the near-wall region of a turbulent boundary layer. The main purpose is to determine whether the flow structure is principally dependent on mean shear rather than on the presence of a solid boundary. The selection of a suitable parameter to correlate mean shear rate with turbulence structure in both types of flow is a challenging problem.

As discussed in section 3.3 and 6.2.4, the dimensionless shear-rate parameter τ_u/τ_s ,

could be used as the basis for comparison. For turbulent boundary layers, it is more convenient to express τ_w/τ_s in terms of ϵ/P and K_{12} , as shown in equation (6.5), since the velocity gradient varies and measurements of τ_w are not always available. While it may be reasonable to assume that $\epsilon/P \approx 1$ in the logarithmic layer, this approximation is not valid in the viscous and buffer layers. Unfortunately inner boundary layer data do not always include measurements of the dissipation to production ratio. Therefore, the turbulent kinetic energy balance measured in the wall region of a pipe flow by Laufer (1954), also reported by Hinze (1975), was used to estimate ϵ/P .

It could also be instructive to compare flow structures by employing k_s as an indication of effective shear. For turbulent boundary layer measurements, the mean velocity profile may be used to determine a local value of k_s at a given distance from the wall. The main drawback of k_s is that it has dimensions of inverse length, and thus there is no guarantee that it could be used for comparing flows generated in different facilities.

In the inner turbulent boundary layer, it has been recognized that the proper length scale is the "viscous length", ν/u_τ , where ν is the kinematic viscosity of the fluid, and u_τ is the friction velocity, defined as:

$$u_\tau = \sqrt{\nu \left[\frac{dU}{dy} \right]_{y=0}} \quad (6.11)$$

Accordingly, the flow parameters depend entirely on the dimensionless parameter $y^+ = yu_\tau/\nu$, where y is the perpendicular distance from the wall. The mean velocity U is typically expressed in the dimensionless form $u^+ = U/u_\tau$. For comparing turbulence structure in the inner region of different boundary layers, therefore, k_s may be non-dimensionalized by the viscous length as follows:

$$k_s^+ = \left[\frac{\nu}{u_\tau} \right] k_s = \frac{1}{u^+} \frac{du^+}{dy^+} \quad (6.12)$$

Due to the lack of a truly intrinsic length scale, it is unclear how the flow generator constant may be appropriately non-dimensionalized in uniform shear flow. The initial value of the streamwise integral lengthscale, L_{110} , which is set by the width of the individual channels of the shear generator and flow separator (TK), may be used as a possible choice. The dimensionless form of the flow generator constant in uniform shear flow would then be:

$$k_s^+ = \frac{L_{110}}{U_c} \frac{d\bar{U}_1}{dx_2} = L_{110} k_s \quad (6.13)$$

In the present experiments, $L_{110} = 12.7$ mm.

In the next two sub-sections, an attempt will be made to compare on an appropriate scale the structure of uniform shear flow with that of turbulent boundary layer flow. The suitability of the above parameters for this purpose can then be assessed.

6.3.2 Non-dimensional Reynolds stresses

The components of the dimensionless Reynolds stress tensor, measured in the range $2 < y^+ < 40$ by Chevrin et al. (1992), are plotted versus τ_u/τ_s in figure 44. The variation of τ_u/τ_s throughout this region is displayed in figure 46(a). Figure 44 includes uniform shear data from present and past experiments, as well as some numerical results. All except the numerical data are plotted versus k_s in figure 45.

It should be noted that the variation of any property with τ_u/τ_s in a turbulent boundary layer is two-valued rather than monotonic. This is because τ_u/τ_s goes through a maximum at about $y^+ = 12$, as shown in figure 46(a), and then tends to zero as the wall is approached.

Damping of the velocity fluctuations at the wall causes the production of turbulent kinetic energy to vanish while the dissipation remains finite. Therefore, as y^+ decreases in the region $y^+ \leq 12$ of a turbulent boundary layer, boundary effects become increasingly dominant, and it is less likely that the turbulence structure would be reproduced in a uniform shear flow. Consequently, the present and previous uniform shear flow data should best be compared to the boundary layer data from approximately further than 12 viscous units from the wall.

At comparable values of the shear-rate parameter τ_u/τ_s , the anisotropy of the diagonal components of K_{ij} is higher in the turbulent boundary layer than in uniform shear, and appears to increase with τ_u/τ_s , as predicted by Lee et al. (1990). For clarification, turbulent boundary layer data from the region $y^+ > 12$ in figure 44 lie along the lower 'arm' of the curve in graph (a), and along the upper 'arm' of the curve in graphs (b), (c) and (d). In particular, K_{22} is significantly lower in the boundary layer than in uniform shear, and decreases as the wall is approached. Although the damping of the normal turbulent fluctuations at the wall is likely responsible, it is not the only cause of the decrease in this component near the wall. The uniform shear data as well as DNS results show that high shear rate produces a similar, though less pronounced, effect.

The boundary layer values of the normal dimensionless stresses are somewhat closer to uniform shear measurements when plotted versus k_s , but higher anisotropy is still evident. Anisotropy in the boundary layer appears to increase with k_s , similar to the findings reported in section 6.2.2.

The variation of $-K_{12}$ with τ_u/τ_s in the region $y^+ > 12$ of the turbulent boundary layer is consistent with, although slightly lower than, uniform shear measurements from the various studies. According to figure 46(a), the present values of $-K_{12}$ are roughly comparable to boundary layer data in the range $12 < y^+ < 30$.

When plotted versus k_s , the boundary layer values of $-K_{12}$ are in good agreement with those measured in uniform shear at high shear rate. Throughout the boundary layer,

$-K_{12}$ decreases steadily with increasing k_s , following the general trend of uniform shear flows. Using k_s as the basis of comparison, the present uniform shear results are very similar to data obtained in the range $25 < y^+ < 40$ of the boundary layer. This can be deduced from figure 46(b), which demonstrates the variation of the local value of k_s with the dimensionless distance from the wall in the turbulent boundary layer. The figure shows that, as the wall is approached, the value of k_s grows at a rate which increases sharply within the viscous sublayer. The varying growth rate is consistent with the mean velocity distribution in the inner layer, and with the relative importance of shear on turbulence characteristics.

6.3.3 The Reynolds stress correlation coefficient

The Reynolds stress correlation coefficient measured in the inner region of a turbulent boundary layer is compared with uniform shear results in figures 47 to 49. In figure 47, the data of Chevrin et al. (1992) and Eckelmann (1974) are plotted versus locally defined values of k_s . The experiments of Chevrin et al. were performed at a pipe Reynolds number of 8923, while Eckelmann's measurements were obtained at $Re=5600$ and $Re=8200$. For this reason the data were plotted against the non-dimensional parameter k_s^+ in figure 48. The variation of the correlation coefficient with the dimensionless shear rate parameter, τ_w/τ_s , is shown in figure 49.

Figure 47 demonstrates excellent agreement between the present uniform shear measurements and the boundary layer data in the same range of k_s . The boundary layer values in the figure were measured between $y^+ = 21$ and $y^+ = 40$, but, even at values of k_s higher than the uniform shear measurements, they appear to continue the same trend.

The data of Eckelmann, obtained in the range $2 < y^+ < 18$ of two different boundary layer flows, represent k_s values greater than 32. Therefore, they can be compared only with the boundary layer data of Chevrin et al. from approximately the same dimensionless distance from the wall. The values of the Reynolds stress correlation coefficient in this region of the boundary layer are well below the previously accepted average of 0.45. The only

exceptions are the measurements of Chevrin et al. in the range $4 < y^+ < 8$, and one value measured by Eckelmann at $y^+ \approx 3$, which, curiously, are well above 0.45. Following the discussion in section 6.3.2, however, it is evident that these values occur in the region where wall effects dominate to such an extent that the flow structure would not likely resemble that of uniform shear at a comparable shear rate. Outside of this region, the correlation coefficient measured by Eckelmann appears to gradually decrease with increasing k_s^+ .

In general, the parameter k_s^+ seems capable of correlating shear rate with turbulence structure. However, because the correlation coefficient is a dimensionless quantity, and the measurements come from more than one experimental facility, it may be more appropriate to plot the data versus k_s^+ , as shown in figure 48. The slight differences from figure 47 are primarily in the ordering of Eckelmann's data, as they were obtained at two different Reynolds numbers. The values of y^+ corresponding to the boundary layer data of figure 48 can be determined from figure 46(c).

The present uniform shear data fall between $k_s^+ = 0.1$ and $k_s^+ = 0.3$, where they compare very well with Eckelmann's measurements in the range $4 < y^+ < 8$. This is closer to the wall than where the uniform shear measurements appear to correlate best in figure 47. However, it should be remembered that the definition used for k_s^+ in uniform shear flow is arbitrary, and different from its definition in a boundary layer. Therefore, figure 48 provides a valid comparison between the various boundary layer results, but not necessarily between boundary layer and uniform shear results. Nevertheless, apart from the few points above 0.45, the Reynolds stress correlation coefficient in the inner boundary layer assumes values which are close to those measured in uniform shear at high shear rate, and it appears to decrease with increasing k_s^+ . In the limit of very high k_s^+ , corresponding to boundary layer measurements (Chevrin et al.) well within the viscous sublayer at $y^+ < 4$, the correlation coefficient is even lower than the one measured in this study.

Comparison between boundary layer and uniform shear data might also be made on the basis of the shear-rate parameter τ_w/τ_s . For this purpose, the data of Chevrin et al. from the

region $y^+ > 12$ were plotted with present and past uniform shear results in figure 49. Values of τ_u/τ_s were not available for the measurements of Eckelmann. Using τ_u/τ_s as an indication of effective shear rate, figure 49 suggests that the shear generated in the present study is comparable to that which exists in the region $18 < y^+ < 30$ of a turbulent boundary layer. In general, figure 49 demonstrates the steady decrease in the Reynolds stress correlation coefficient with τ_u/τ_s , both in uniform shear and in the inner region of boundary layer flow, beyond approximately 20 viscous units from the wall. In particular, the boundary layer curve appears to attain an asymptotic value of approximately 0.35 in the region $20 < y^+ < 30$, which is equal to the average value measured in the present uniform shear flows.

6.4 Comparison with numerically simulated flow structure

6.4.1 Effective shear-rate parameter

Turbulence statistics obtained from the direct numerical simulation of homogeneous shear flow (Lee et al. 1990; Rogers & Moin 1987) are now compared to uniform shear flow measurements. Since there is no mean convection in the numerically simulated flows, or, in other words, $\bar{U}_c = 0$, k_s cannot be computed for the DNS results. Therefore, τ_u/τ_s is used as an effective shear-rate parameter. Lee et al. denoted this parameter as $S^* = S\bar{q}^2/\epsilon$, where S is the magnitude of the mean velocity gradient perpendicular to the streamwise direction. They found that S^* was the most appropriate dimensionless parameter in terms of its capacity to distinguish different turbulent structures.

6.4.2 Non-dimensional Reynolds stresses

Figure 44 shows that the components of the Reynolds stress tensor in the DNS of homogeneous shear flow at low shear rate (Rogers & Moin 1987) are in excellent agreement with the previous uniform shear flow data, with the exception of perhaps K_{22} , which is slightly lower in the simulated flow. By comparison, the diagonal components of the Reynolds stress tensor in the simulated flow at high shear rate (Lee et al. 1990) display a greater degree

of anisotropy than those measured in the present uniform shear flows. This is expected, since the DNS data represent higher values of the dimensionless shear rate, and anisotropy increases with τ_u/τ_s (Lee et al. 1990). Among the normal stresses, the greatest difference with respect to the present values was observed in the transverse component, K_{22} , while the best agreement was found with the spanwise component, K_{33} . This indicates that the transverse normal stress may be the most sensitive to mean shear. It also confirms that the principal effects of mean shear on the normal stresses are the suppression of the transverse component and the transfer of most of its energy to the streamwise component. All of these observations are consistent with the measurements in uniform shear flow. However, upon comparing the diagonal components of the Reynolds stress tensor in the highly sheared simulated flow with the turbulent boundary layer data, it appears that the value of 34 for τ_u/τ_s in the DNS flow has been overestimated. In fact, the magnitudes of the normal stresses in the DNS flow are approximately the same as those in the turbulent boundary layer flow at $y^* \approx 12$, which is where the maximum value $\tau_u/\tau_s \approx 20$ occurs.

With increasing τ_u/τ_s , the shear stress component $-K_{12}$ behaves much the same in the simulated flows as it does in uniform shear and boundary layer flows. In fact, the average value of $-K_{12}$ in the present study was approximately equal to that obtained via DNS of homogeneous flow at high shear rate, and both low and high shear DNS data appears to fall on the same curve as the uniform shear flow data in figure 44(d). Here, also, it should be taken into account that the shear rate parameter in the highly sheared DNS flow may be overestimated. Nevertheless, the DNS results provide further support to the conjecture that high shear rate was indeed responsible for the relatively low values of $-K_{12}$ measured in the present study.

Although mean shear has a similar effect on the dimensionless Reynolds stress tensor in boundary layers, uniform shear flow and simulated homogeneous shear flow, the relatively poor agreement of the diagonal components, compared to the shear stress component, suggests that the normal stresses would be affected by other factors as well. Upon analysis of the results from the various shear flows, it appears that K_{12} is primarily dependent on the rate of mean shear, whereas the normal stresses, and particularly K_{22} , seem to be also influenced by the shear

generation mechanism. It seems plausible that a solid boundary would suppress K_{22} due to the kinematic constraint (no penetration), while a strong free shear would have a much lesser effect or none at all. This is a logical result, since K_{12} is closely related to the production of turbulent kinetic energy, while the normal stresses reflect how this energy is distributed among its components.

6.4.3 The Reynolds stress correlation coefficient

Despite the very good agreement between experimental and simulated homogeneous shear flow in terms of $-K_{12}$, figure 49 reveals that the Reynolds stress correlation coefficient is considerably higher in the DNS flows. This is likely due to very low DNS values of K_{22} . However, the figure indicates that the correlation coefficient decreases with τ_u/τ_s , in conformity with the trend exhibited by past and present uniform shear flow measurements.

It can be concluded that, although the experimental and simulated turbulence quantities did not always appear to match at the same dimensionless shear rate, increasing this rate had a similar effect on the turbulence structure of both types of flow.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

Nearly homogeneous, uniformly sheared turbulent flow has been generated at shear rates as high as 700 s^{-1} in an attempt to simulate shearing conditions in the inner boundary layer. The measurements show that the turbulence structure attains a self-similar state with approximately constant dimensionless stresses and exponential kinetic energy growth. These results are consistent with those previously obtained in uniform shear flows at lower shear rates.

The main difference from realizations at lower shear rates is a marked decrease in the turbulent shear stress. The shear stress component of the dimensionless Reynolds stress tensor, $-K_{12}$, is approximately 30% lower in the present uniform shear flows, and there are indications that it may further decrease as the mean shear rate increases. The normal components of the stress tensor were roughly the same as previous measurements. The Reynolds stress correlation coefficient was, on average, 22% lower than its value in uniform shear flow at lower shear rates.

The turbulent shear stress in the inner boundary layer has been shown to follow the same trend as it does in uniform shear flow at high shear rate. The component $-K_{12}$ decreases monotonically with increasing proximity to the wall, which coincides with an increase in the rate of mean shear. Boundary layer measurements have also confirmed the reduction in the shear stress correlation coefficient due to strong shear. There were relatively large differences between the diagonal components of the Reynolds stress tensor measured in the inner boundary layer and values obtained in uniform shear at a comparable shear rate. This is particularly evident in the transverse component K_{22} .

The equations of motion demonstrate that turbulent kinetic energy is produced from the interaction of turbulent shear stress with mean shear. Experimental results imply that, in boundary layers as well as in uniformly sheared flow, the magnitude of the shear stress is directly related to the rate of mean shear, whereas the normal stresses may also be influenced by the presence of a solid boundary. Comparison with directly simulated, homogeneous shear flows at high shear rates supports the above hypotheses. It may be concluded that, although the partition of turbulent kinetic energy among its components most likely depends on the proximity of a wall, the rate of production of turbulence in shear flow depends mainly on the rate of mean shear, irrespectively of the shear generation mechanism.

7.2 Recommendations

7.2.1 Improvements in experimental techniques

There are a number of ways in which the experimental apparatus and instrumentation could be improved in the future. The rate of data acquisition by the LDV system might be increased by using a more effective seeding material. As discussed in Chapter 4, the atomized liquid particles tended to accumulate on the test section window over a period of time. This hampered data acquisition and slowed down the measurement process considerably. The data rate was sufficiently high for most one-point statistics, but was too low to measure turbulence spectra and autocorrelation functions. Window blockage by droplets was also most likely

responsible for "drop out" in the LDV signal. Appropriate seeding with solid particles might be the solution to this problem.

Although the linearity of the velocity profiles was generally excellent, the homogeneity of the turbulence could be improved by fine-tuning the perforated plate in the shear generator. With smaller perforations, the porosity of the plate could be made to vary more gradually across the shear direction, which perhaps would lead to better transverse uniformity of the turbulent fluctuations. However, better spanwise uniformity might be obtained if the plate porosity for each channel was created by one large slot, instead of a row of holes. The ideal plate design may be a compromise between improved transverse and spanwise homogeneity.

7.2.2 Suggestions for future work

It is hoped that uniform shear flows will be extended to higher Mach numbers in order to examine the effect of compressibility. The mean Mach number in the present uniform shear flows was below 0.2. Measurements in flows with initial turbulent Mach numbers $M_{t,0}$ of up to 0.6 would provide a valuable comparison with the recent numerical simulations of compressible, homogeneous shear flow.

The present facilities are ideal for generation of compressible, uniform shear flow. For example, the pilot wind tunnel is capable of running at speeds ranging from low subsonic to close to sonic in the 127x127 mm test section. In addition, the shear generator would require very little modification. In order to avoid excessively high velocities near one wall, new perforated plates, designed to have lower solidity than plates #1 to #3, would have to be fabricated.

In terms of strength, the shear generator frame and perforated plates should be able to withstand the increased force. However, the flow separator module, which is the weakest component of the shear generator, may need to be strengthened. There is a danger that speeds of over Mach 0.2 could cause permanent deformation of the very thin separator plates, and/or

failure of the epoxy bonds between the separator plates and supporting side plates. It may be recalled that the original flow separator incurred similar damage, during a preliminary test of the shear generator at $M = 0.15$. As a result, although higher speeds had initially been considered for the present study, it was decided to leave generation of compressible shear flow for future work.

The following are suggestions for reinforcing the flow separator module. The separator plates could be made slightly thicker without too much disturbance to the flow. If possible, a more effective bonding material could be used, or an even better method could be devised, to fix the separator plates into the grooved side plates. Finally, the separator plates could be further supported at one or more critical points along their span, by properly securing very thin spacer blocks between them. Since the blocks need not be thick to dramatically improve the rigidity of the module, their wakes can be minimized.

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FIGURES

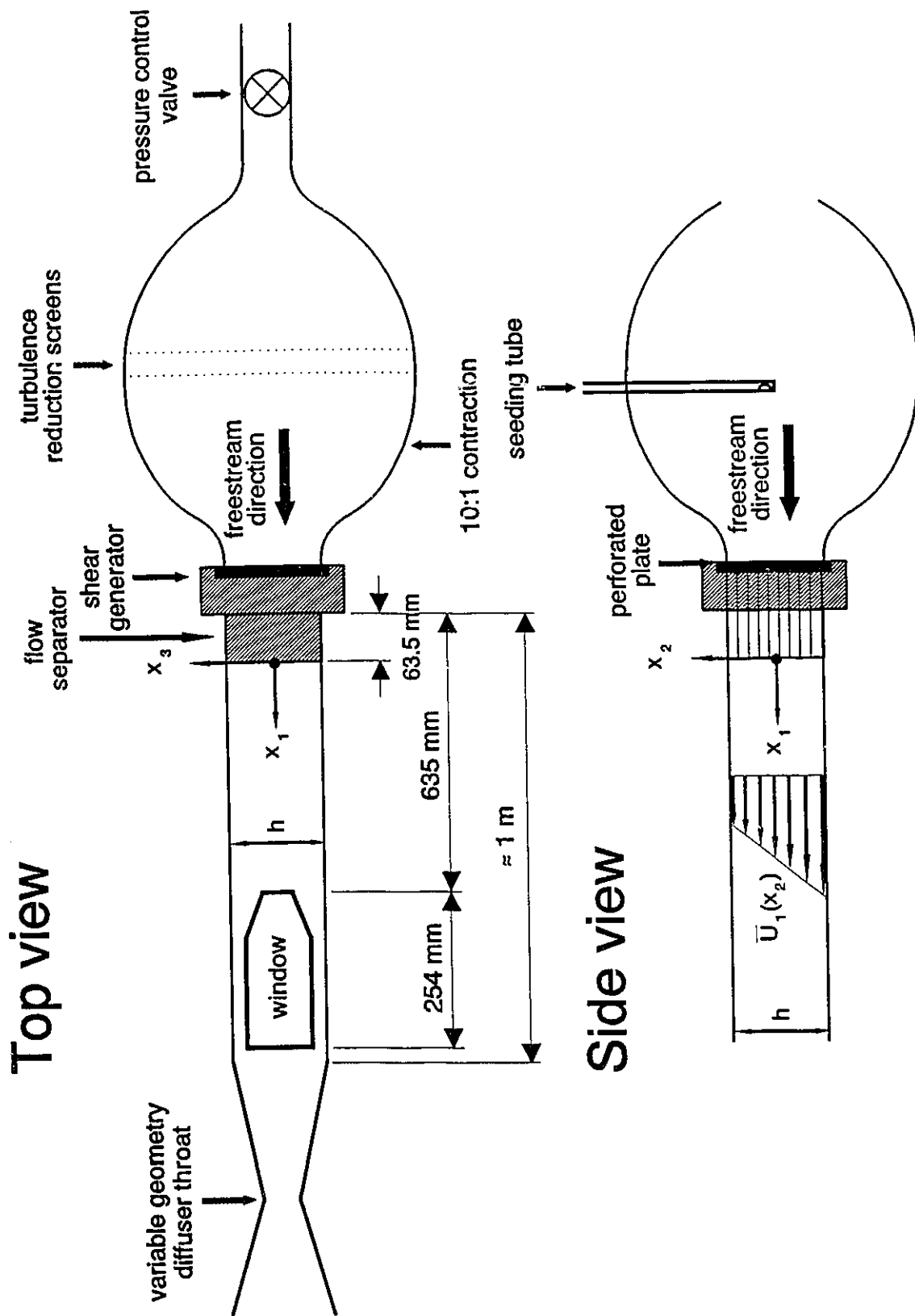


Figure 1 Sketch of wind tunnel and test section. Shear is oriented vertically. $h=127$ mm.

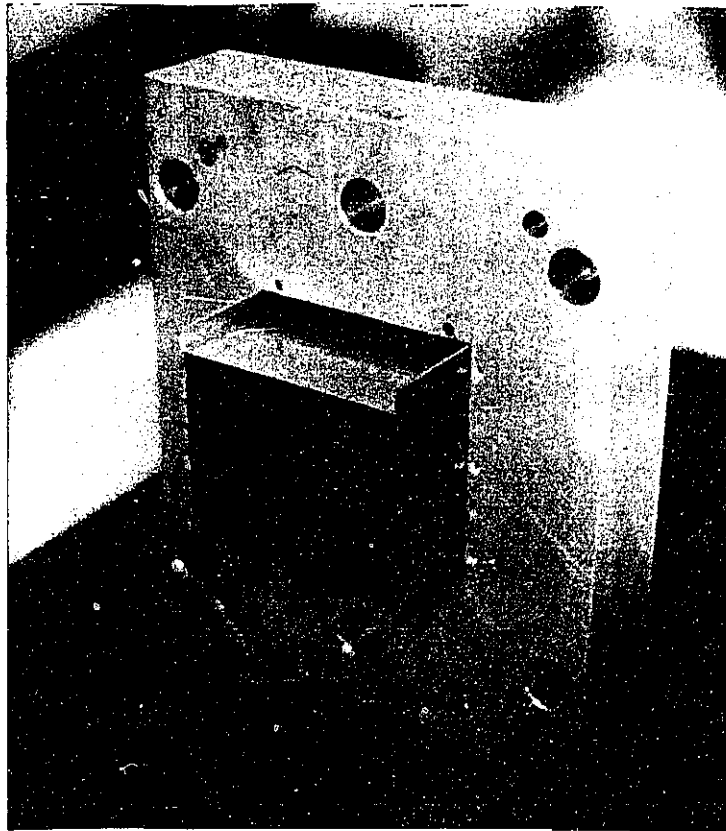
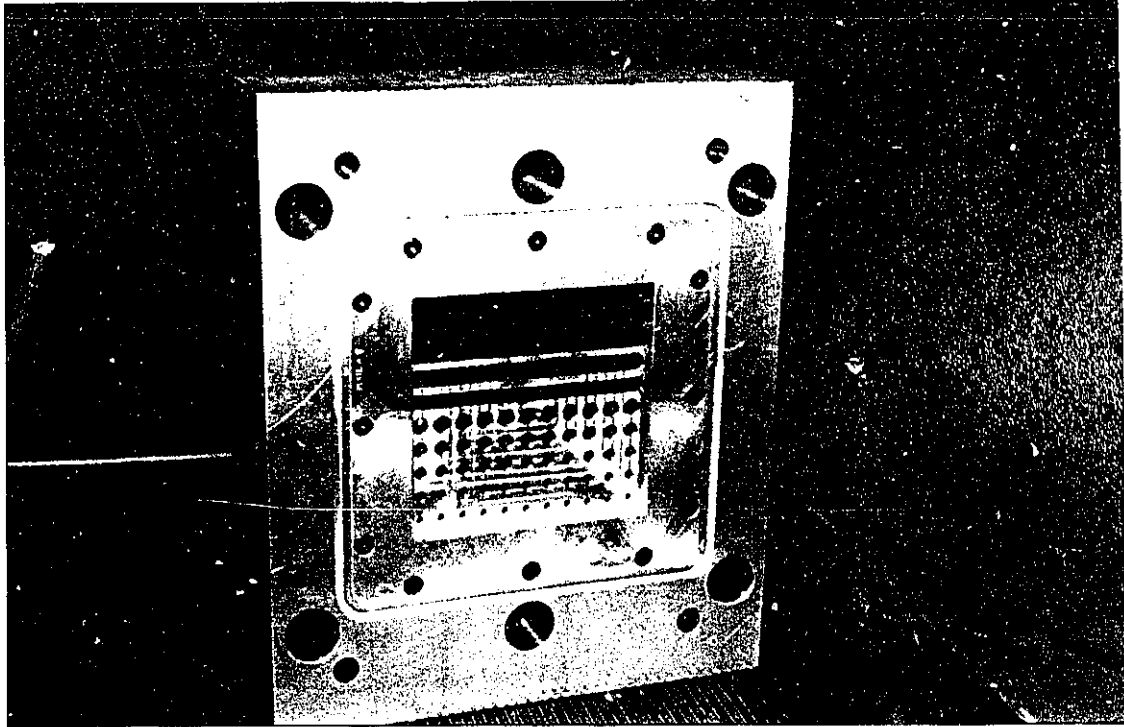


Figure 2 Photographs of the shear generator. Top: view from upstream. Bottom: view from downstream.

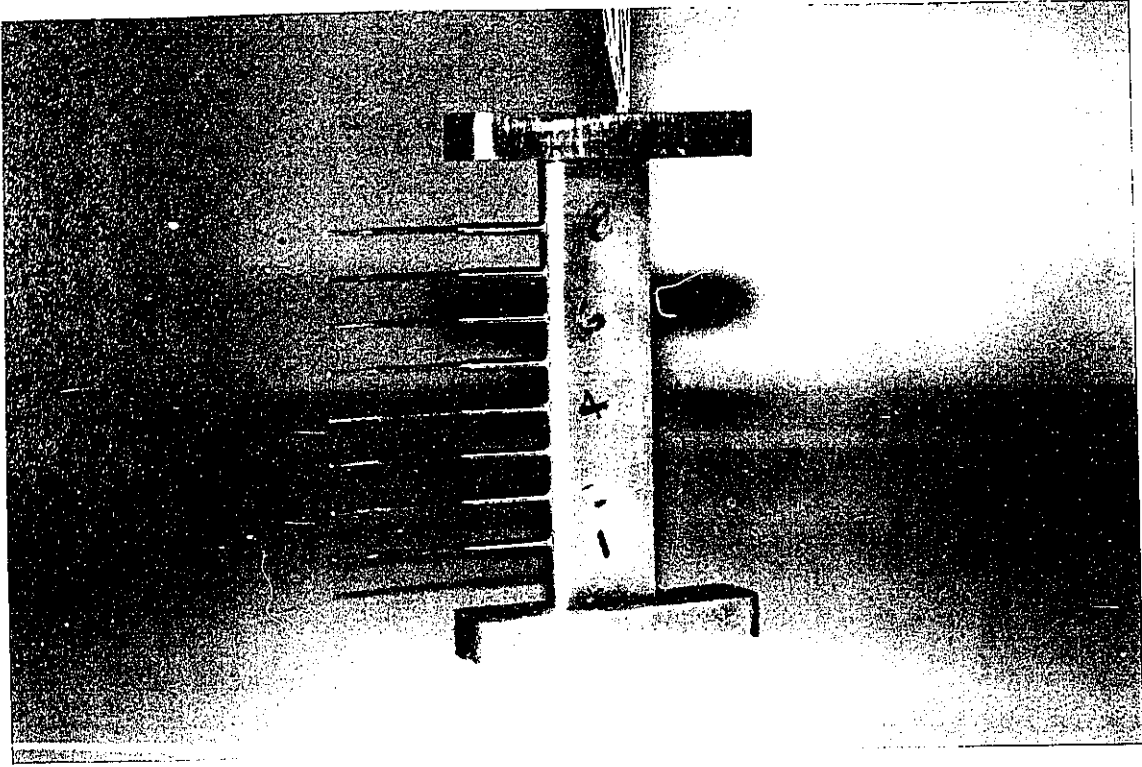


Figure 3 Photograph of the Eight-probe Pitot tube rake.

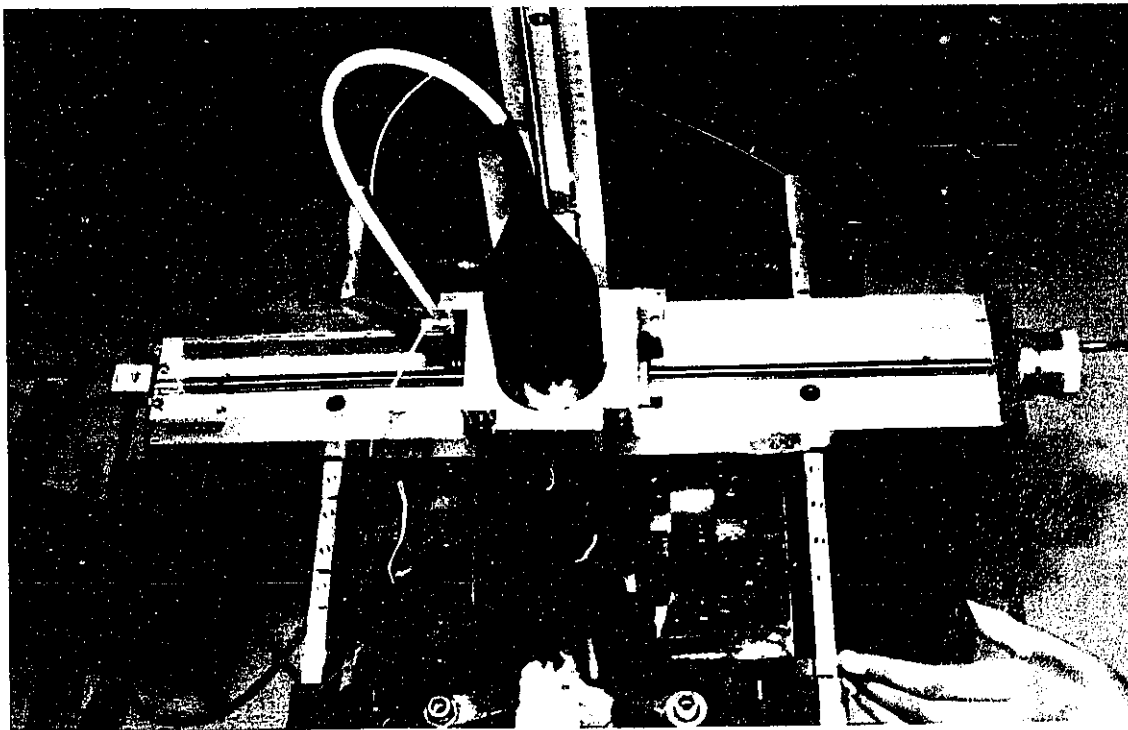
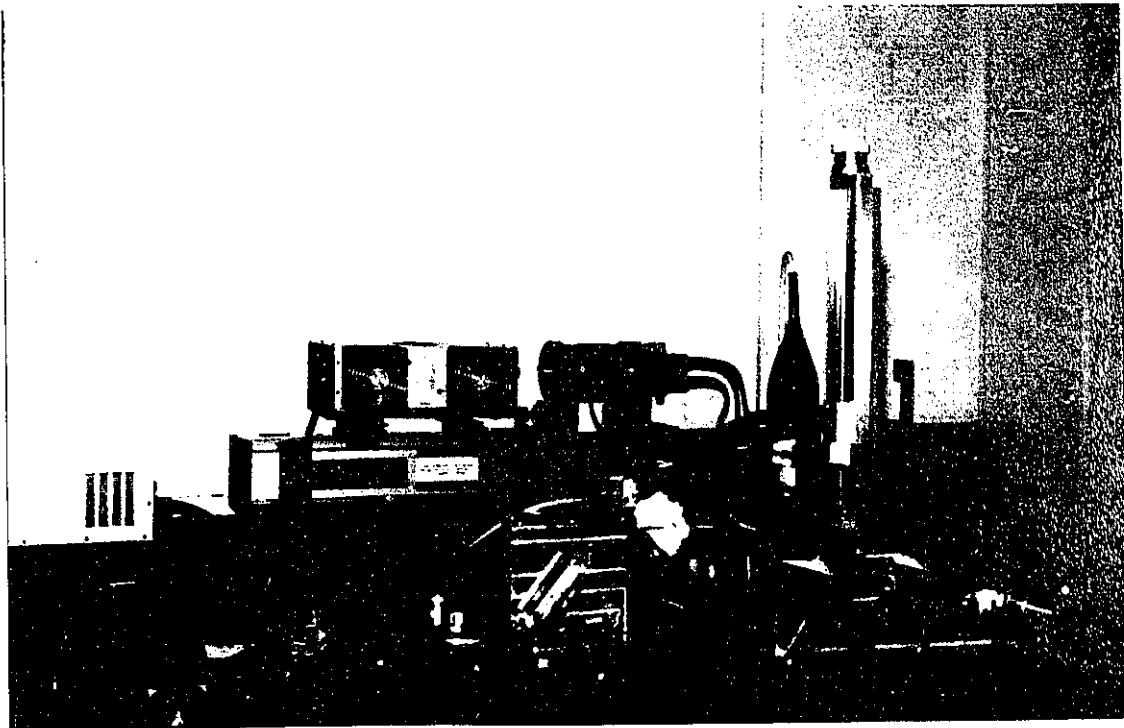


Figure 4 Top: Photograph of the laser-Doppler Velocimetry system (DANTEC) and traversing gear. Bottom: close-up of traversing gear.

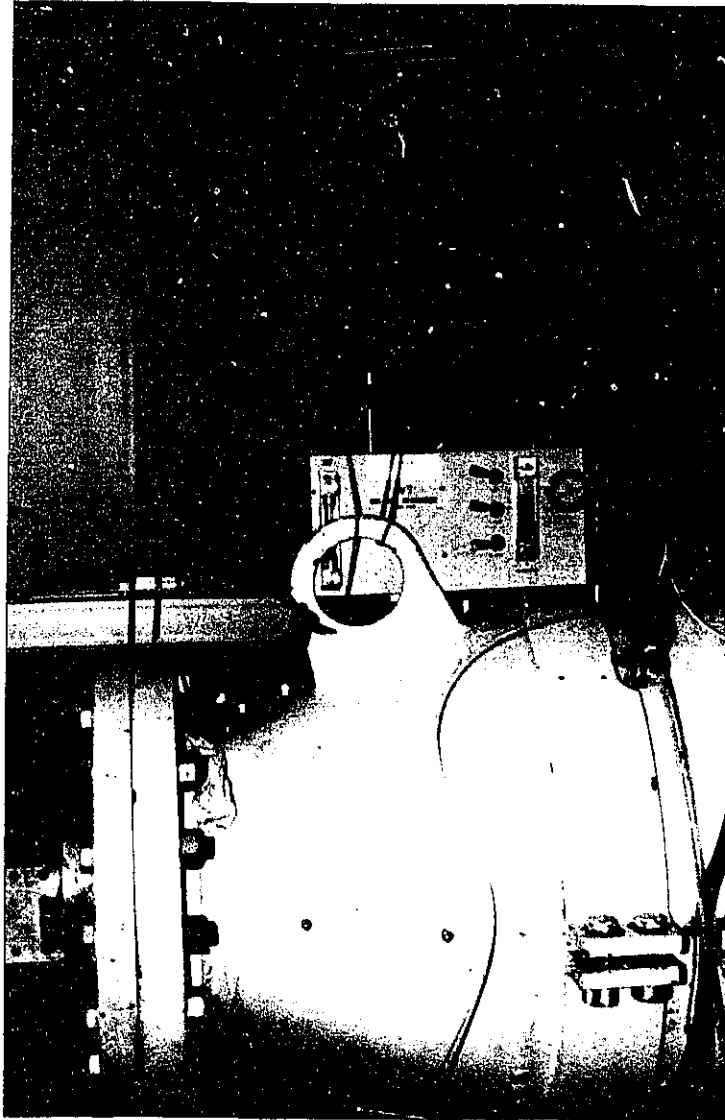


Figure 5 Photograph of six-jet atomizer (TSI model 9306) mounted above wind tunnel contraction section.

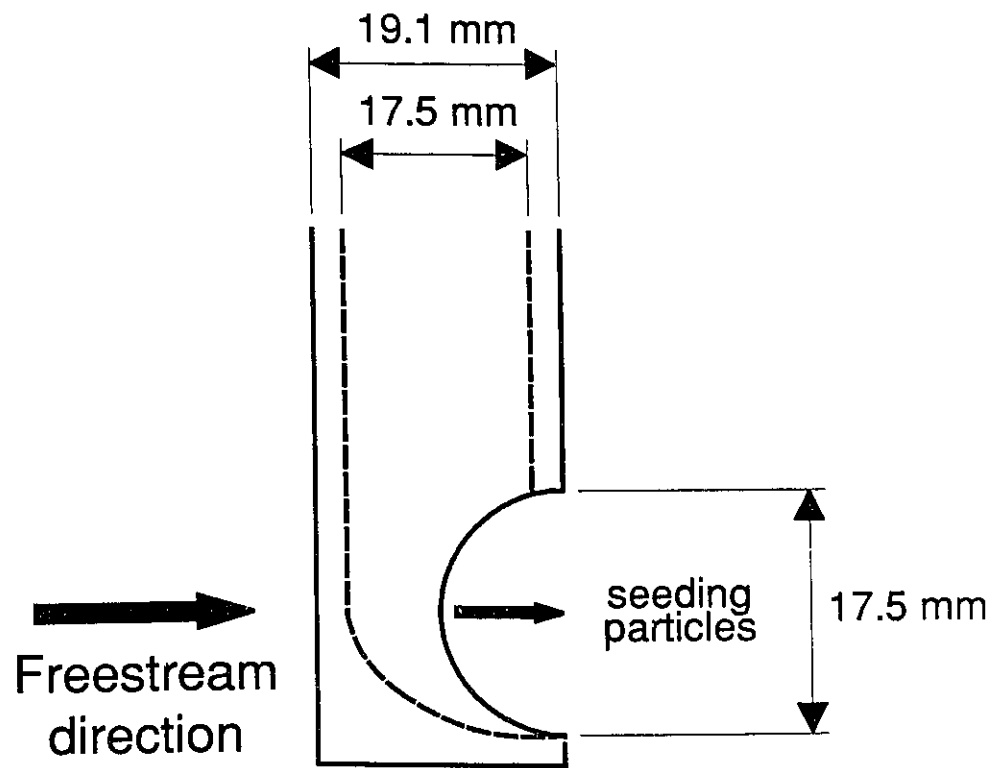


Figure 6 Sketch of outlet of seeding tube.

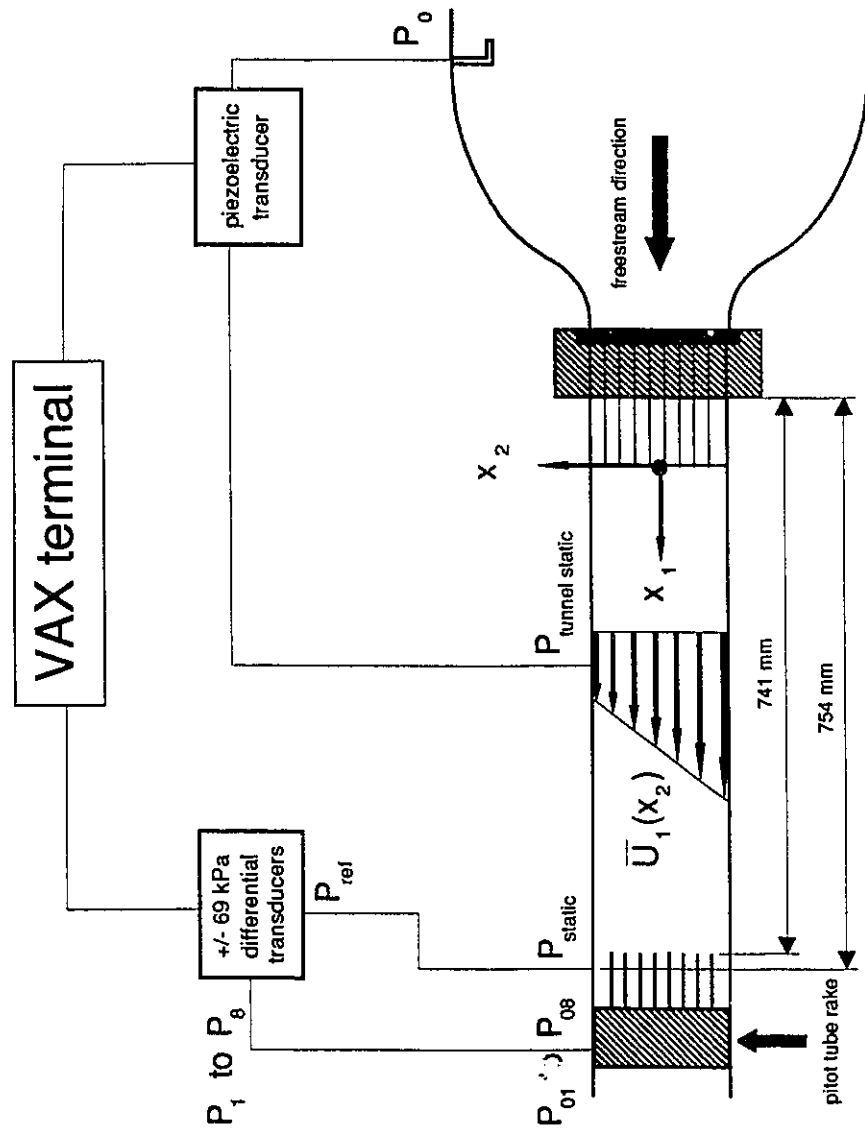


Figure 7 Data acquisition set-up for preliminary velocity profile measurements.

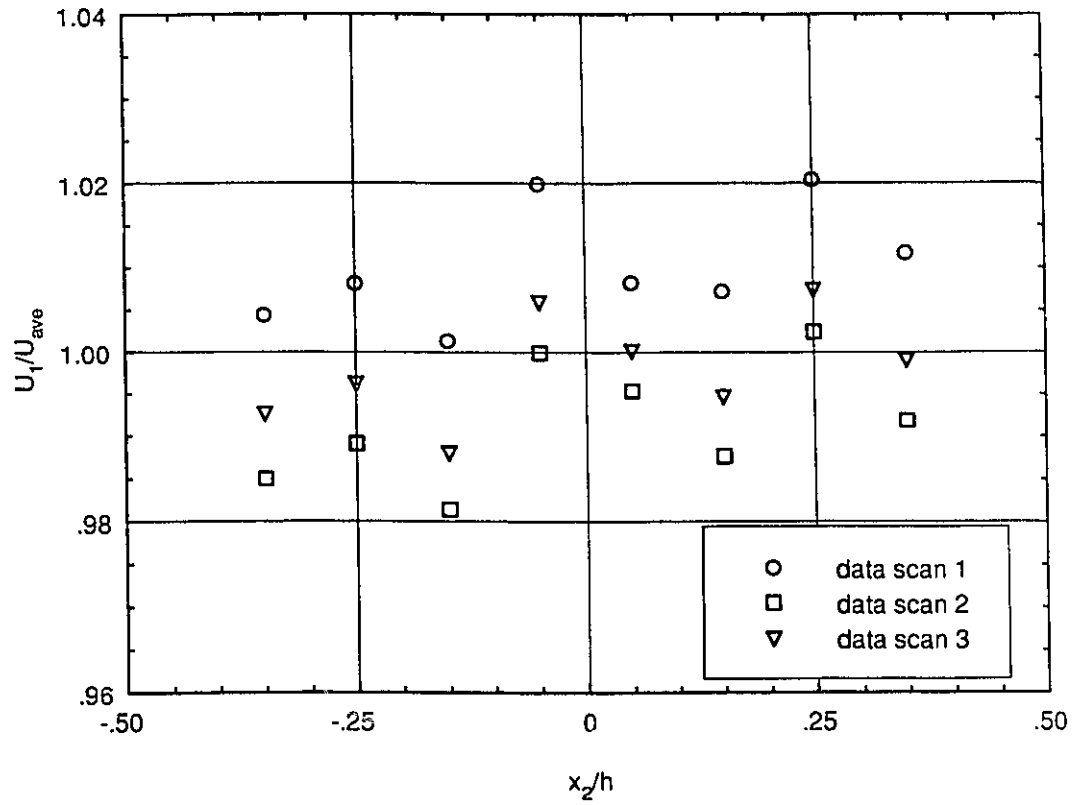


Figure 8 Velocity profile measured by Pitot tube rake in empty tunnel at $M=0.1$ and $P_0=193$ kPa. $U_{ave}=35.7$ m/s.

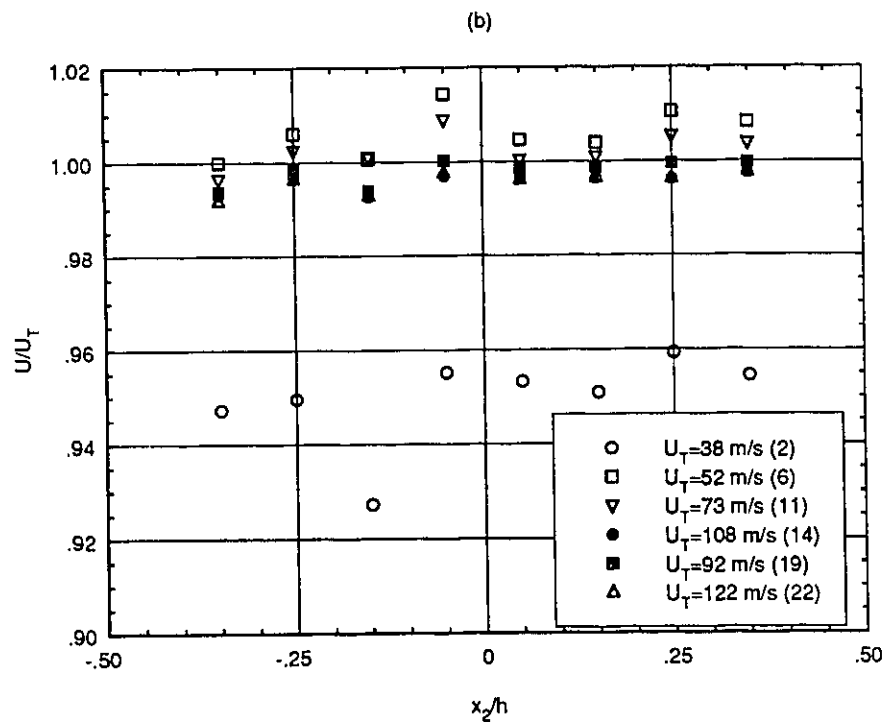
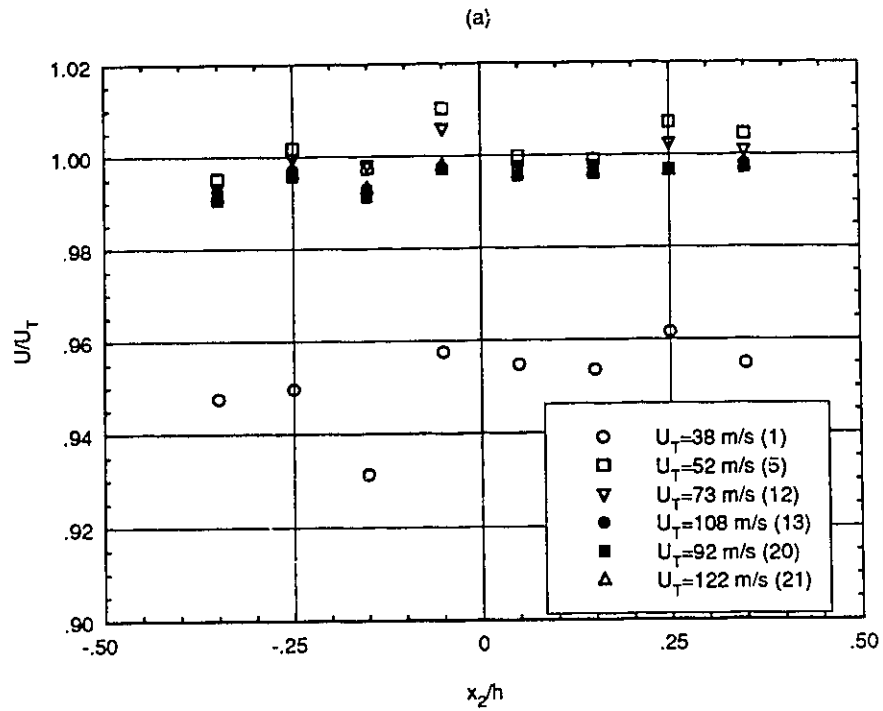


Figure 9 (a,b). For caption see next page.

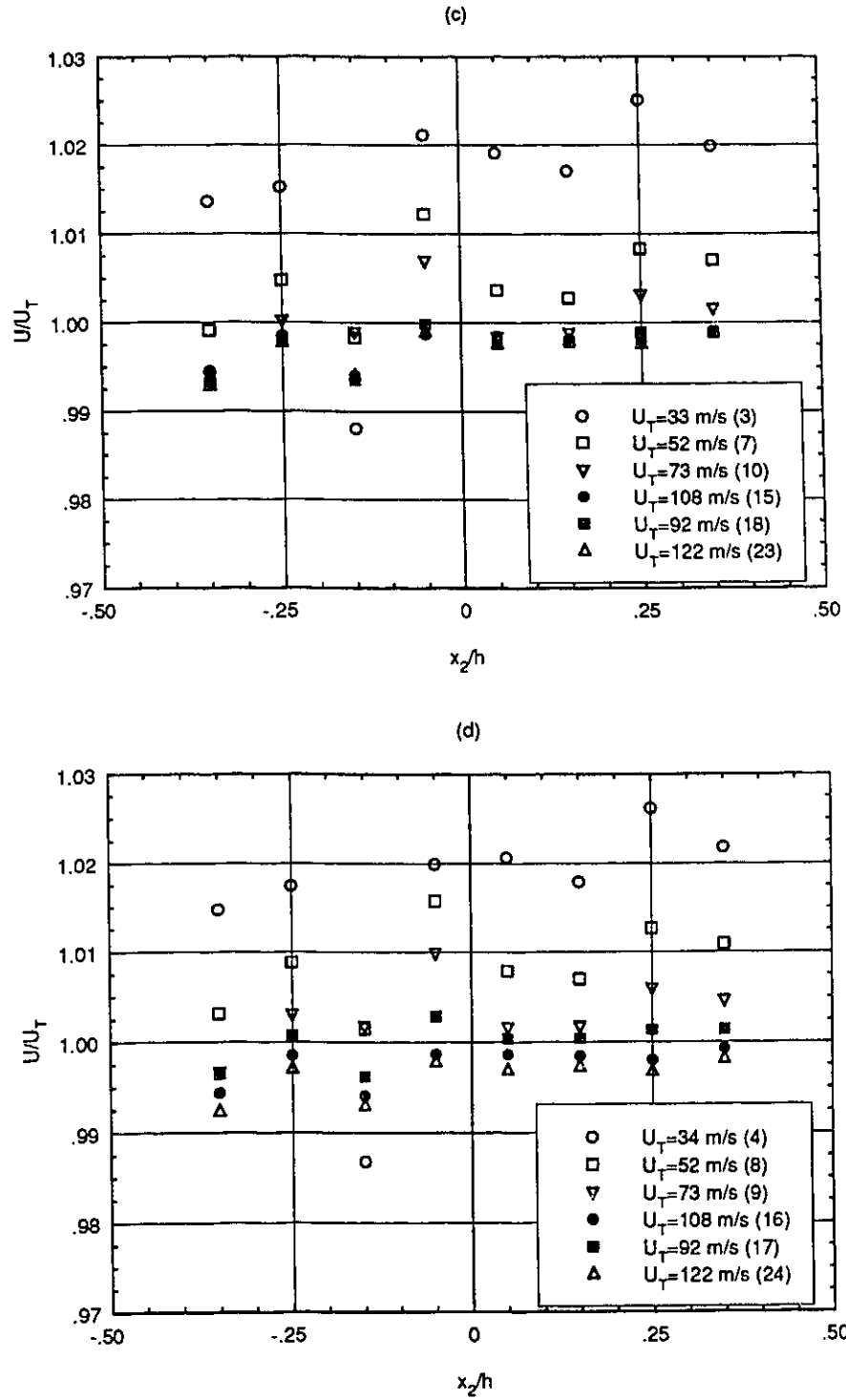


Figure 9 Pitot tube rake response in empty tunnel. The sequence of runs is indicated in brackets on legends. (a) $P_0=165$ kPa; (b) $P_0=179$ kPa; (c) $P_0=193$ kPa; (d) $P_0=207$ kPa.

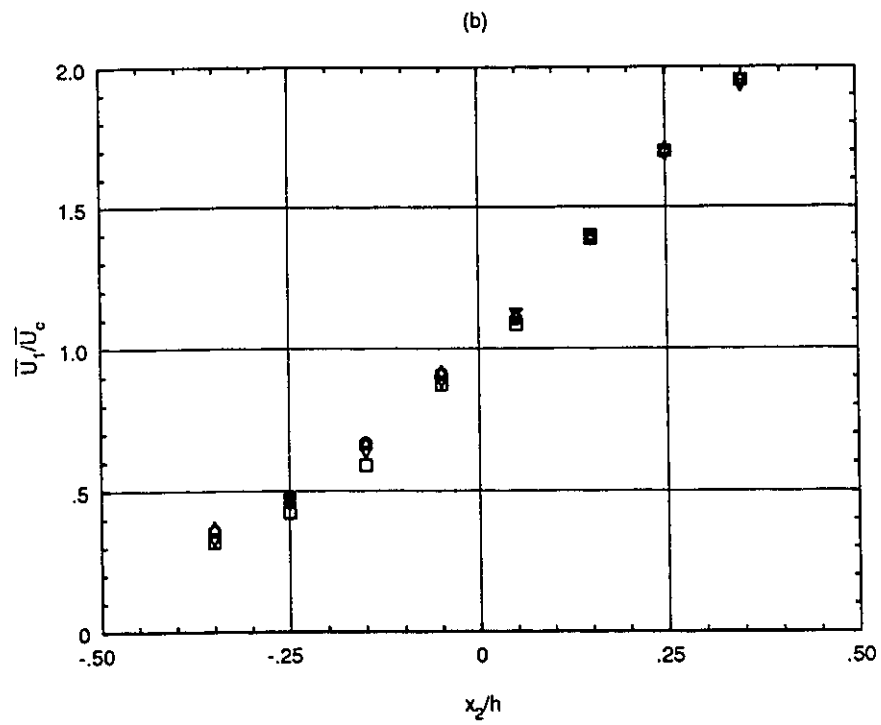
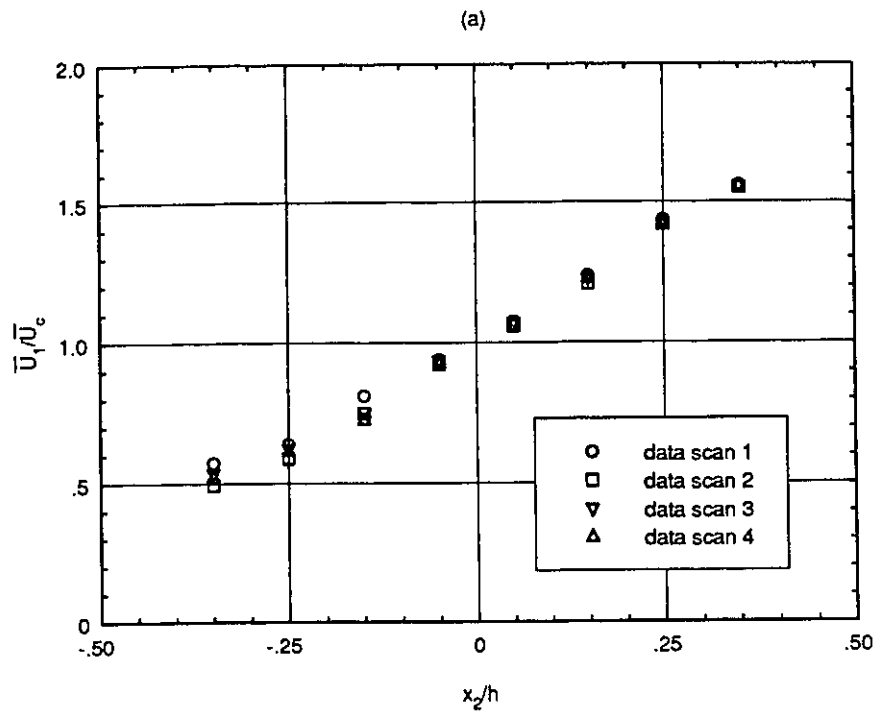


Figure 10 (a,b). For caption see next page.

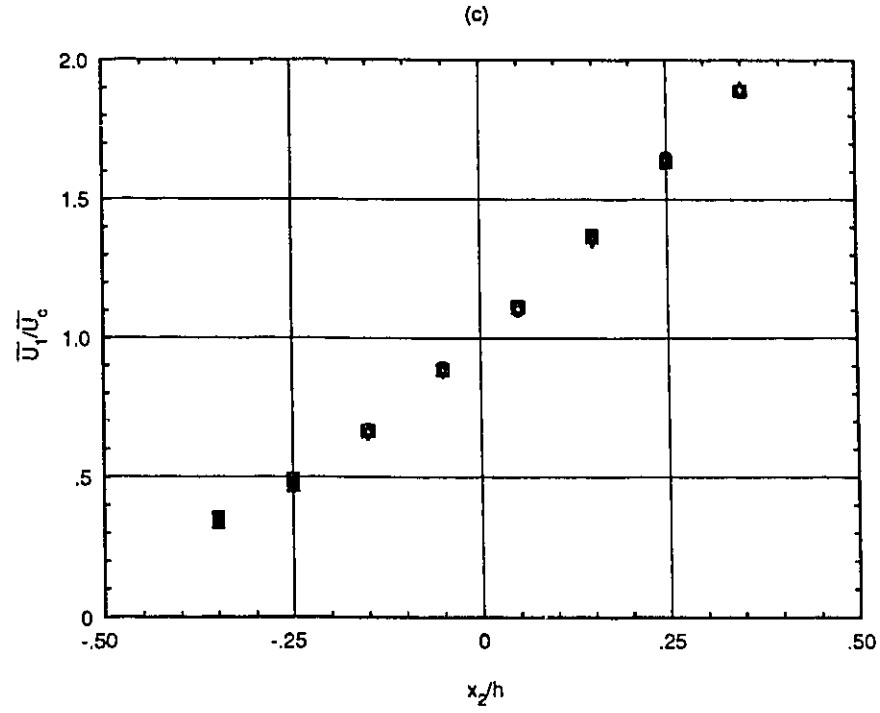


Figure 10 Initial test of shear generator with perforated plates #1 and #2. Symbols as in (a). (a) Plate #1, $\bar{U}_c=35.5$ m/s; (b) Plate #2, $\bar{U}_c=32.1$ m/s; (c) Plate #2, $\bar{U}_c=47.2$ m/s.

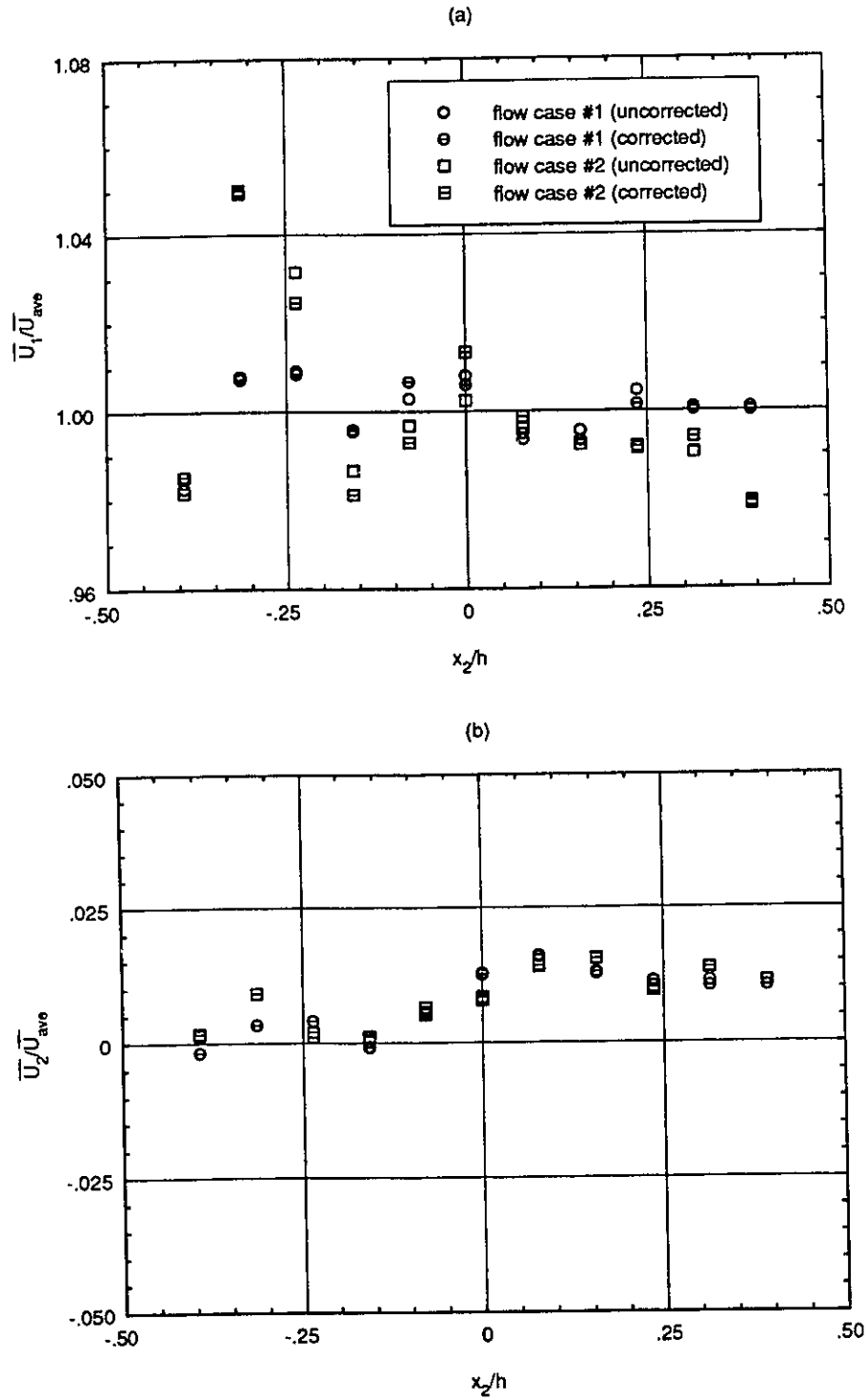


Figure 11 (a,b). Transverse variation of mean velocities in empty tunnel via LDV. Symbols as in (a). (a) streamwise mean velocity; (b) spanwise mean velocity.

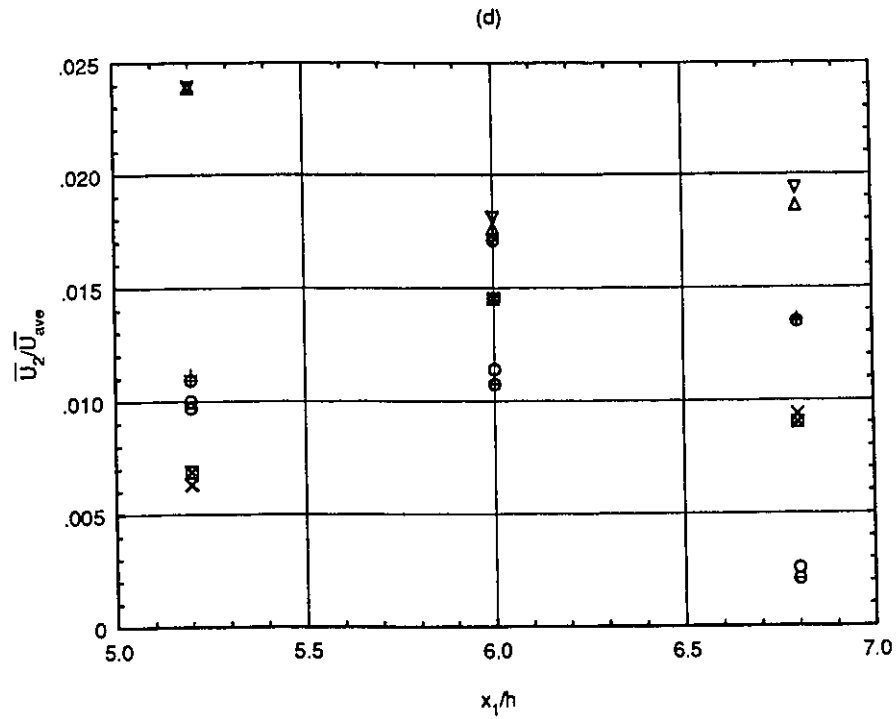
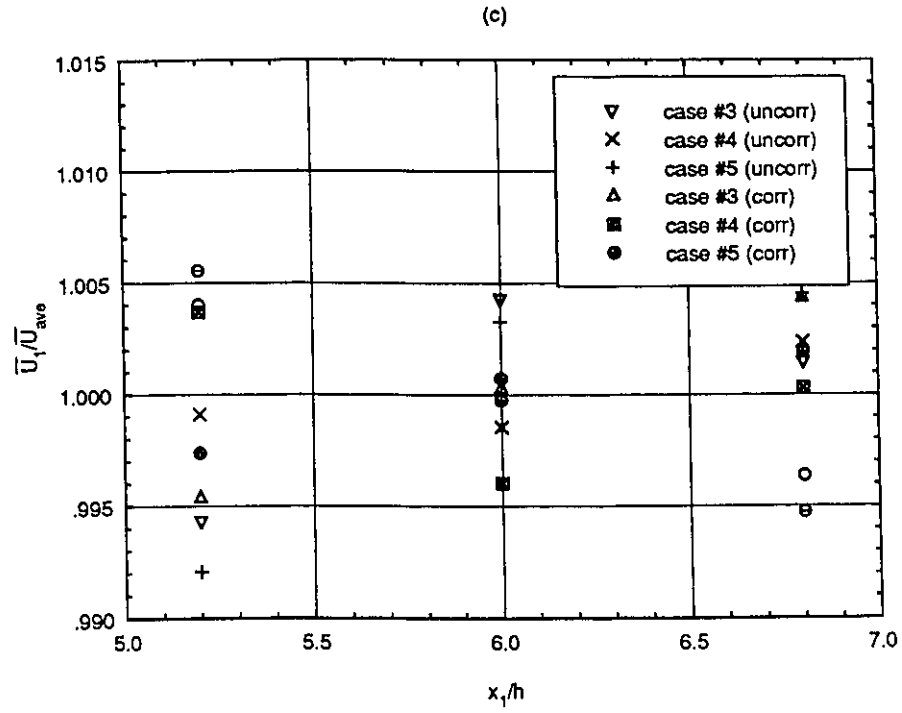


Figure 11 (c,d). Downstream development of mean velocities in empty tunnel measured by LDV. Symbols as in (a) and (c). (c) streamwise mean velocity; (d) spanwise mean velocity.

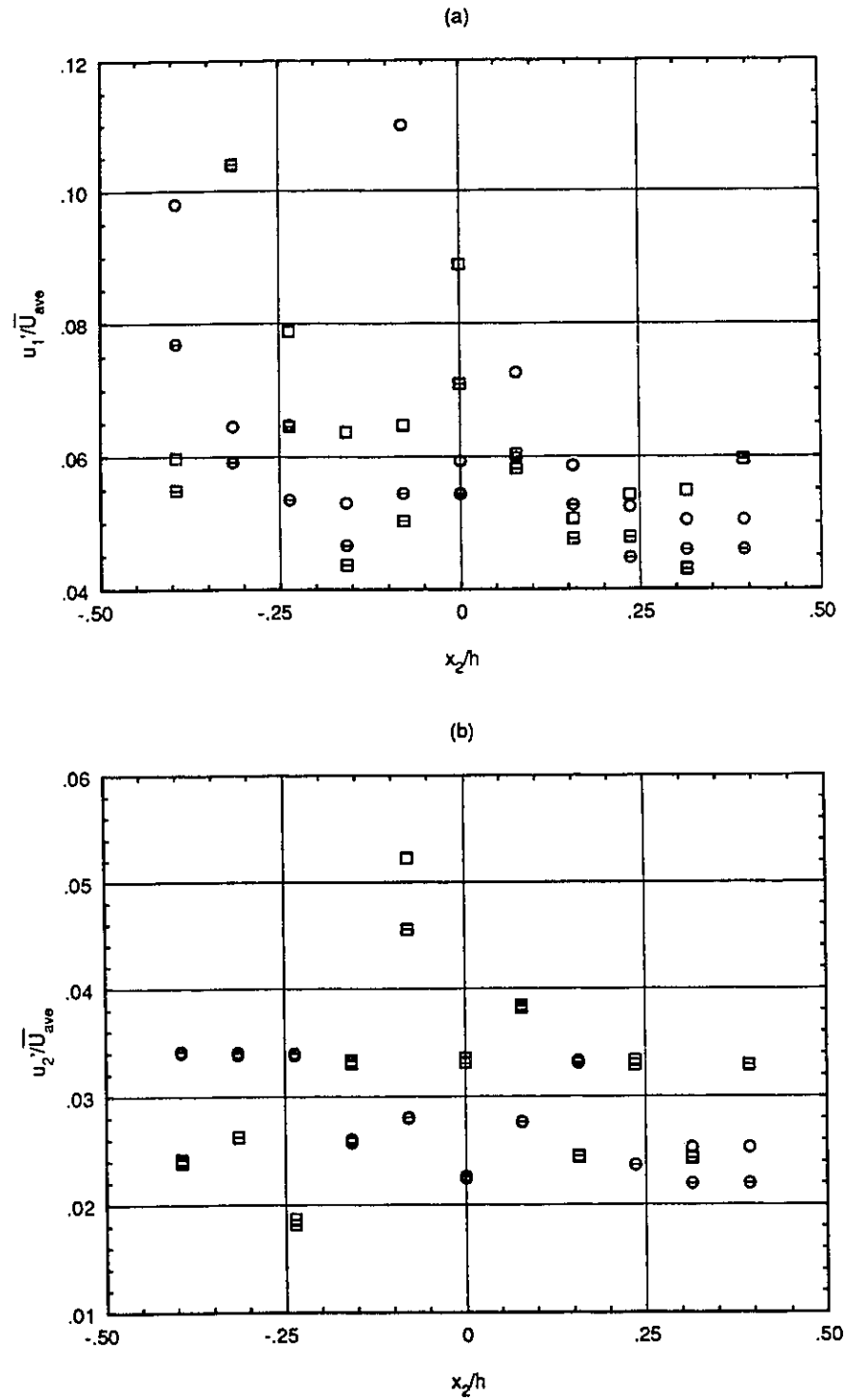


Figure 12 (a,b). Transverse variation of turbulent fluctuations in empty tunnel measured by LDV. Symbols as in figure 11. (a) streamwise velocity fluctuation; (b) spanwise velocity fluctuation.

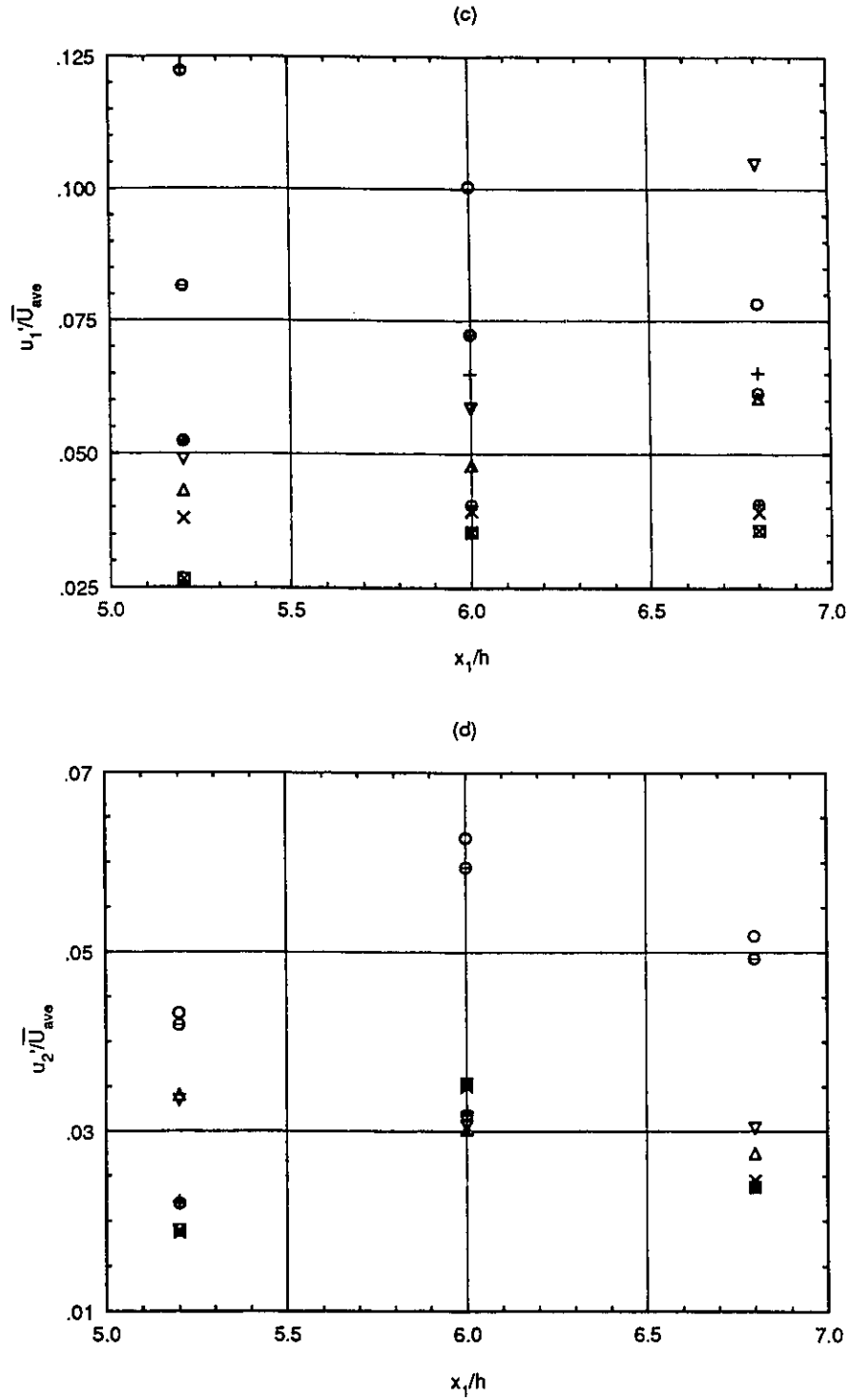


Figure 12 (c,d). Downstream development of turbulent fluctuations in empty tunnel measured by LDV. Symbols as in figure 11. (c) streamwise velocity fluctuation; (d) spanwise velocity fluctuation.

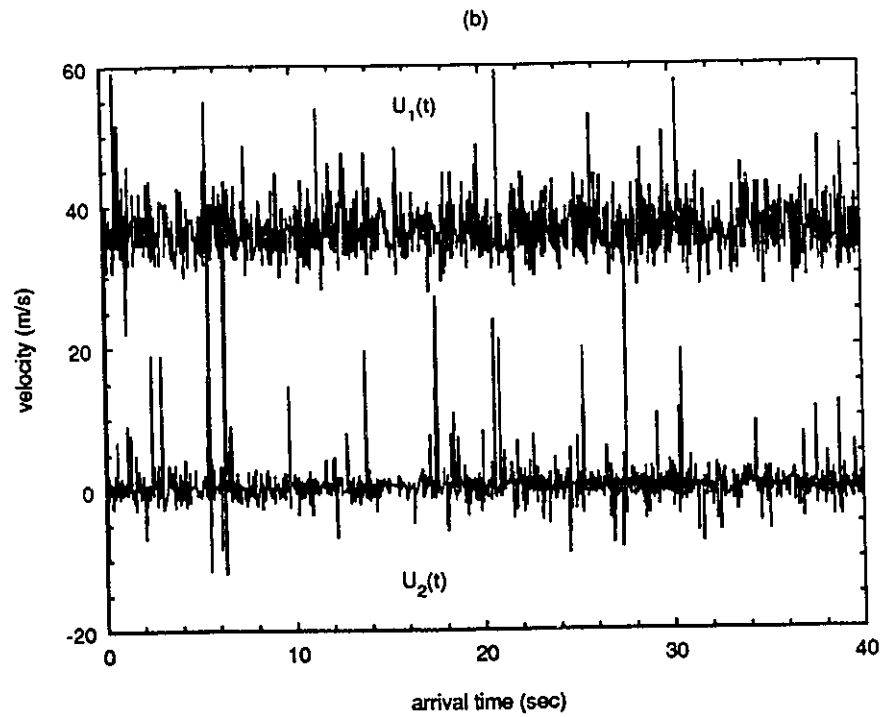
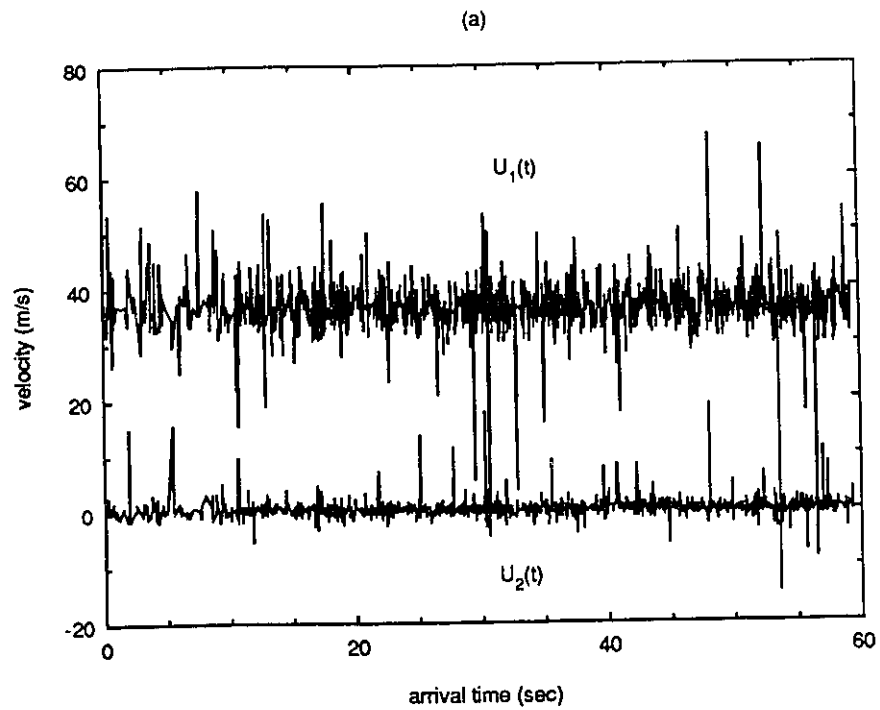


Figure 13 (a,b). For caption see next page.

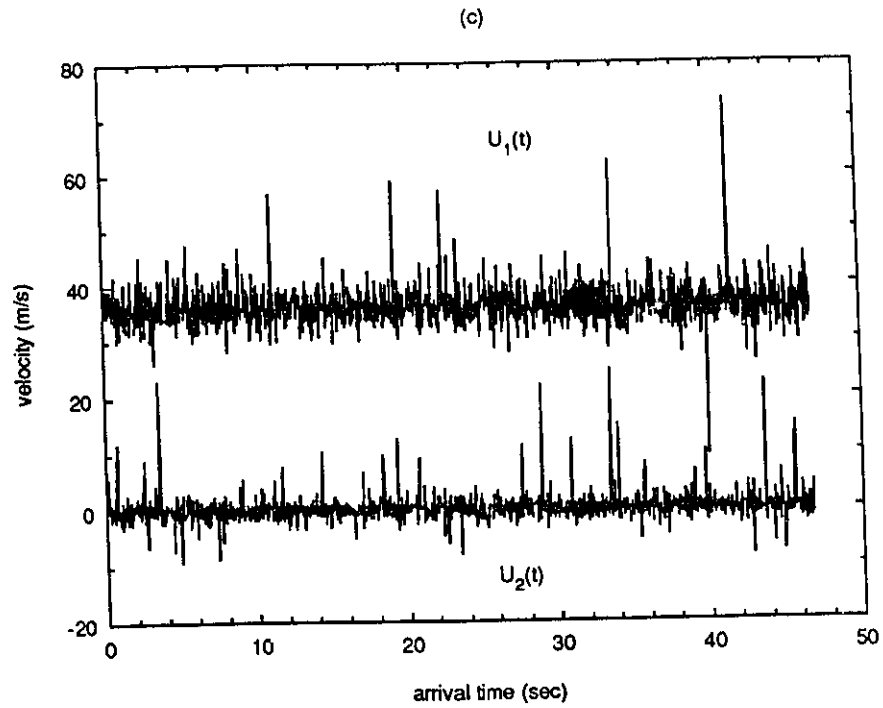


Figure 13 Velocity time series in empty tunnel for flow case #1. (a) $x_1/h=5.2$; (b) $x_1/h=6.0$; (c) $x_1/h=6.8$.

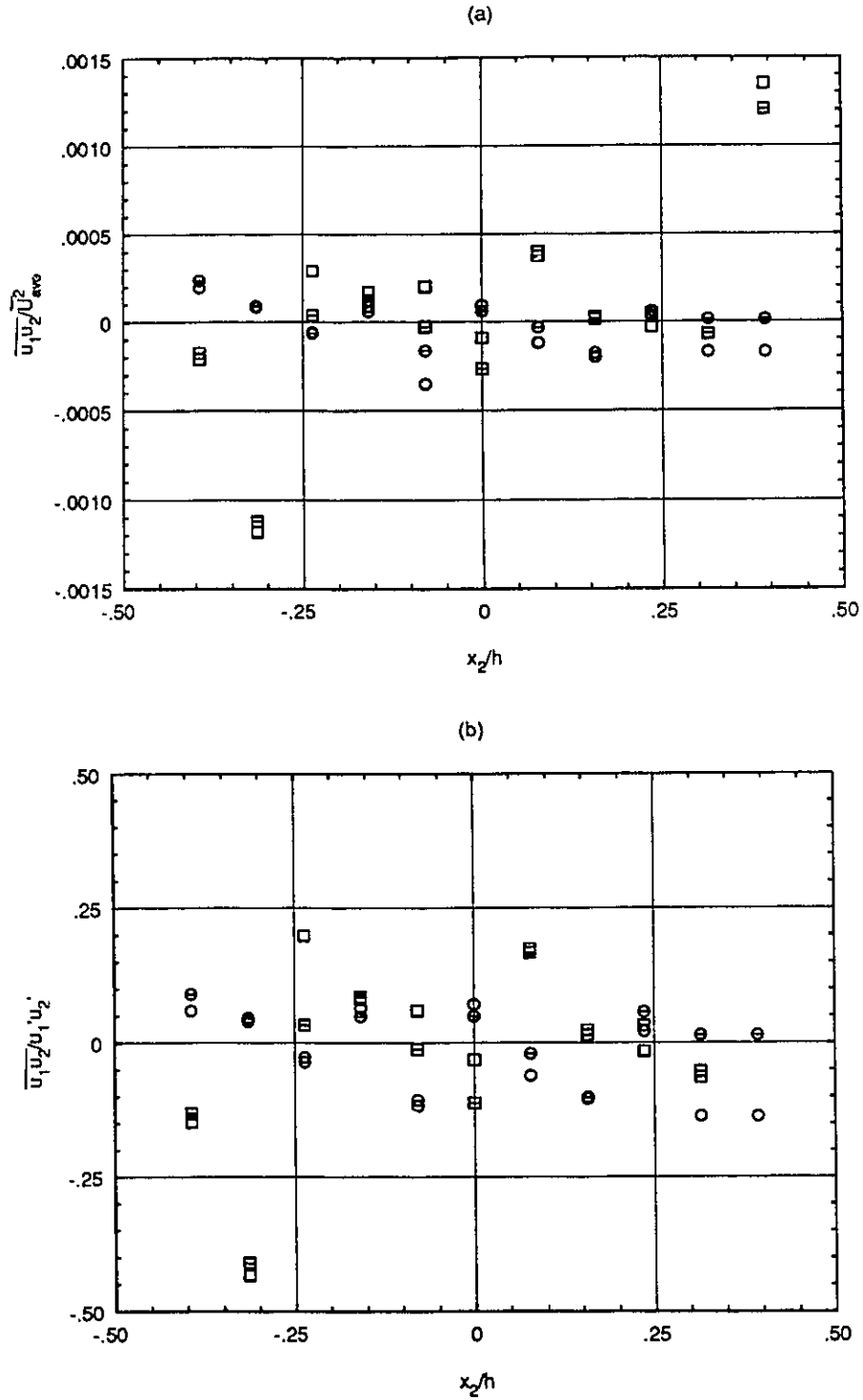


Figure 14 (a,b). Transverse variation of Reynolds shear stress in empty tunnel via LDV. Symbols as in figure 11. (a) dimensionless covariance; (b) Reynolds stress correlation coefficient.

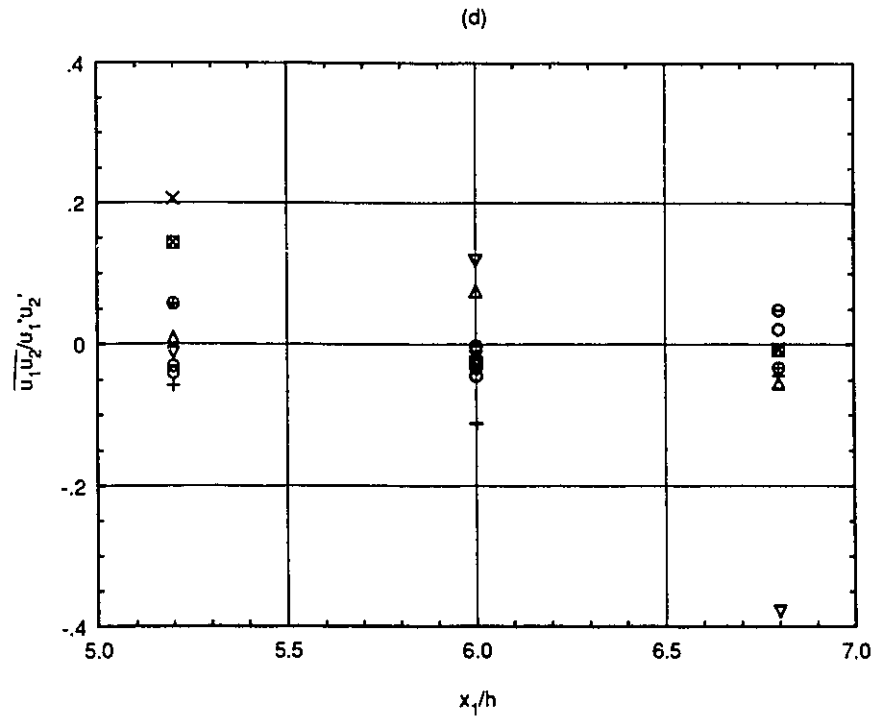
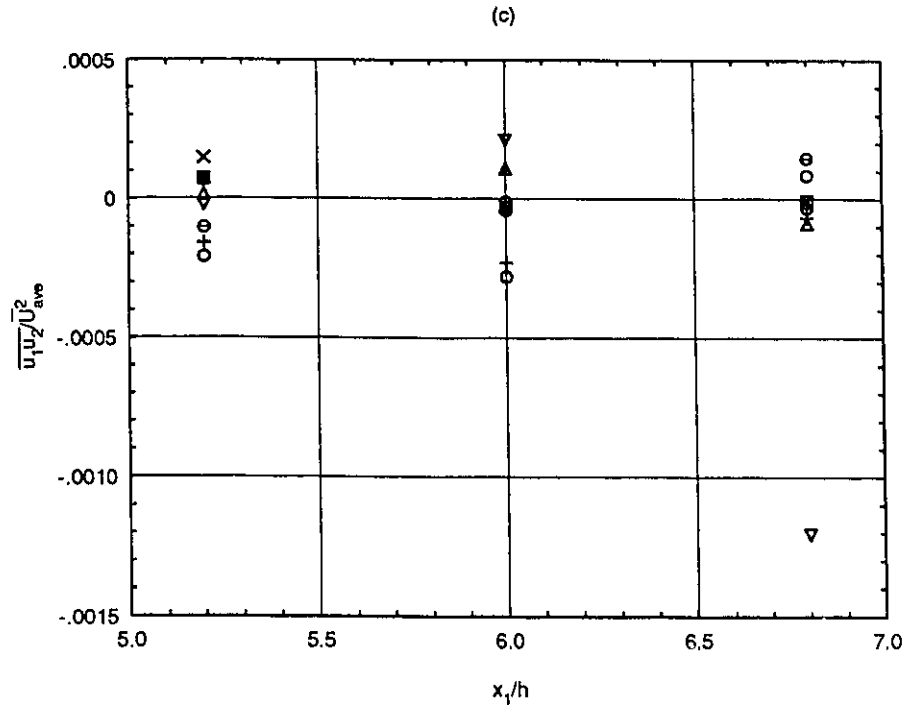


Figure 14 (c,d). Downstream development of Reynolds shear stress in empty tunnel measured by LDV. Symbols as in figure 11. (c) dimensionless covariance; (d) Reynolds stress correlation coefficient.

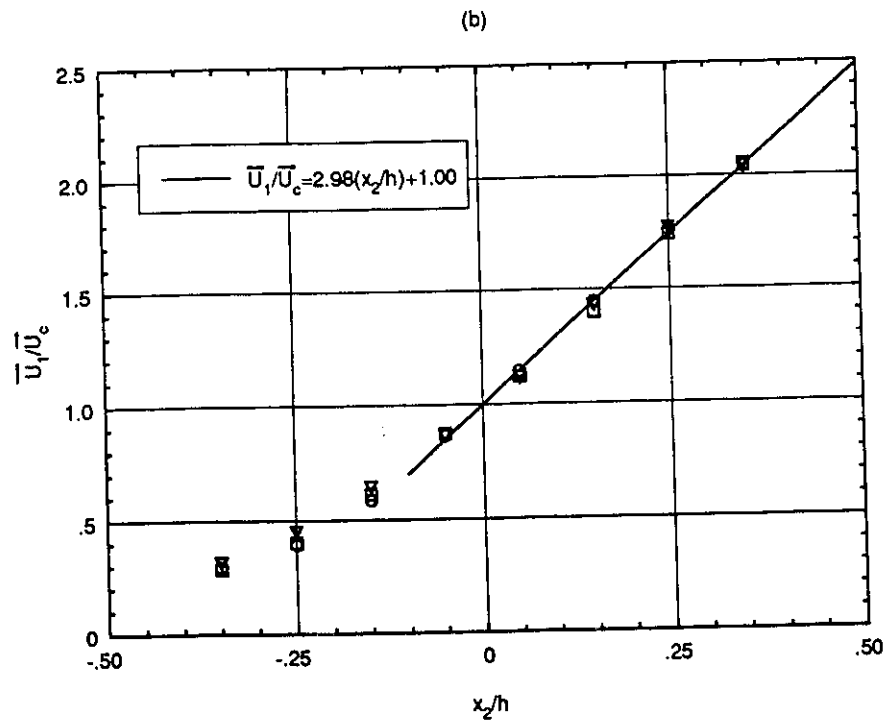
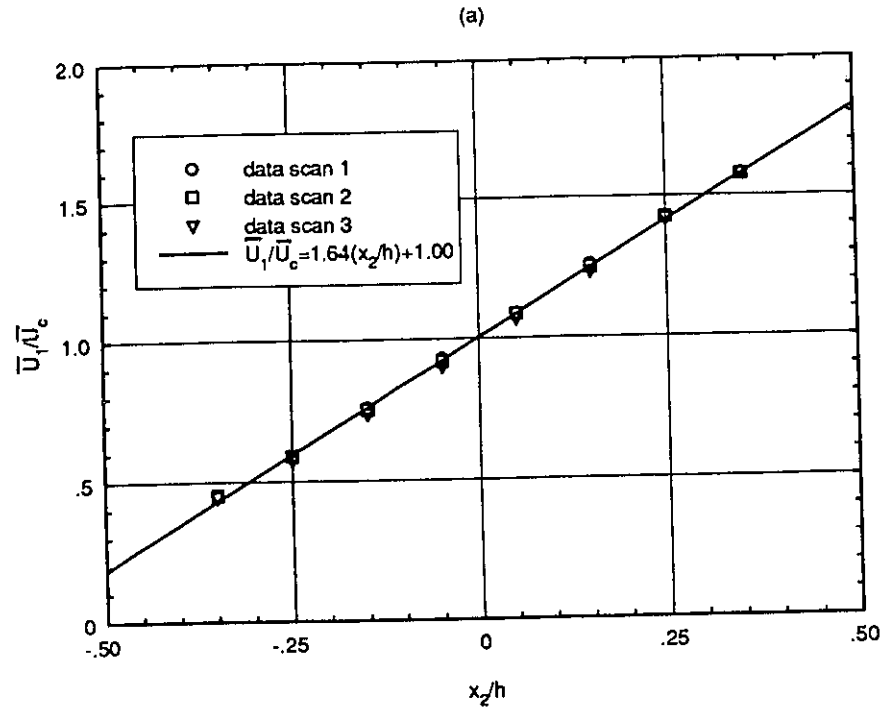


Figure 15 (a,b). For caption see next page.

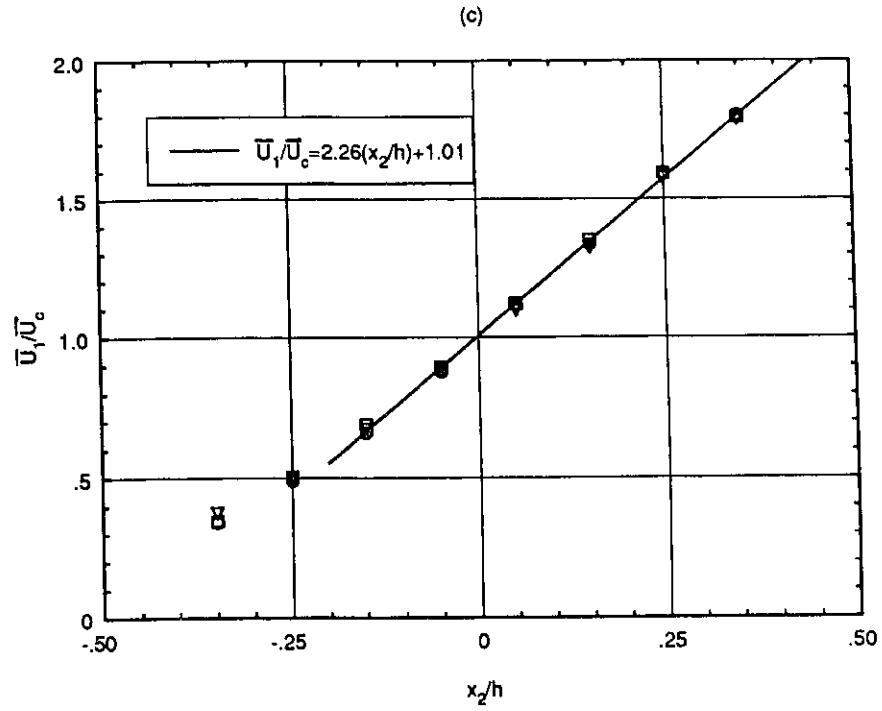


Figure 15 Mean velocity profiles measured by the Pitot tube rake. Symbols as in (a). (a) Plate #1, $\bar{U}_c=36.1$ m/s; (b) Plate #2, $\bar{U}_c=31.6$ m/s; (c) Plate #3, $\bar{U}_c=34.6$ m/s.

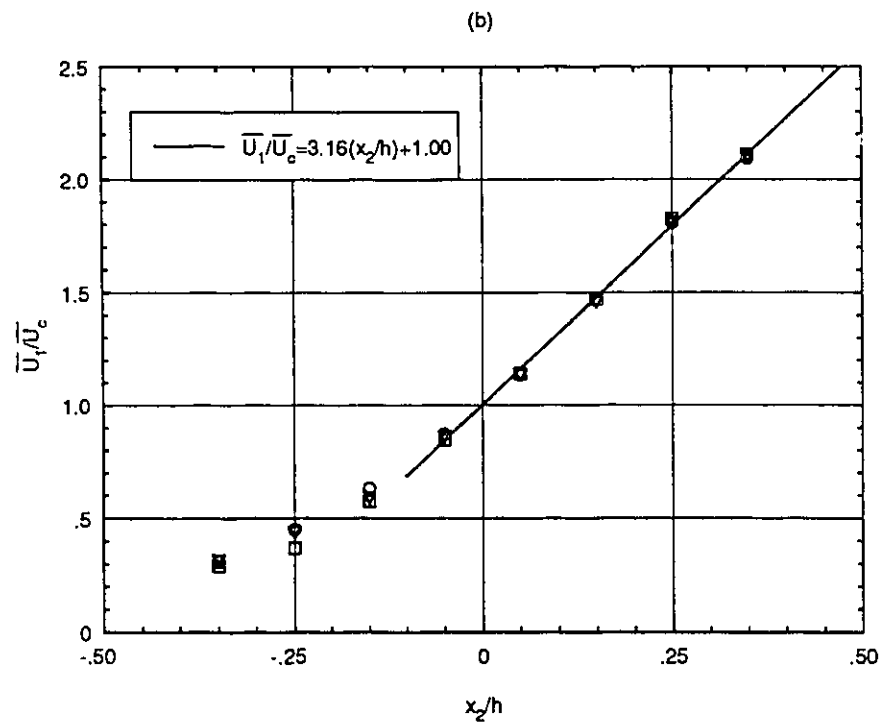
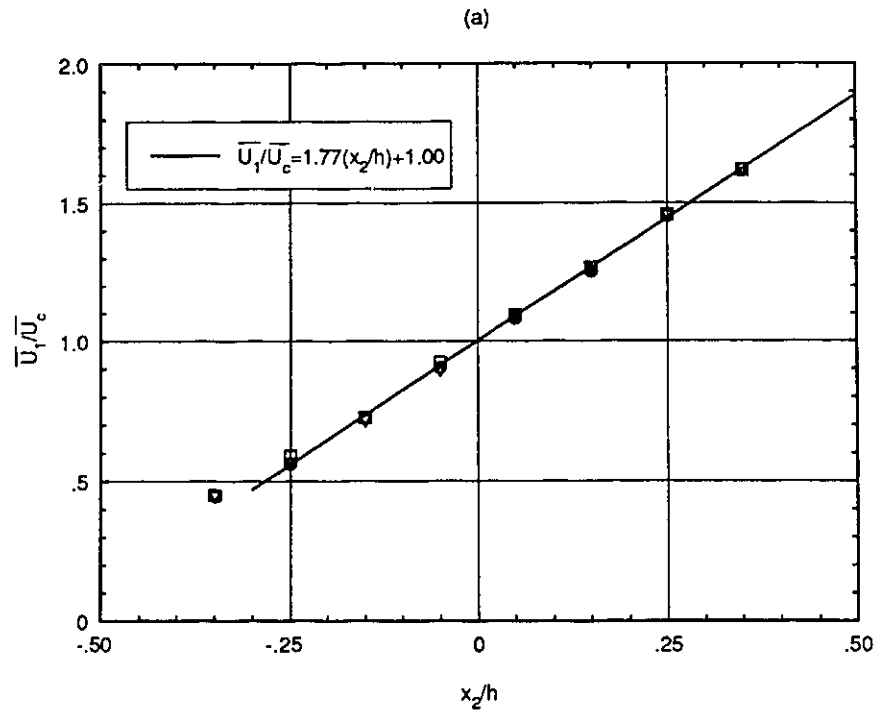


Figure 16 (a,b). For caption see next page.

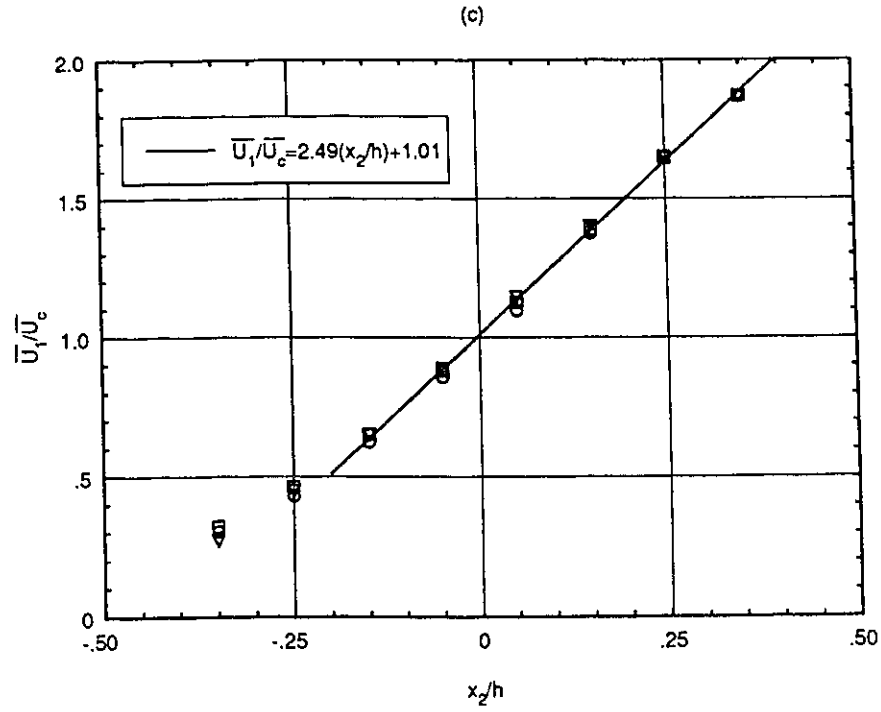


Figure 16 Velocity profiles via rake, bottom channel of generator blocked. Symbols as in figure 15. (a) Plate #1, $\bar{U}_c=35.8$ m/s; (b) Plate #2, $\bar{U}_c=31.2$ m/s; (c) Plate #3, $\bar{U}_c=33.8$ m/s.

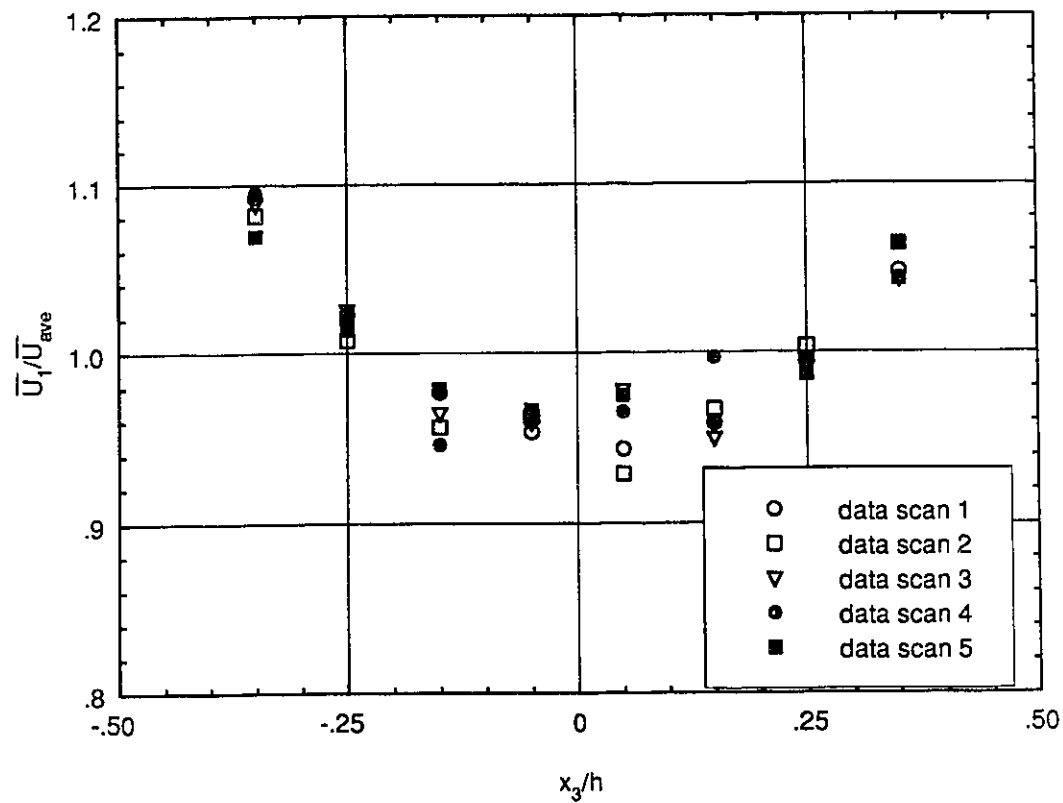


Figure 17 Spanwise variation of mean velocity measured by Pitot tube rake. Plate #3, $\bar{U}_{ave}=33.0$ m/s.

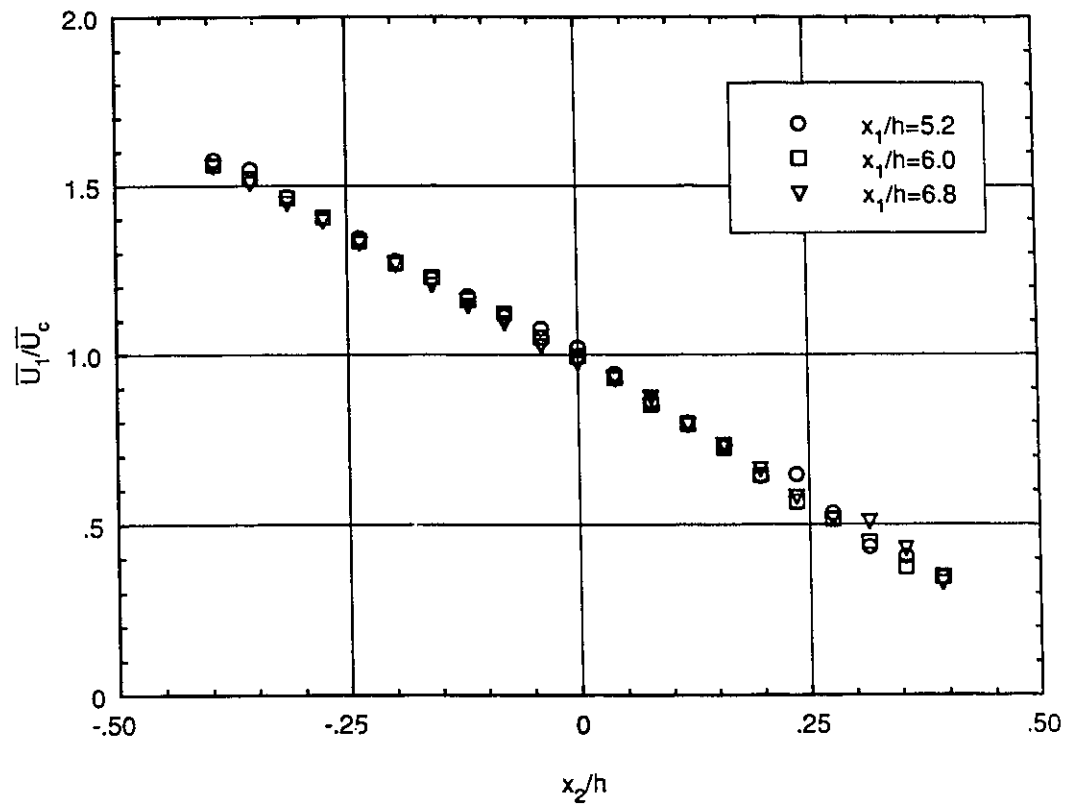


Figure 18 Transverse variation of streamwise mean velocity. Flow case #1.

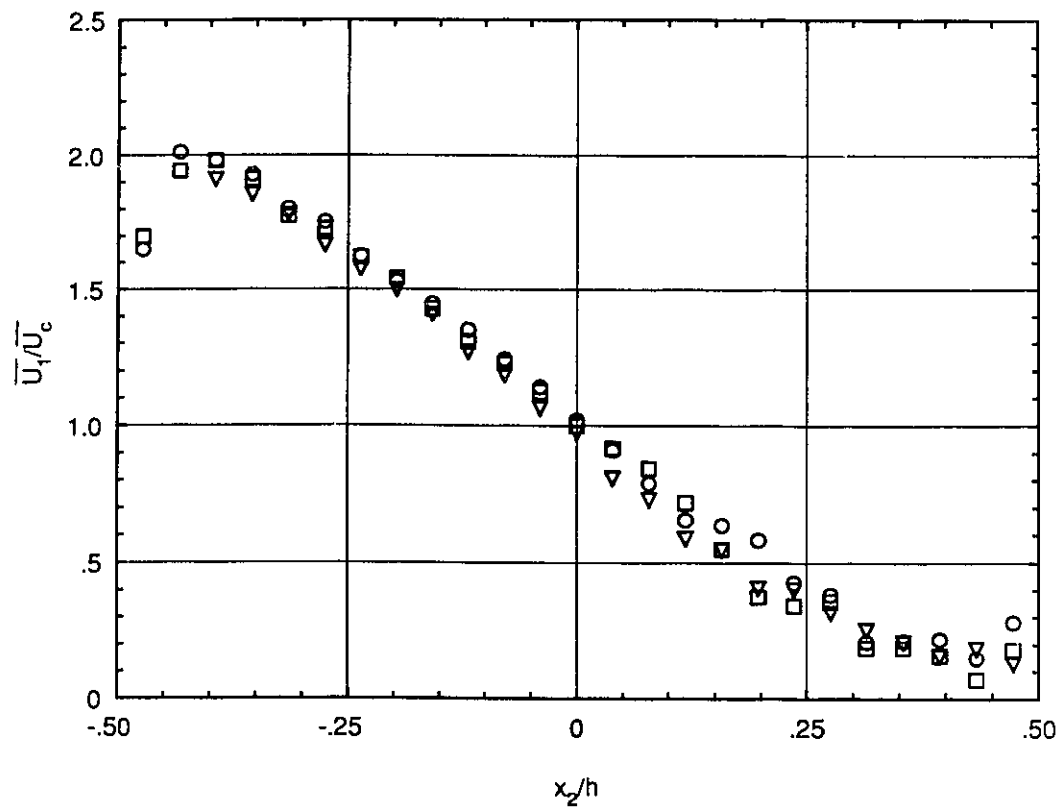


Figure 19 Transverse variation of streamwise mean velocity. Flow case #2. Symbols as in figure 18.

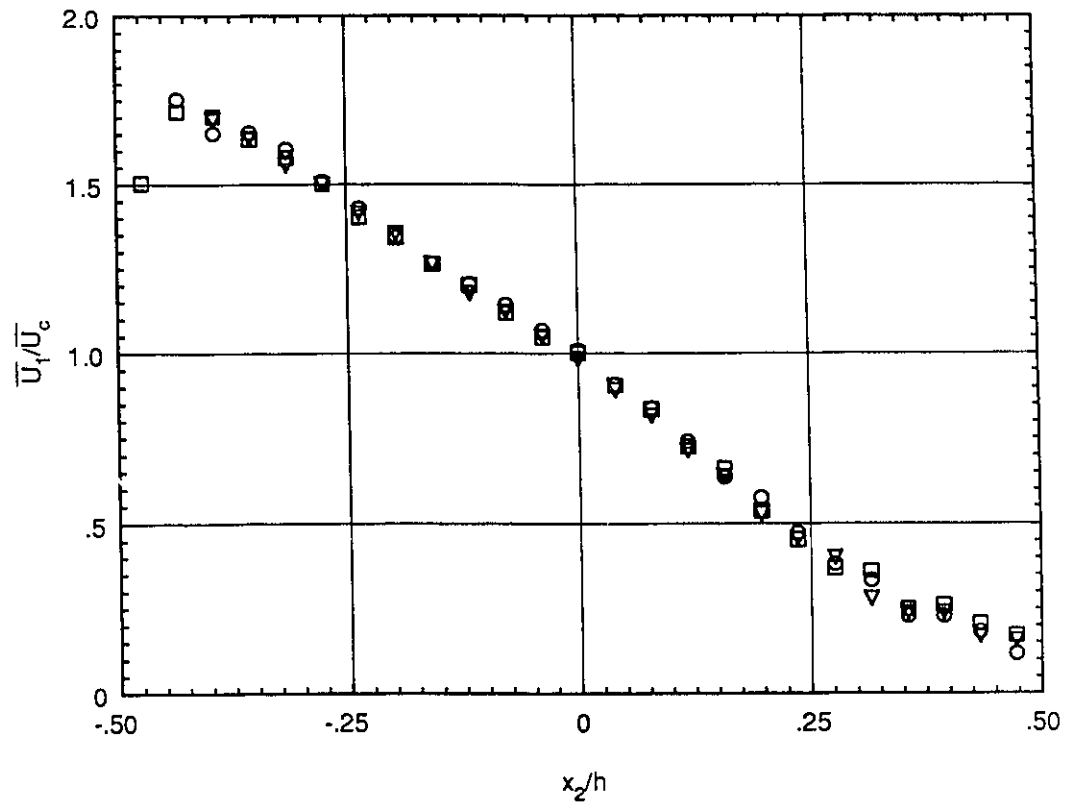


Figure 20 Transverse variation of streamwise mean velocity. Flow case #3. Symbols as in figure 18.

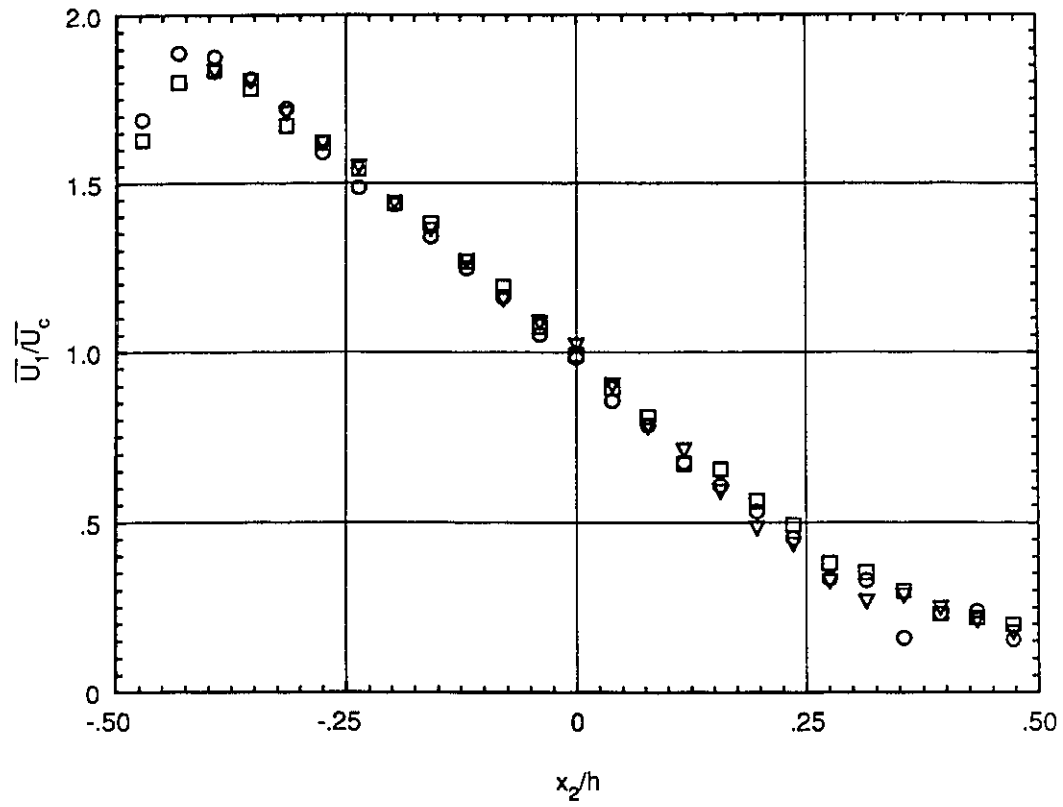


Figure 21 Transverse variation of streamwise mean velocity. Flow case #4. Symbols as in figure 18.

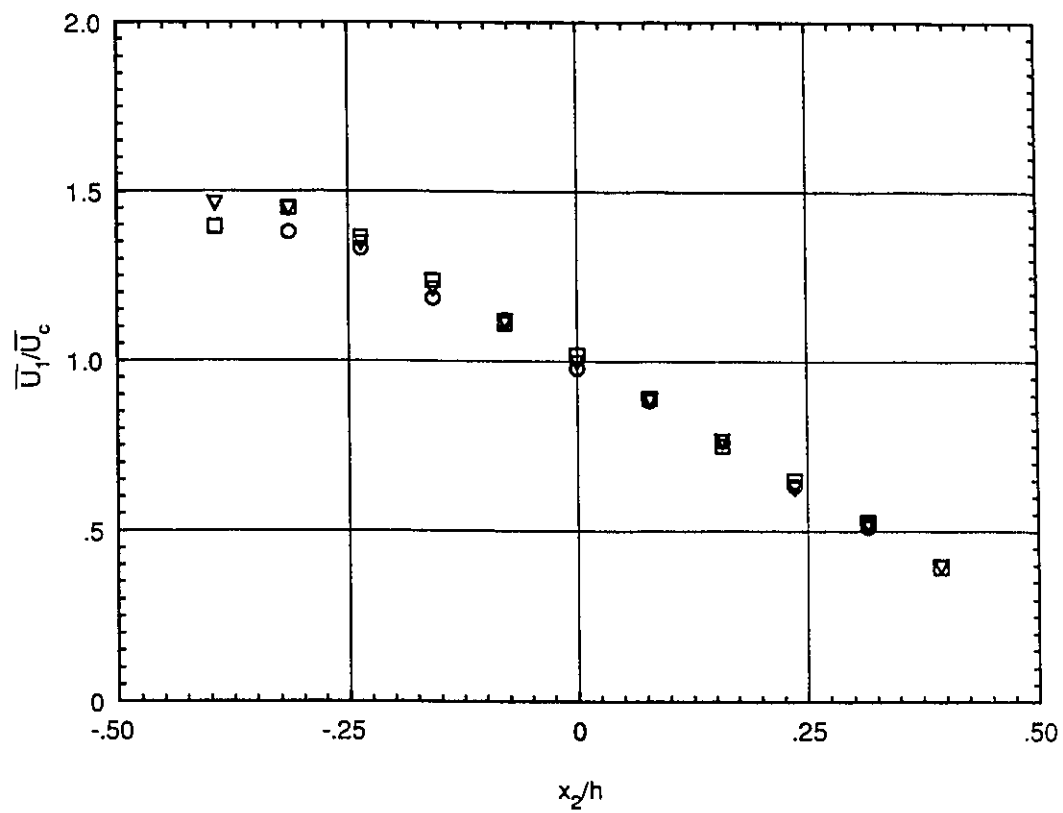


Figure 22 Transverse variation of streamwise mean velocity. Flow case #5. Symbols as in figure 18.

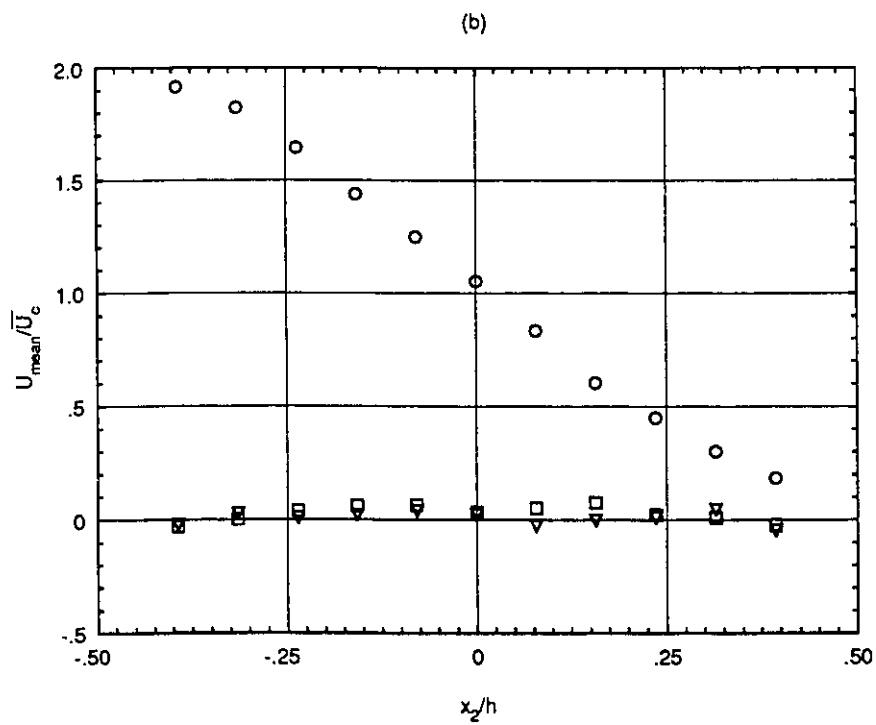
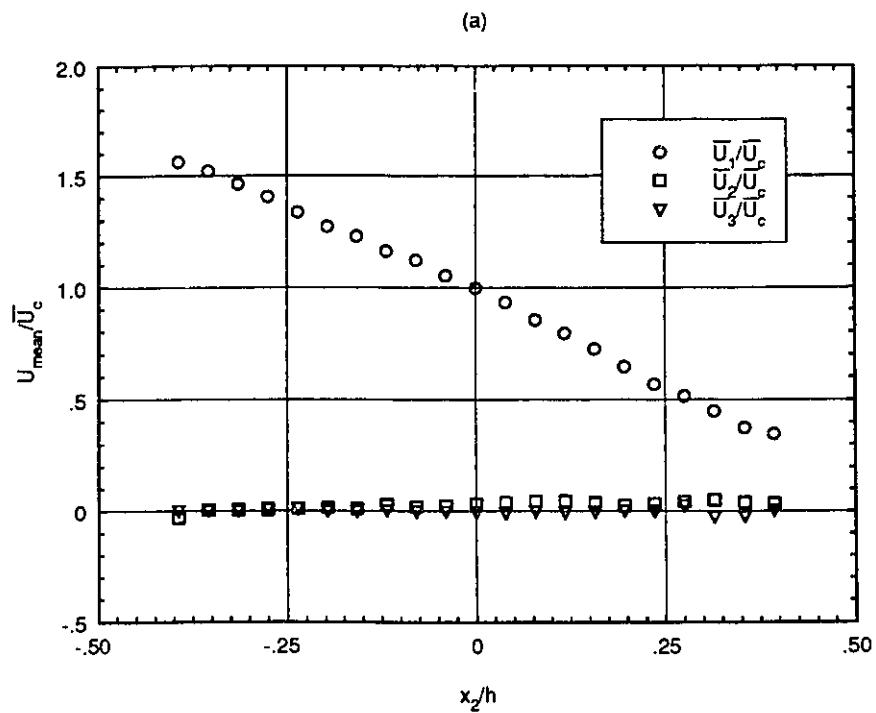


Figure 23 (a,b). For caption see page after next.

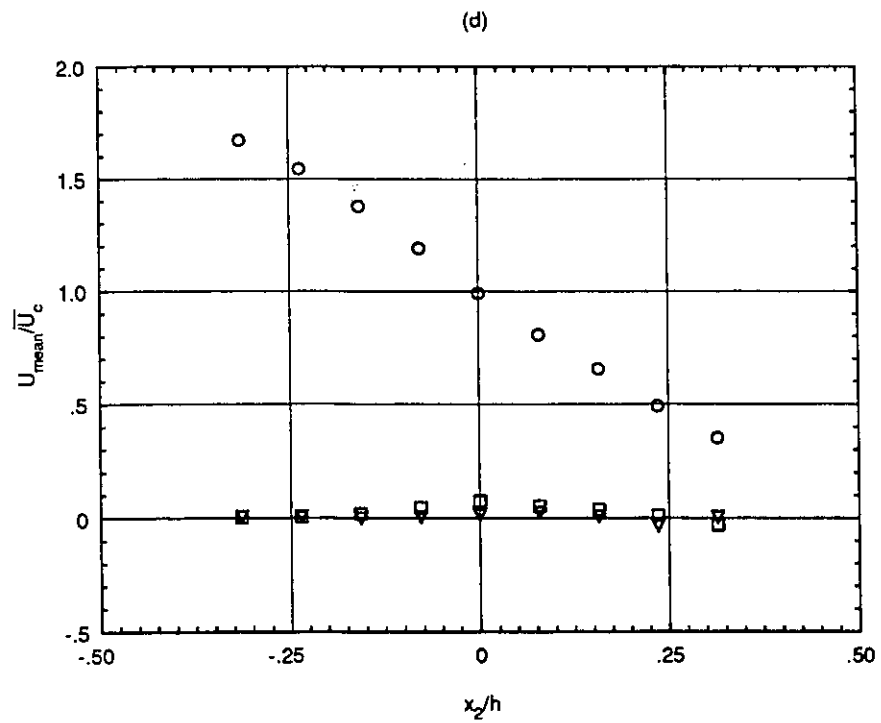
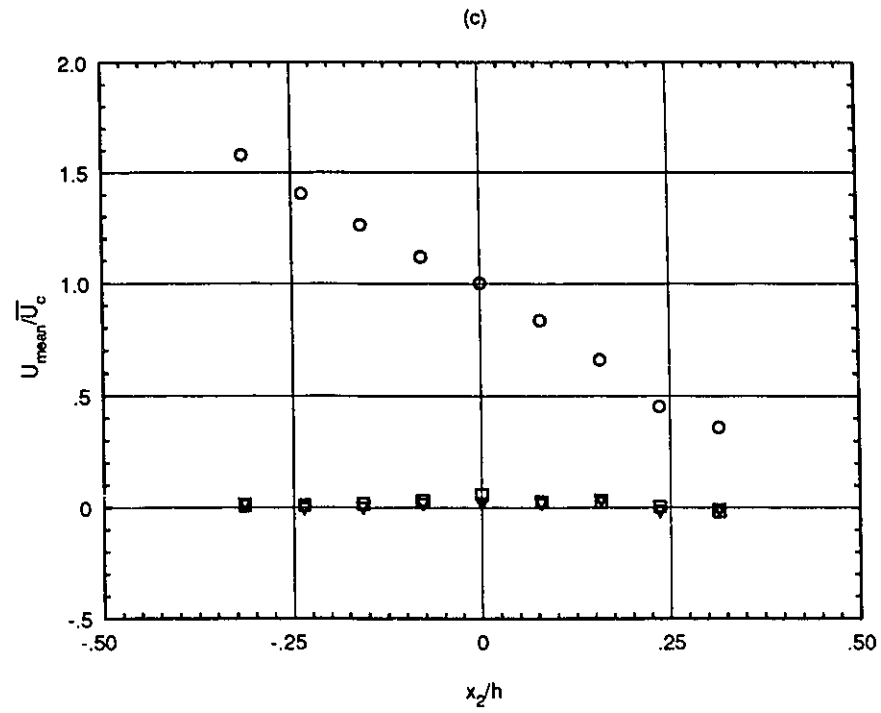


Figure 23 (c,d). For caption see next page.

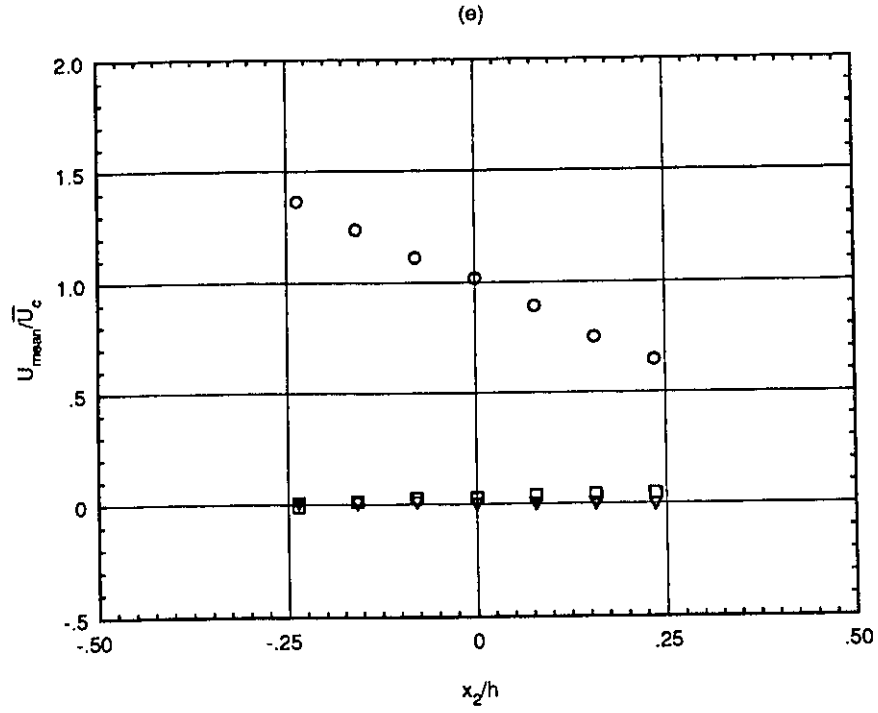


Figure 23 Transverse variation of mean velocities at $x_1/h=6.0$, $x_3/h=0$. Symbols as in (a). (a) Case #1; (b) Case #2; (c) Case #3; (d) Case #4; (e) Case #5.

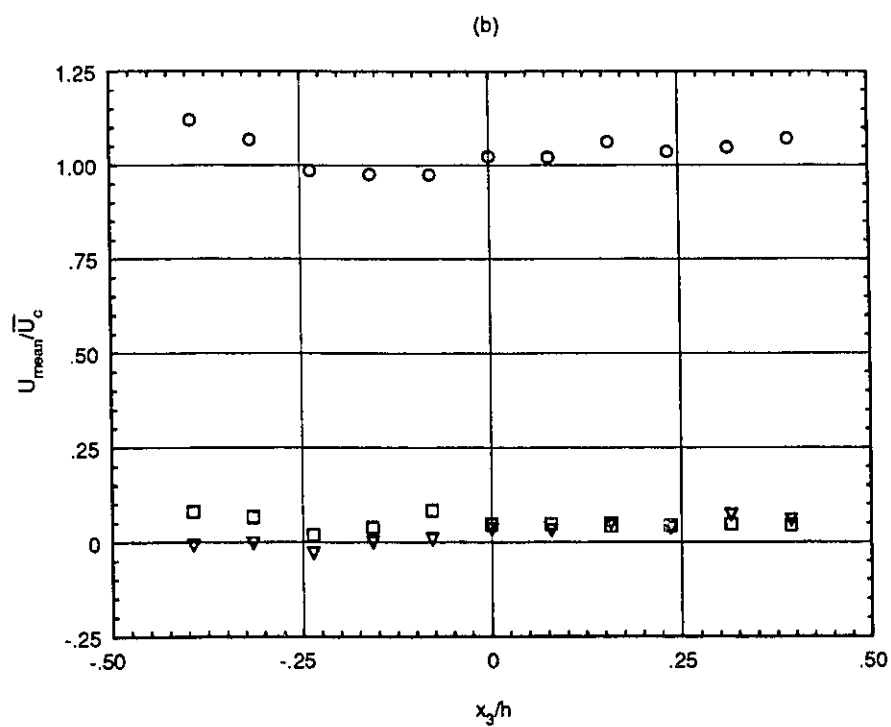
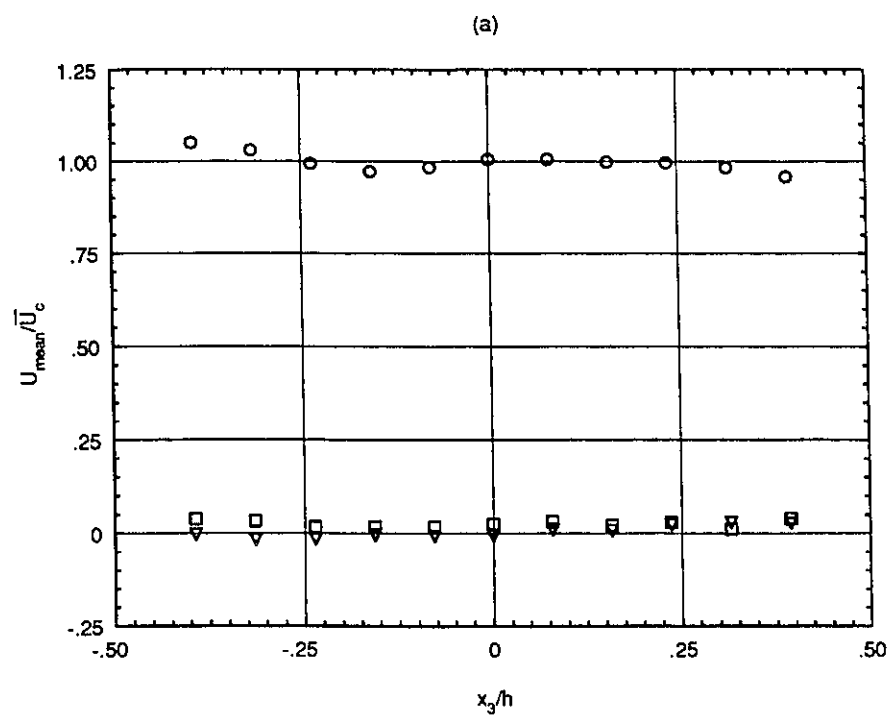


Figure 24 (a,b). For caption see page after next.

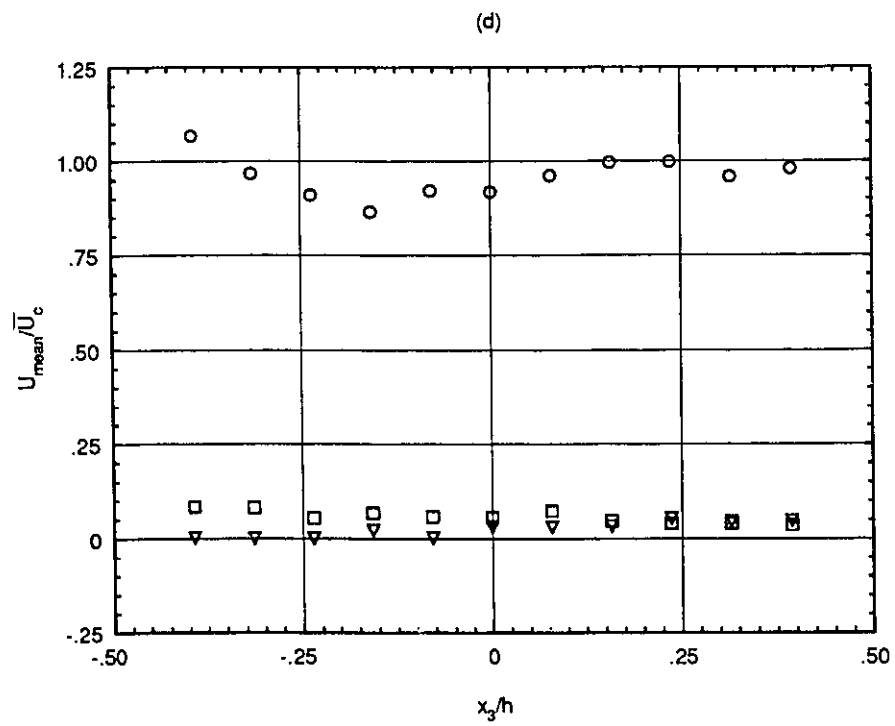
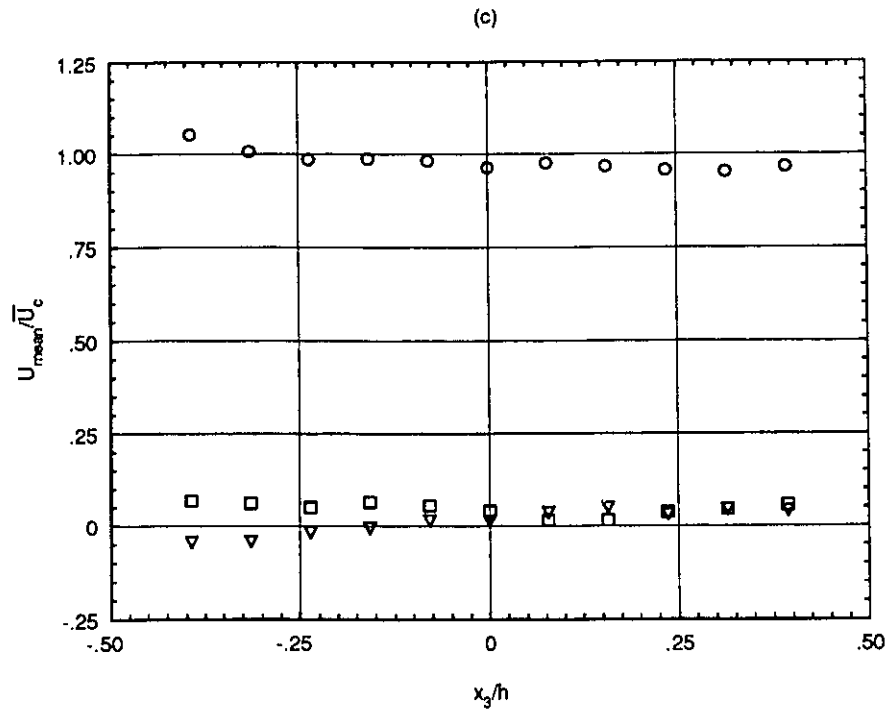


Figure 24 (c,d). For caption see next page.

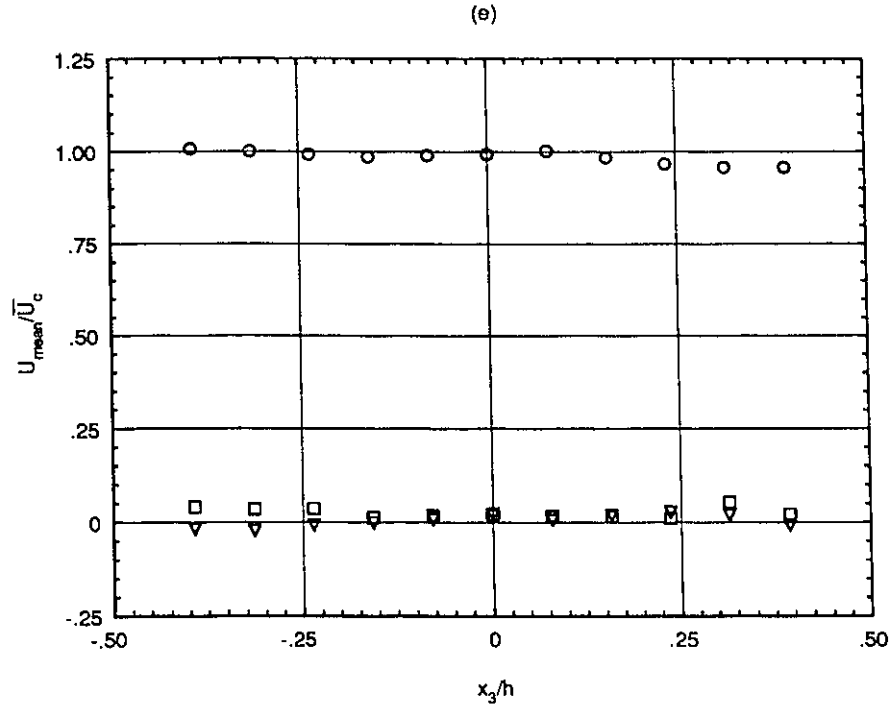


Figure 24 Spanwise variation of mean velocities at $x_1/h=6.0$, $x_2/h=0$. Symbols as in figure 23. (a) Case #1; (b) Case #2; (c) Case #3; (d) Case #4; (e) Case #5.

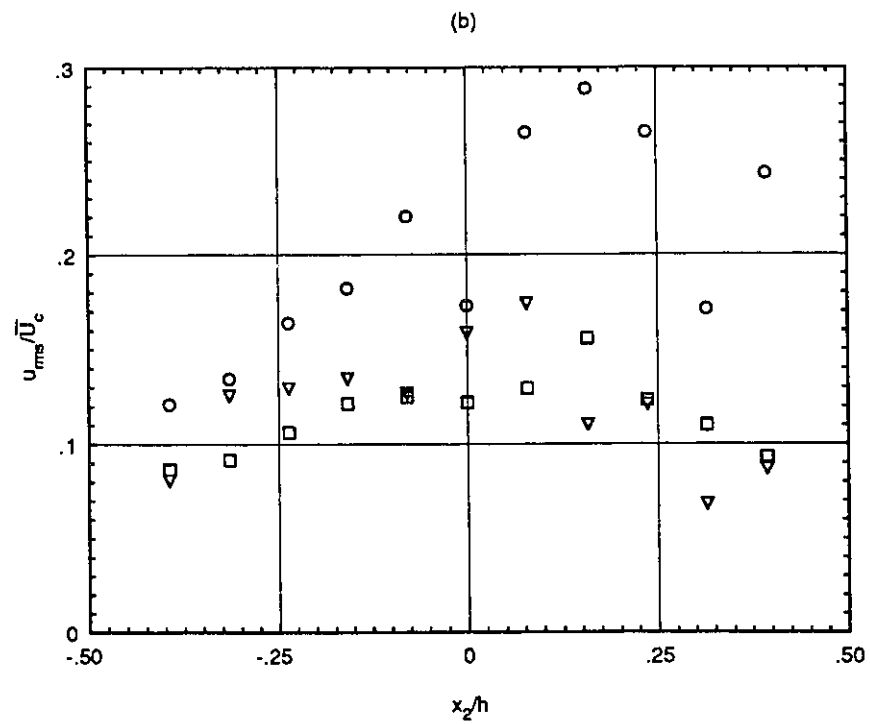
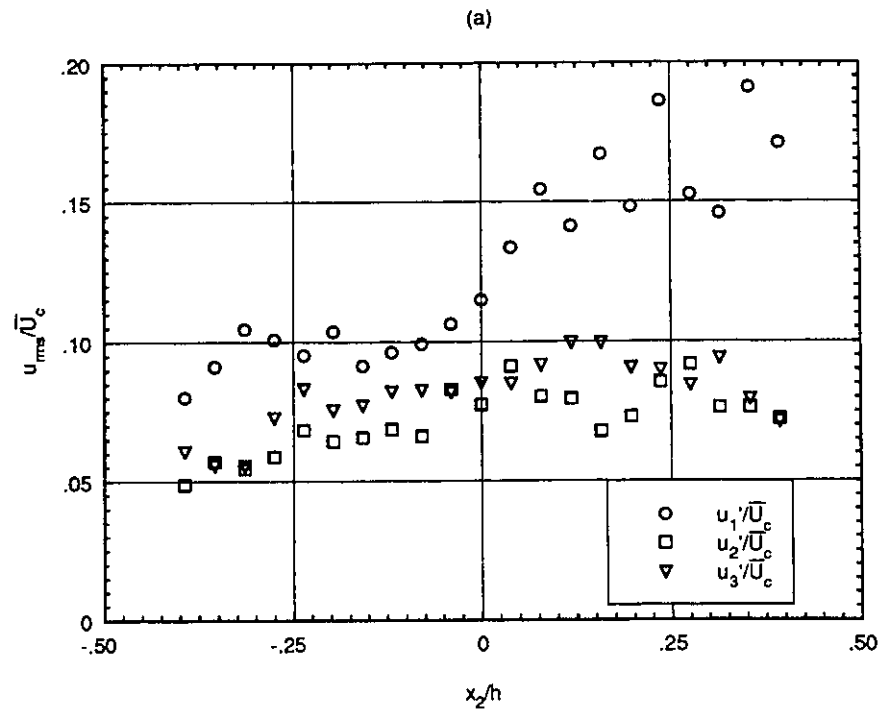


Figure 25 (a,b). For caption see page after next.

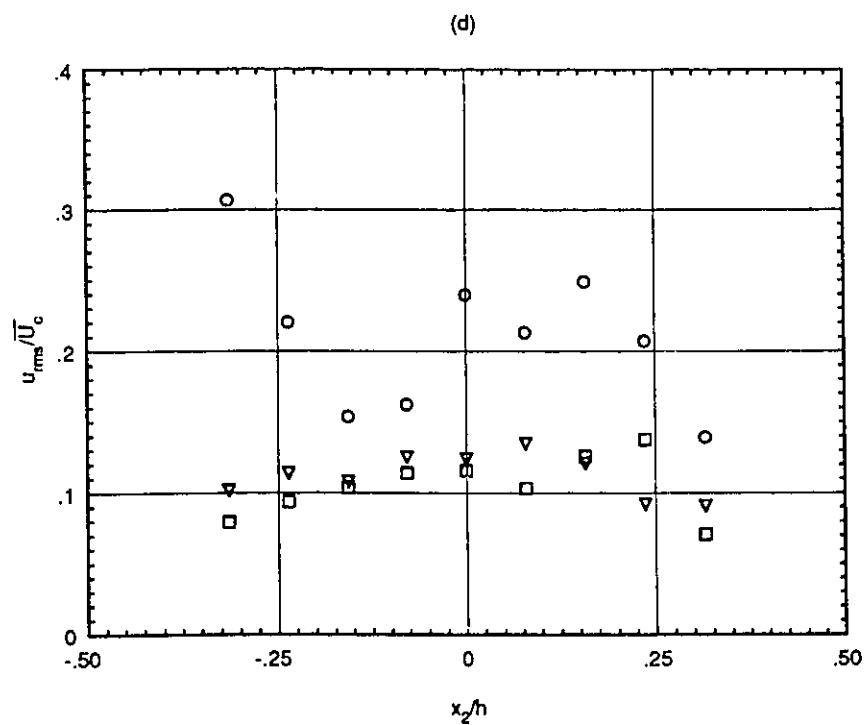
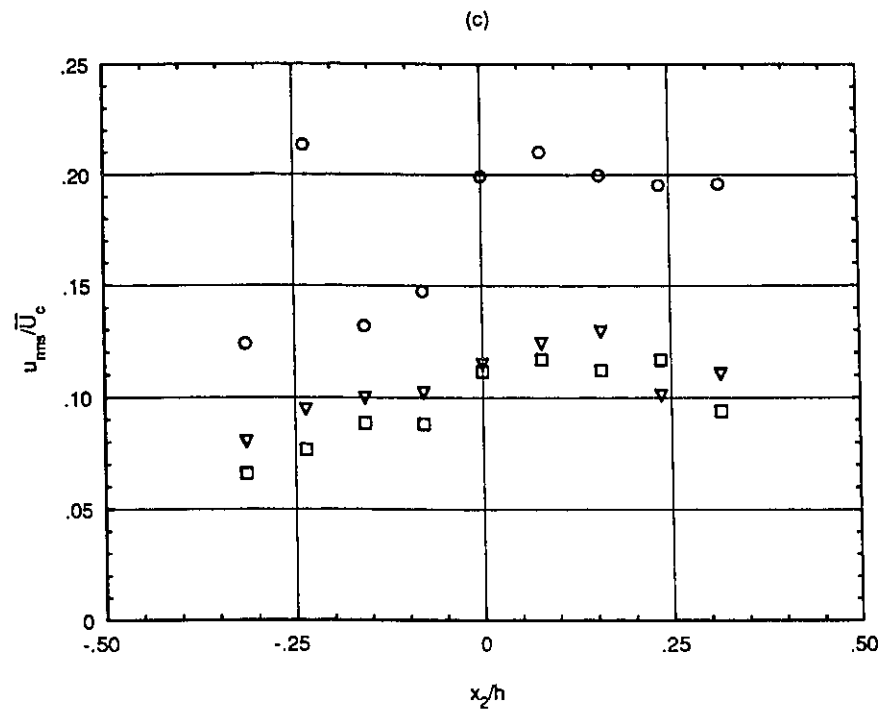


Figure 25 (c,d). For caption see next page.

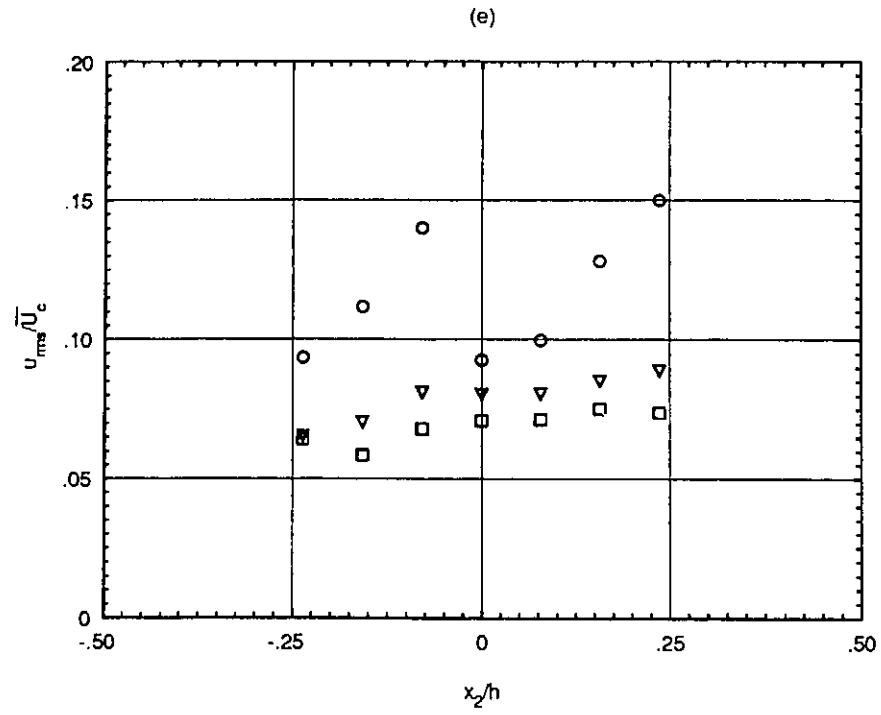


Figure 25 Transverse variation of rms velocities at $x_1/h=6.0$, $x_3/h=0$. Symbols as in (a). (a) Case #1; (b) Case #2; (c) Case #3; (d) Case #4; (e) Case #5.

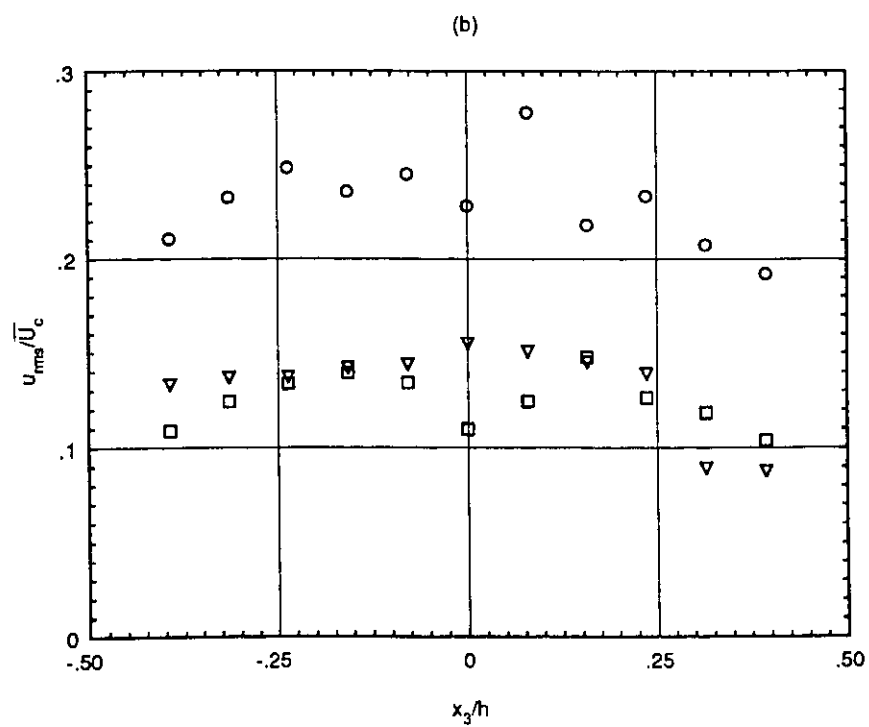
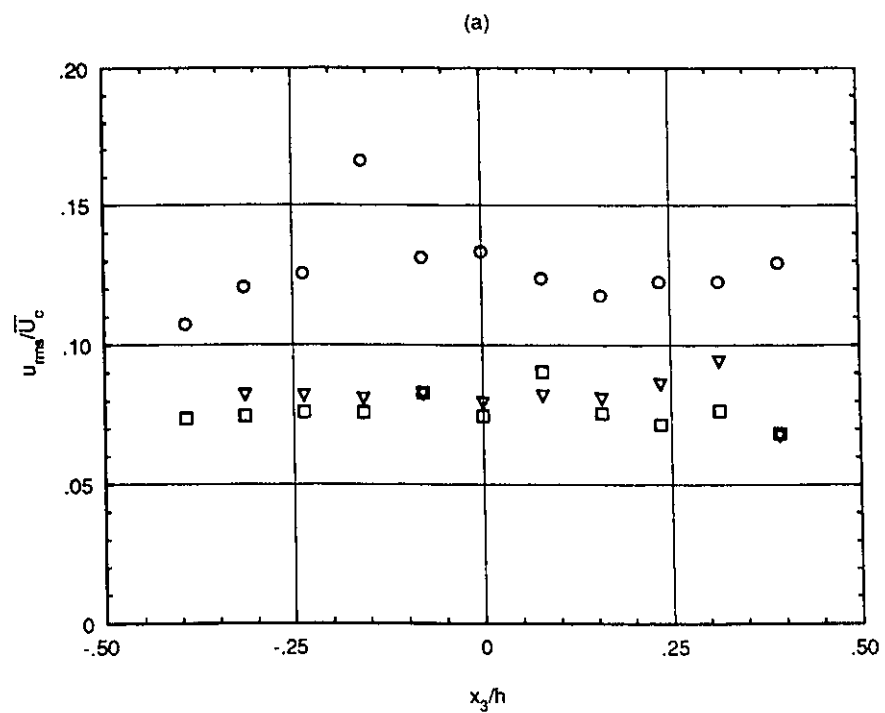


Figure 26 (a,b). For caption see page after next.

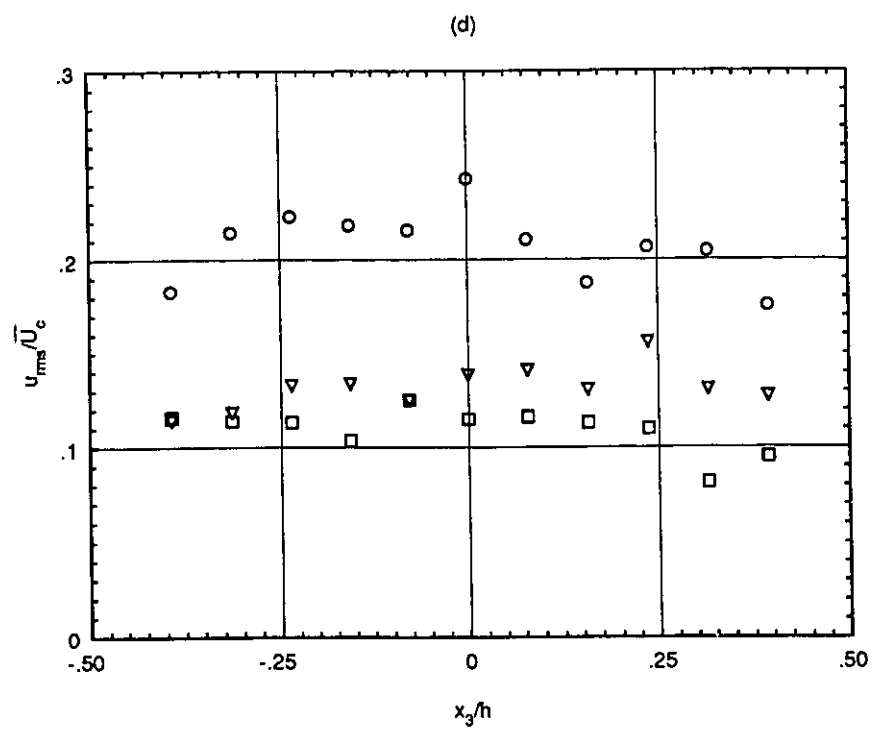
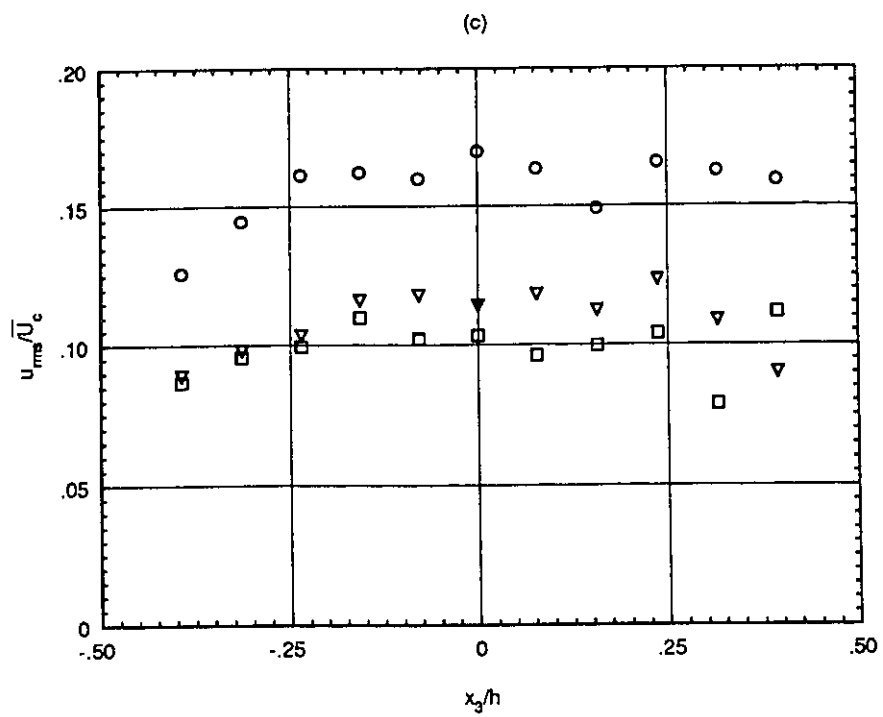


Figure 26 (c,d). For caption see next page.

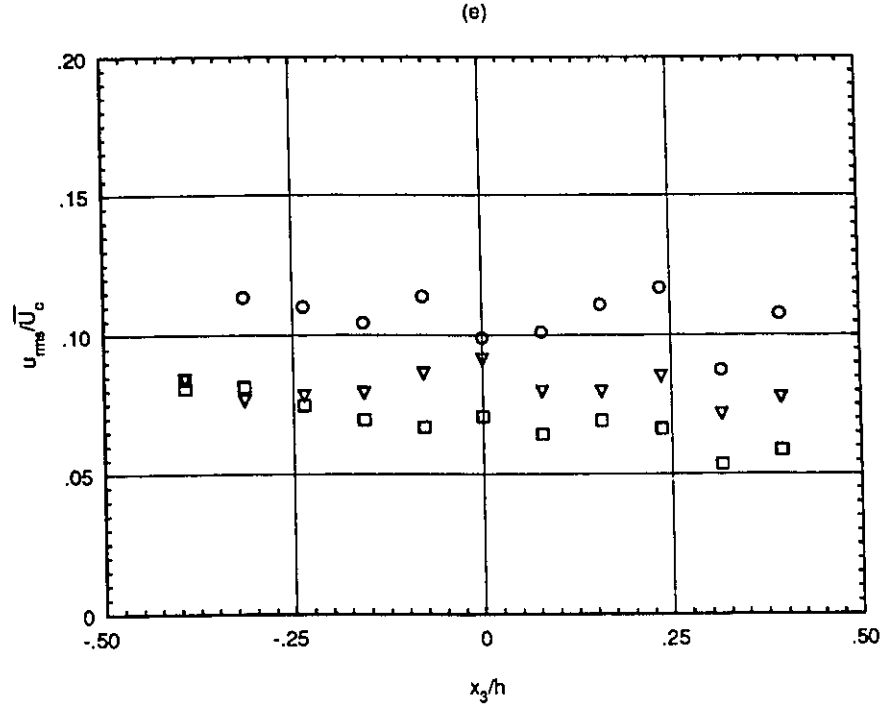


Figure 26 Spanwise variation of rms velocities at $x_1/h=6.0$, $x_2/h=0$. Symbols as in figure 25. (a) Case #1; (b) Case #2; (c) Case #3; (d) Case #4; (e) Case #5.

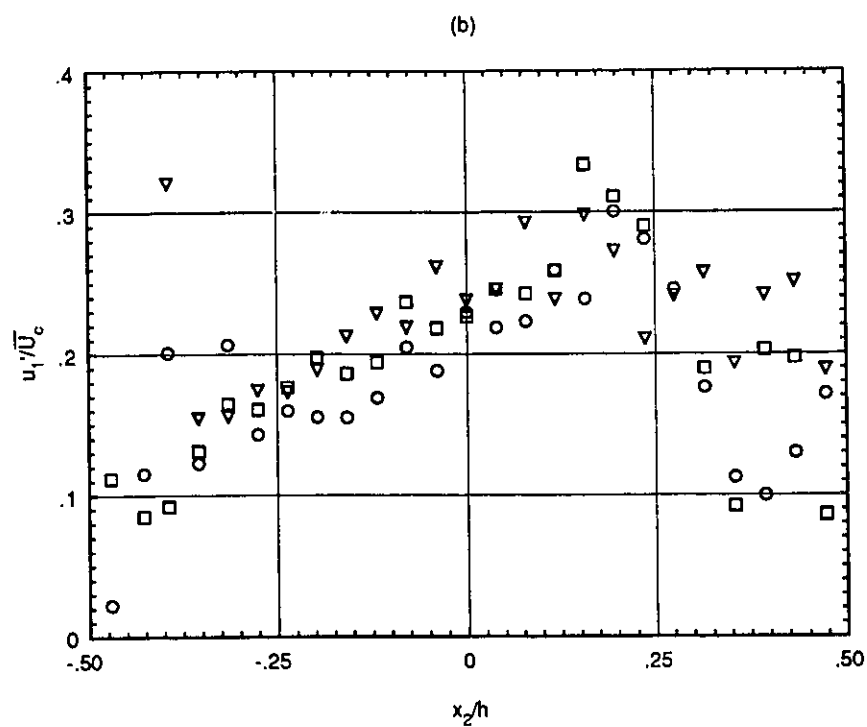
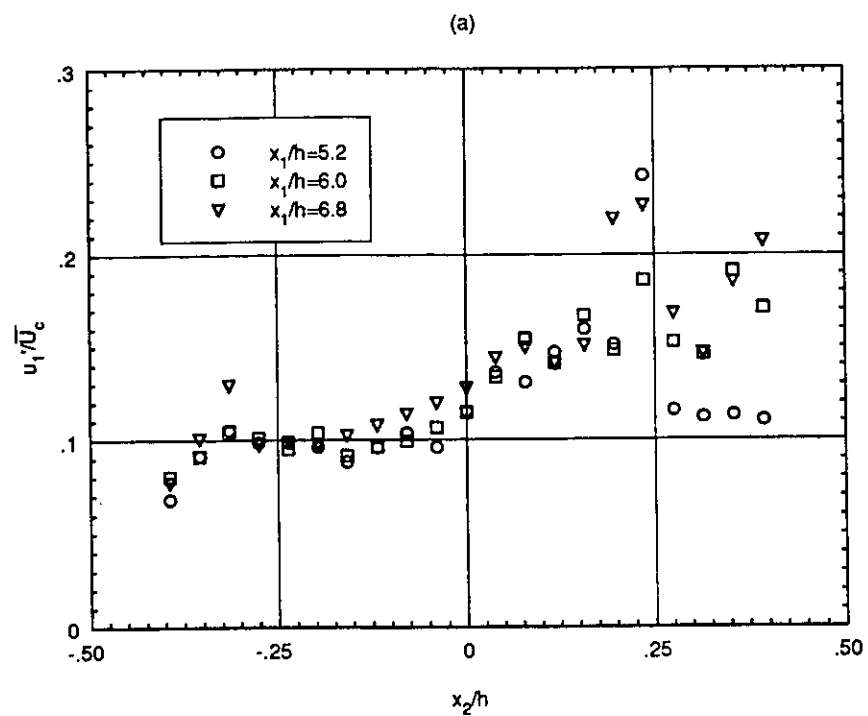


Figure 27 (a,b). For caption see page after next.

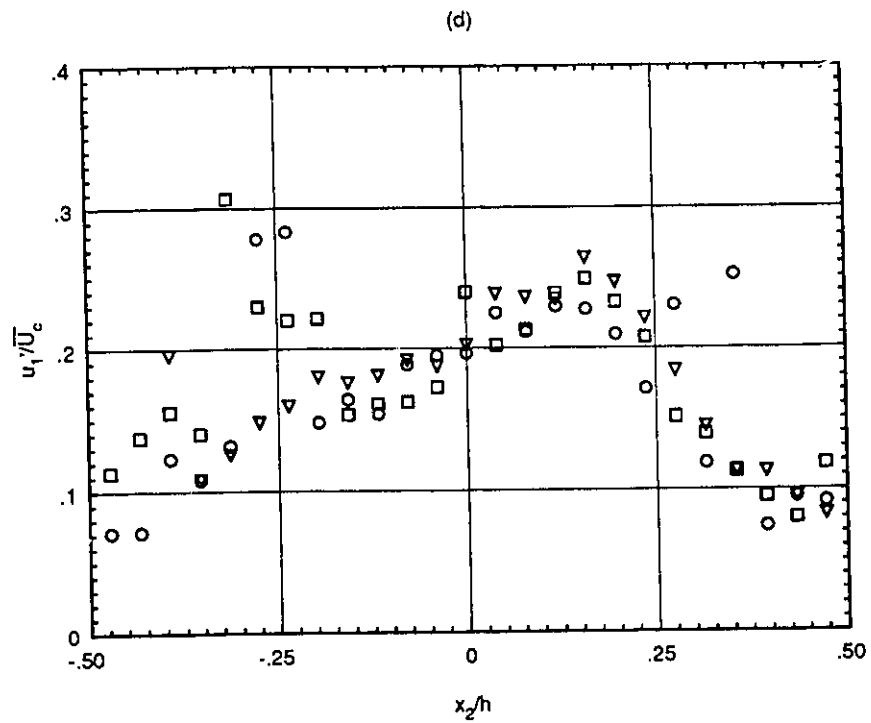
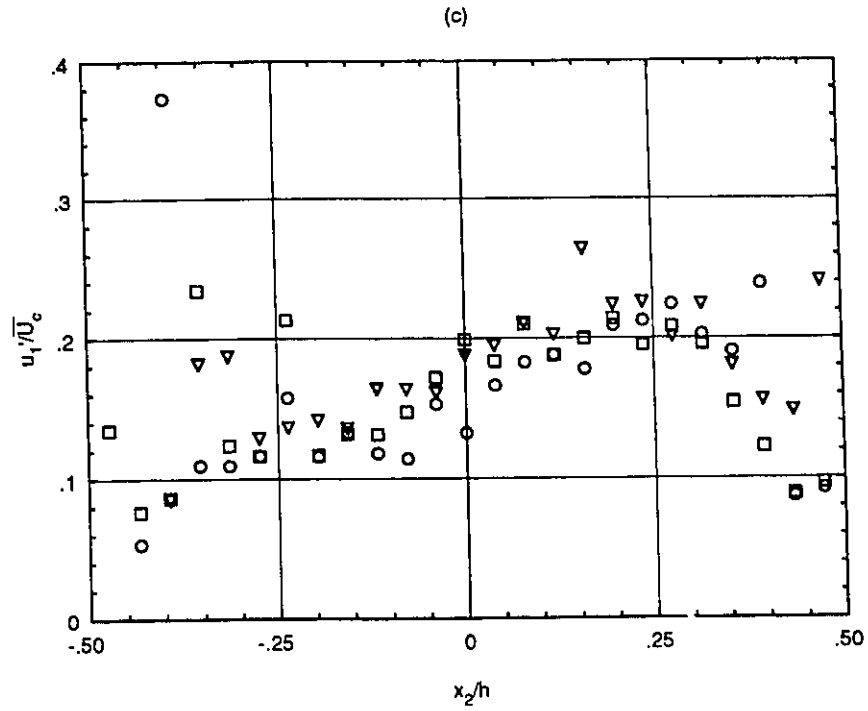


Figure 27 (c,d). For caption see next page.

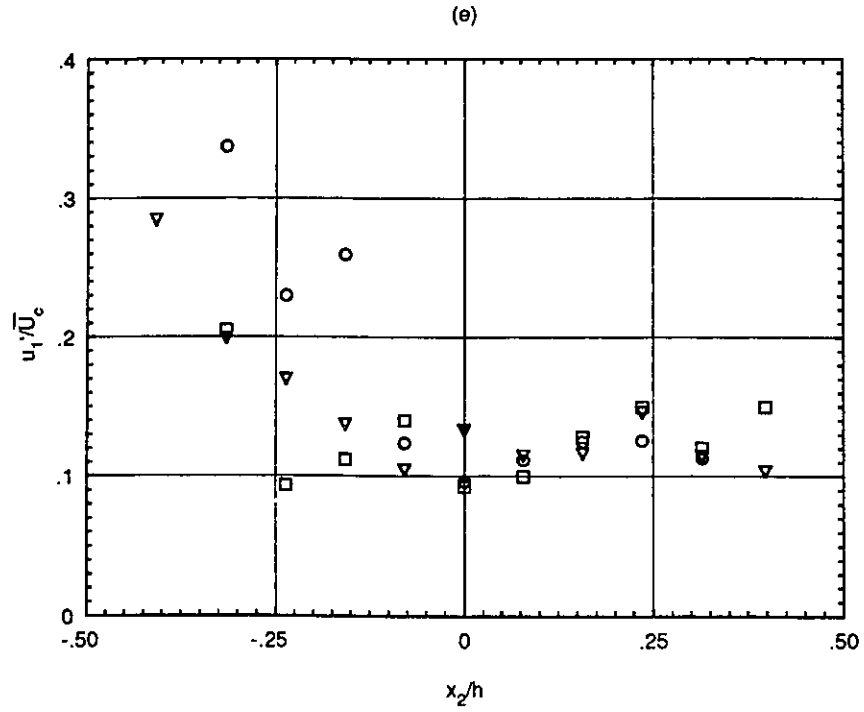


Figure 27 Transverse variation of streamwise rms velocity fluctuations, $x_3/h=0$. Symbols as in (a). (a) Case #1; (b) Case #2; (c) Case #3; (d) Case #4; (e) Case #5.

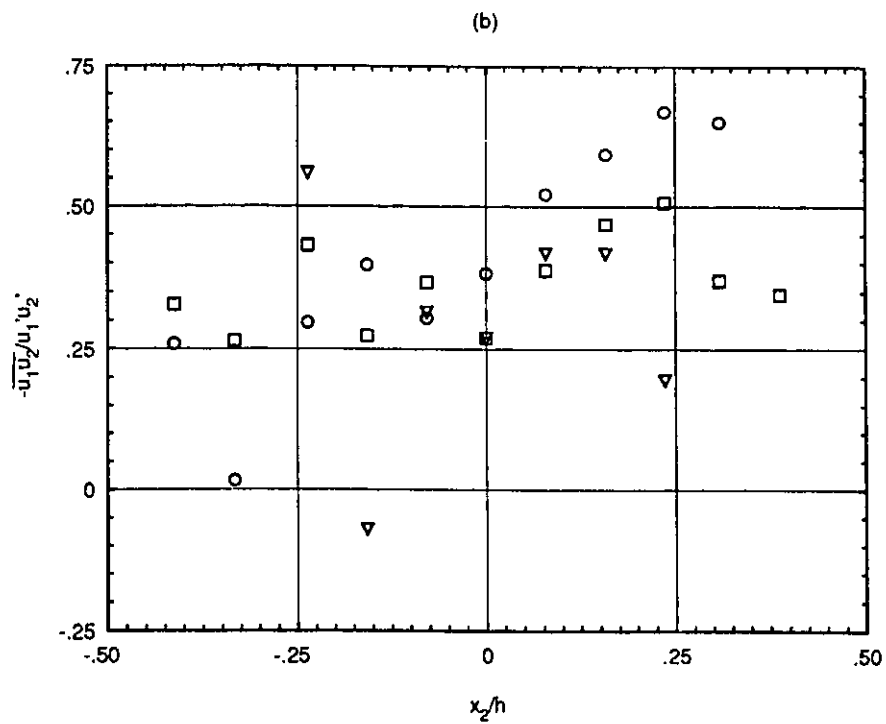
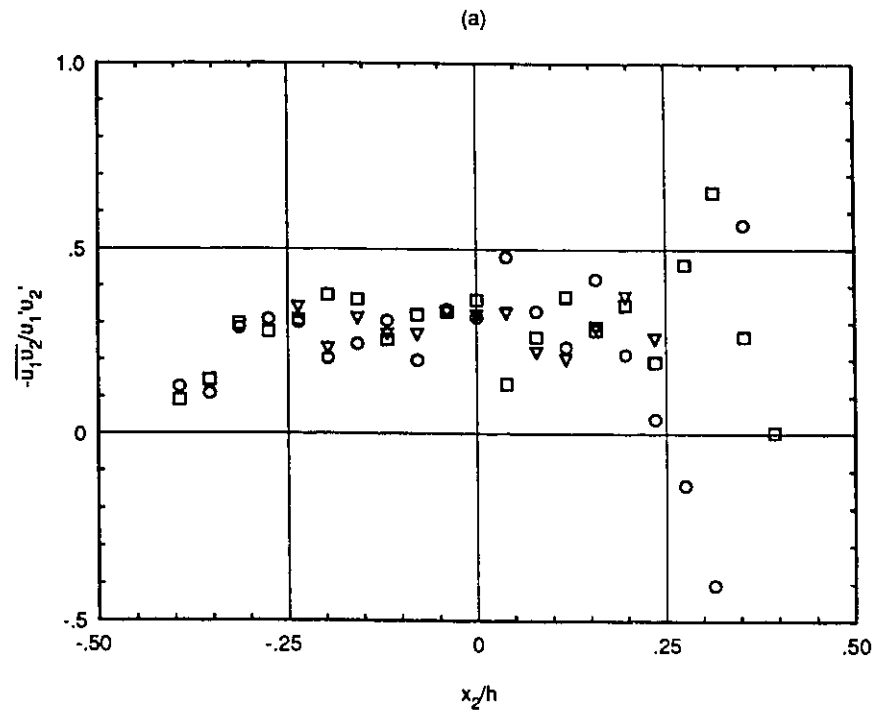


Figure 28 (a,b). For caption see page after next.

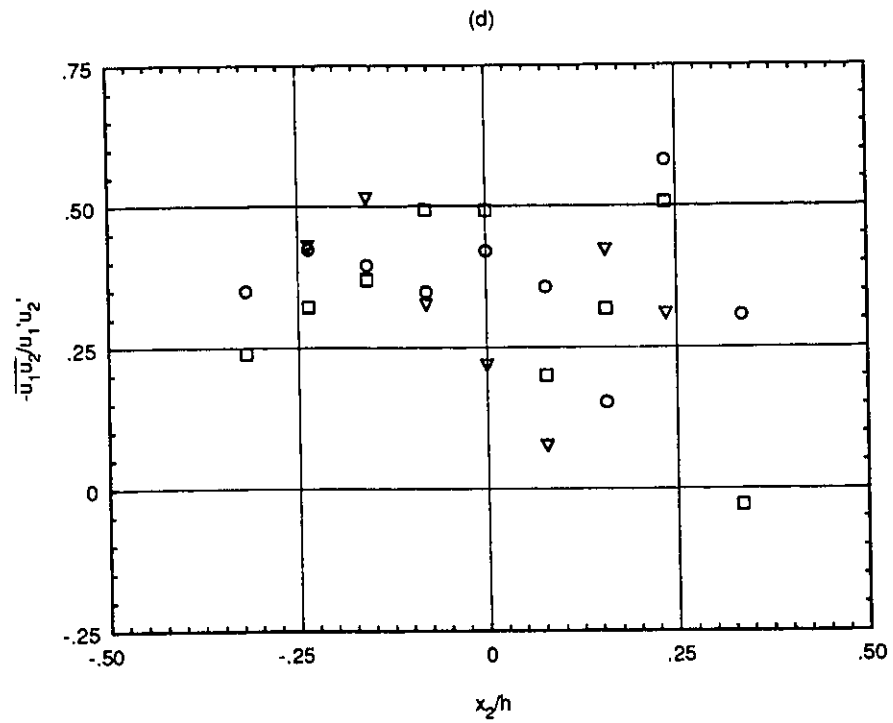
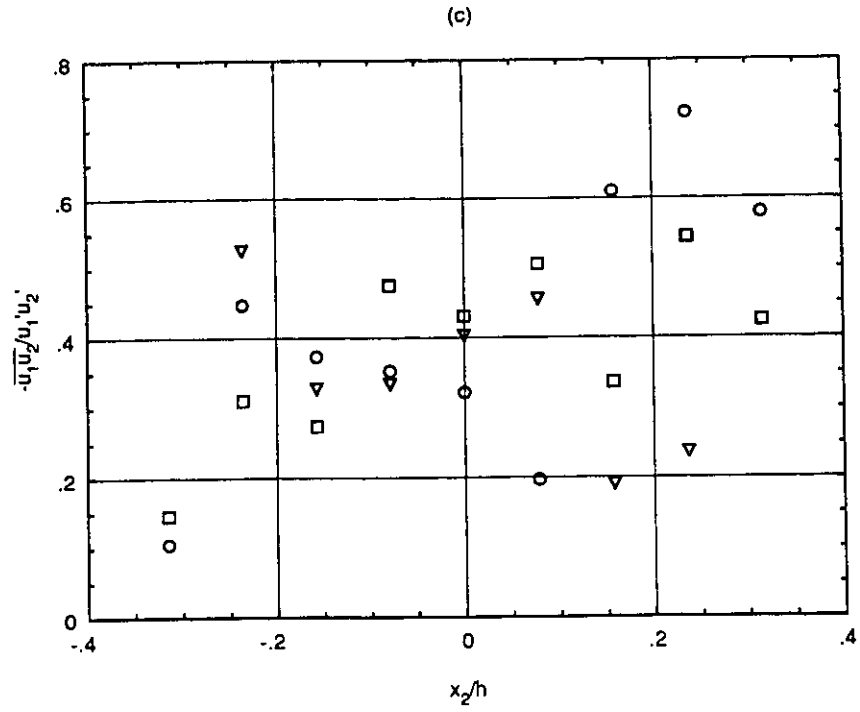


Figure 28 (c,d). For caption see next page.

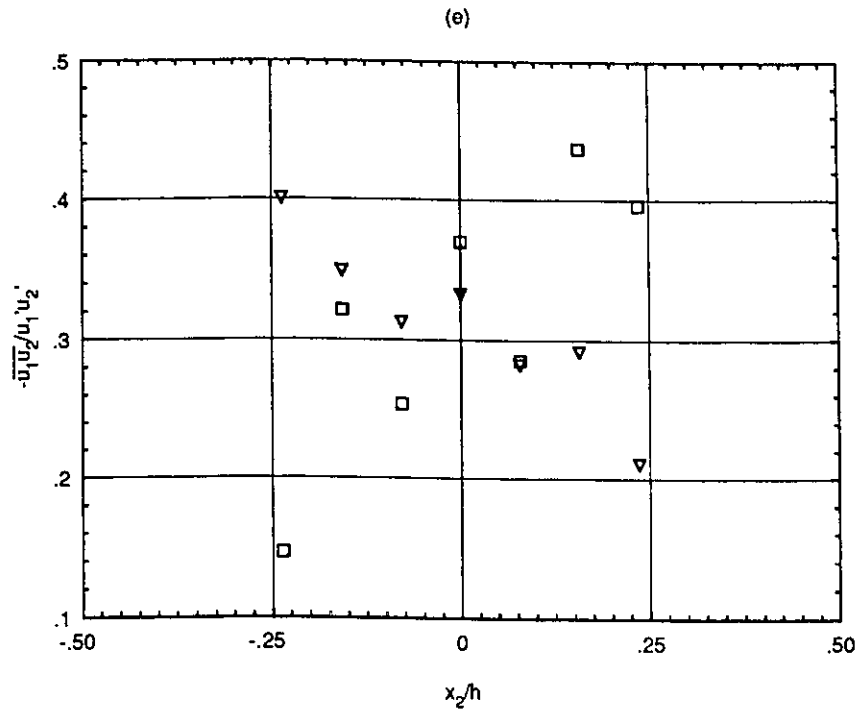


Figure 28 Transverse variation of the Reynolds stress correlation coefficient, $x_3/h=0$. Symbols as in figure 27. (a) Case #1; (b) Case #2; (c) Case #3; (d) Case #4; (e) Case #5.

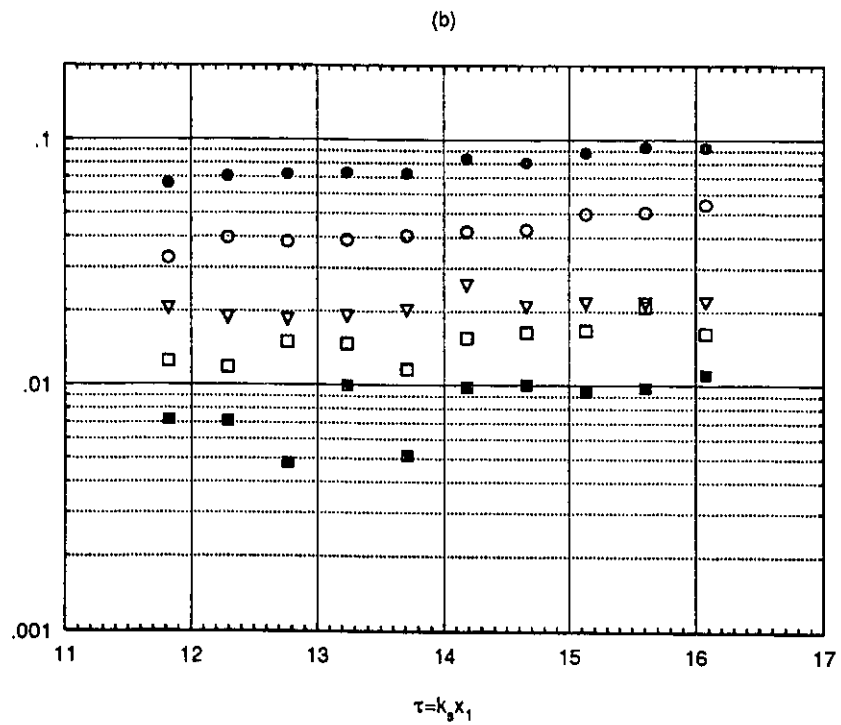
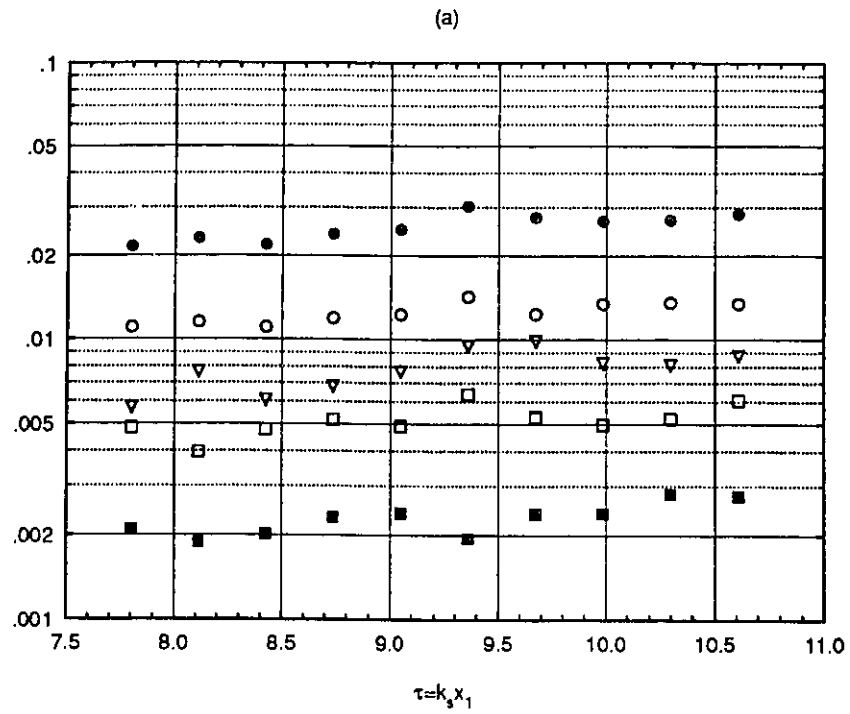


Figure 29 (a,b). For caption see page after next.

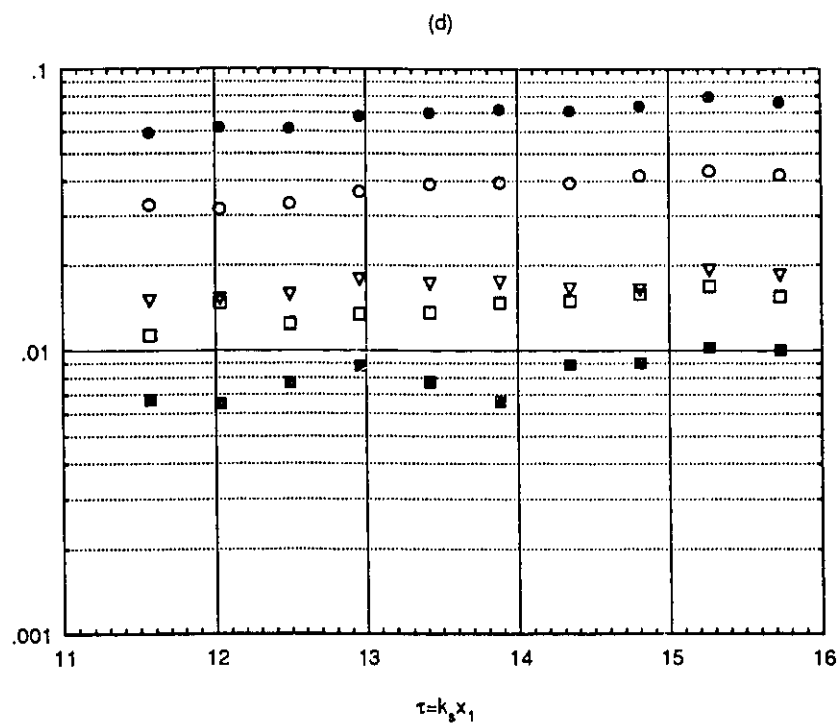
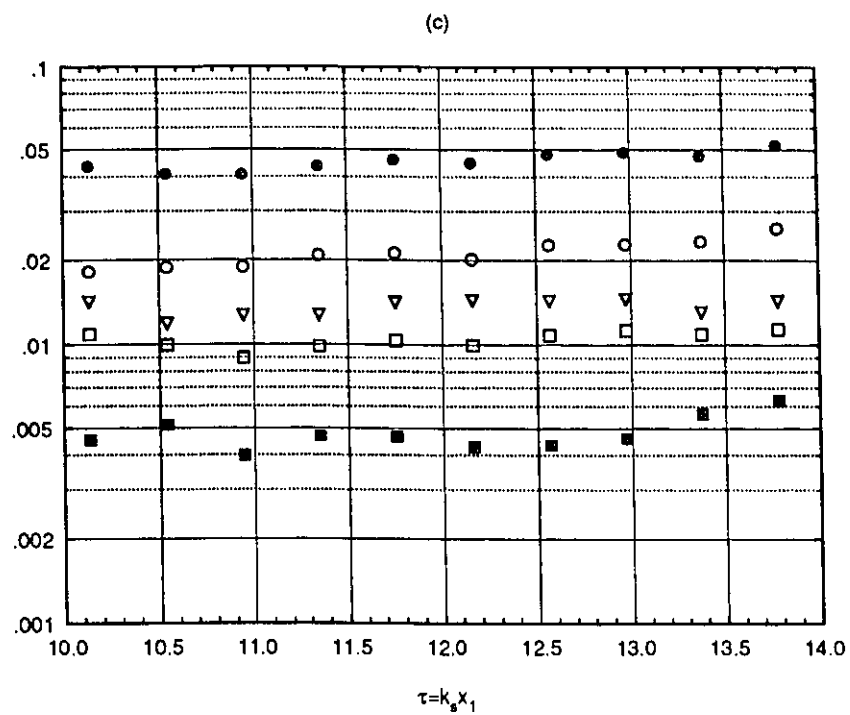


Figure 29 (c,d). For caption see next page.

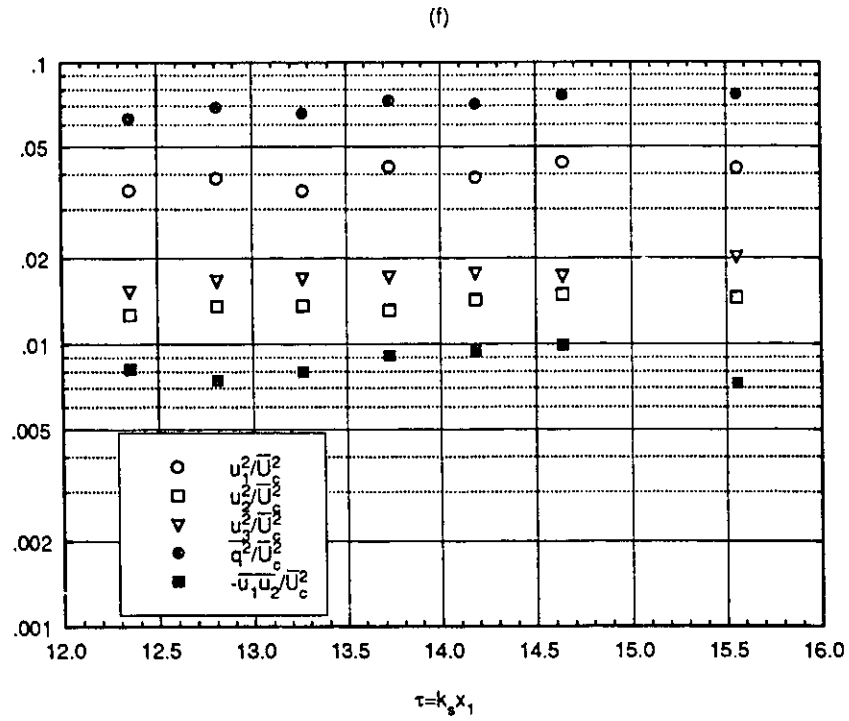
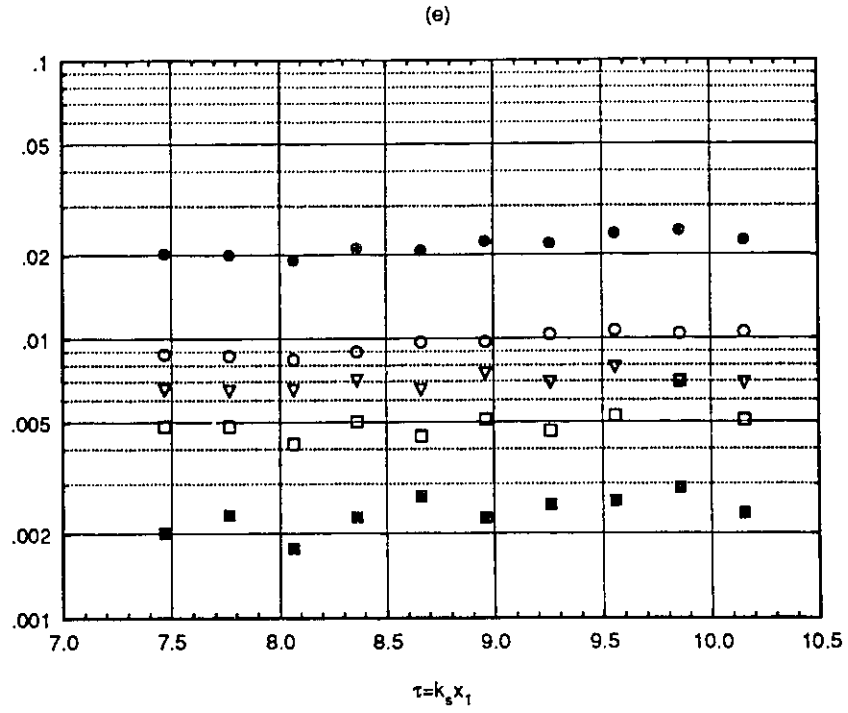


Figure 29 Downstream development of the Reynolds stresses and the turbulent kinetic energy. Symbols as in (f). (a) Case #1; (b) Case #2; (c) Case #3; (d) Case #4; (e) Case #5; (f) Case #6.

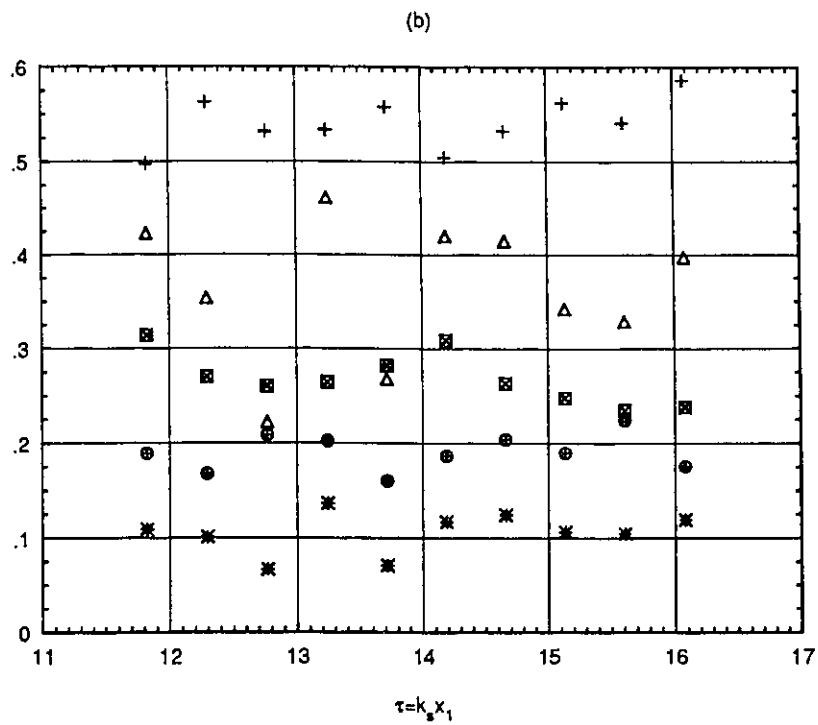
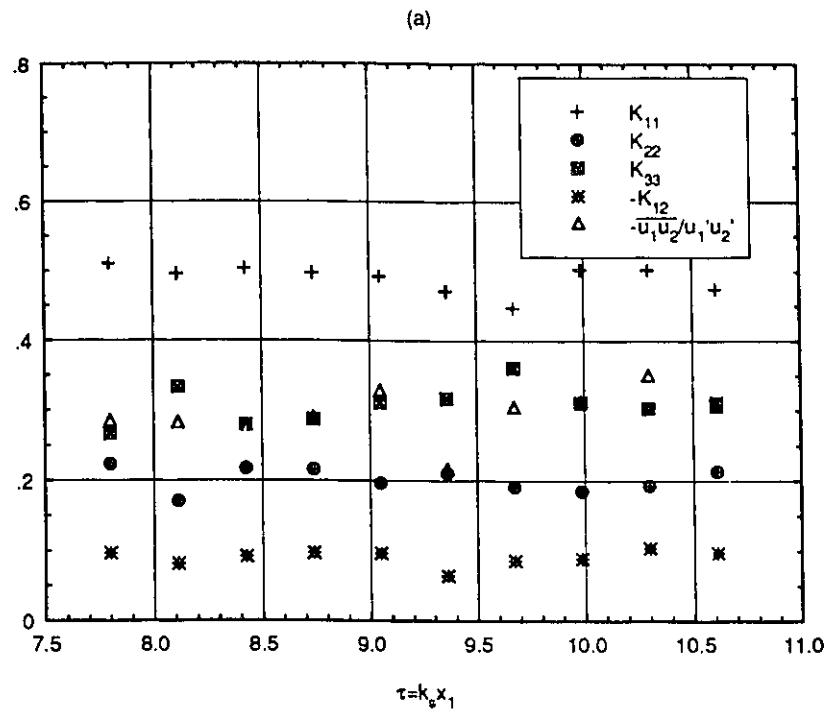


Figure 30 (a,b). For caption see page after next.

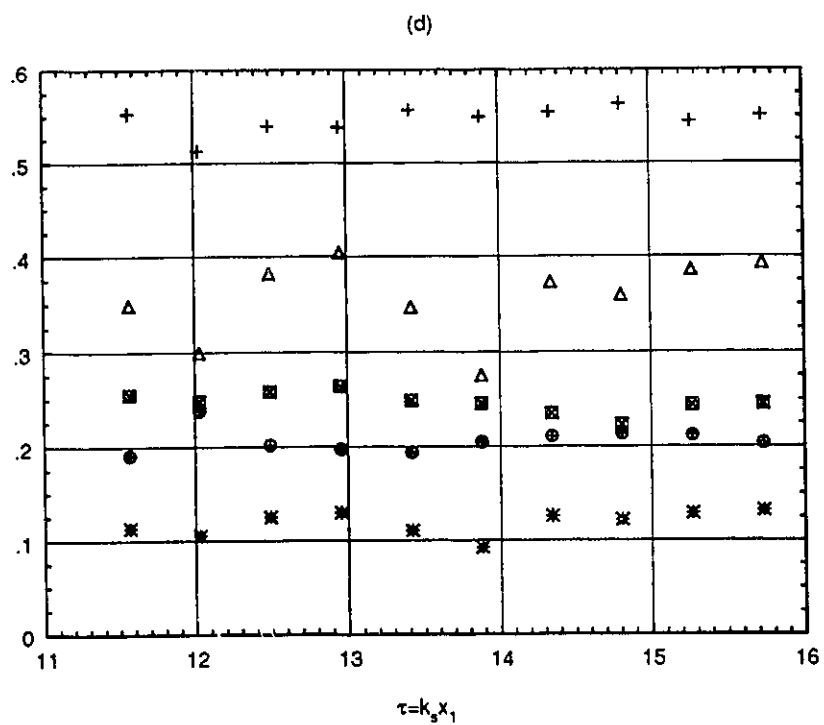
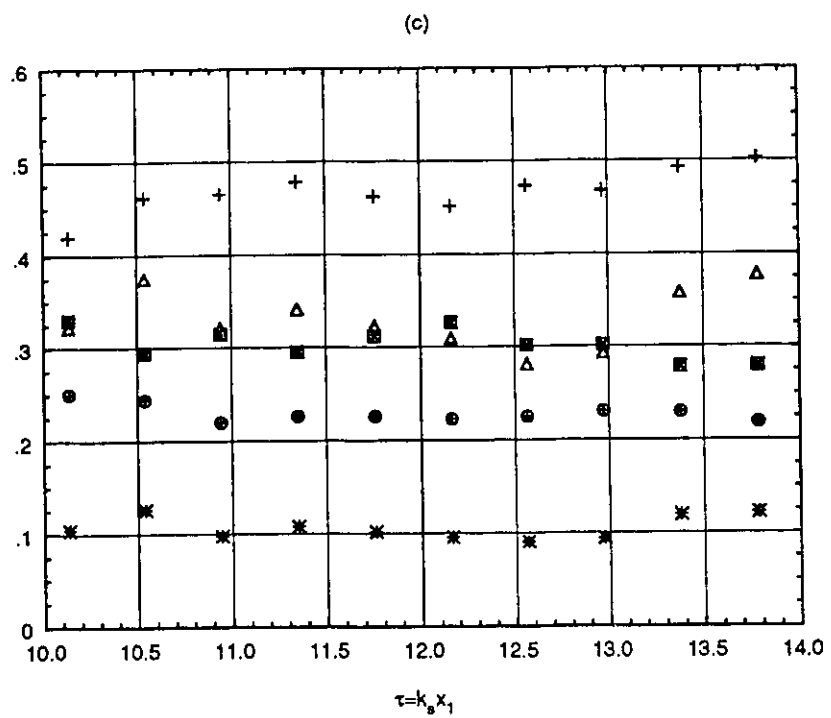


Figure 30 (c,d). For caption see next page.

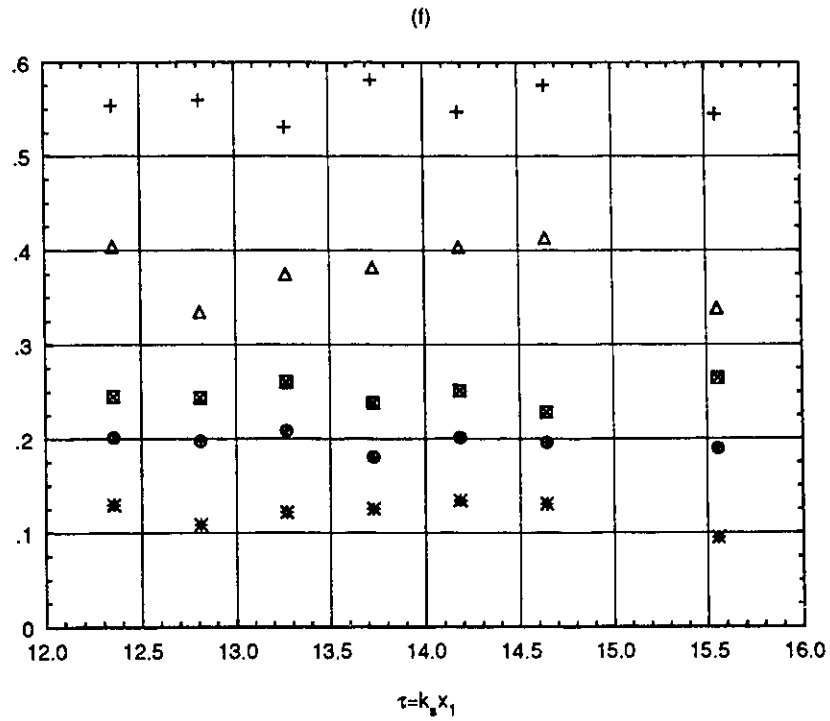
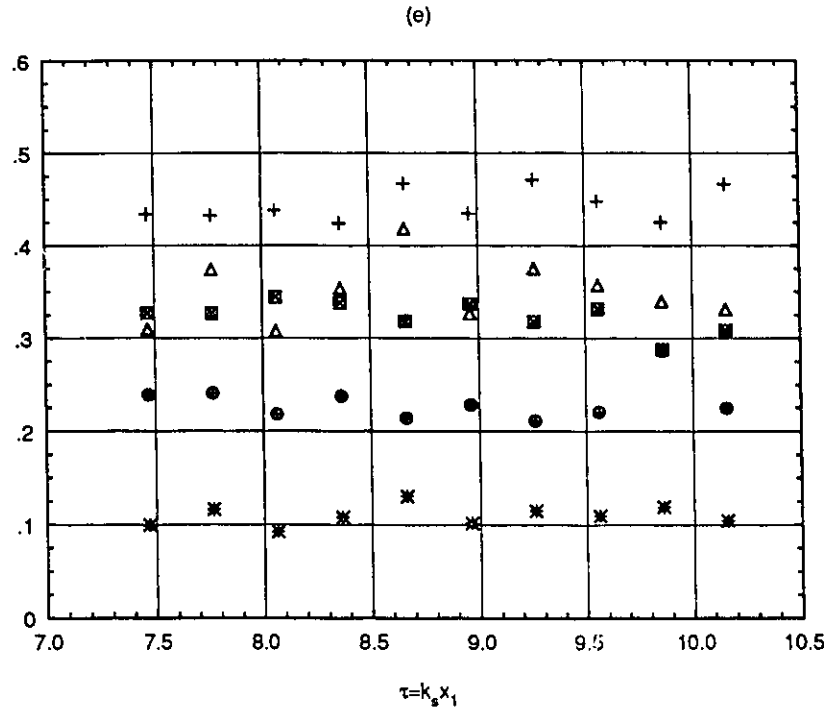


Figure 30 Downstream development of dimensionless Reynolds stresses and correlation coefficient. Symbols as in (a). (a) Case #1; (b) Case #2; (c) Case #3; (d) Case #4; (e) Case #5; (f) Case #6.

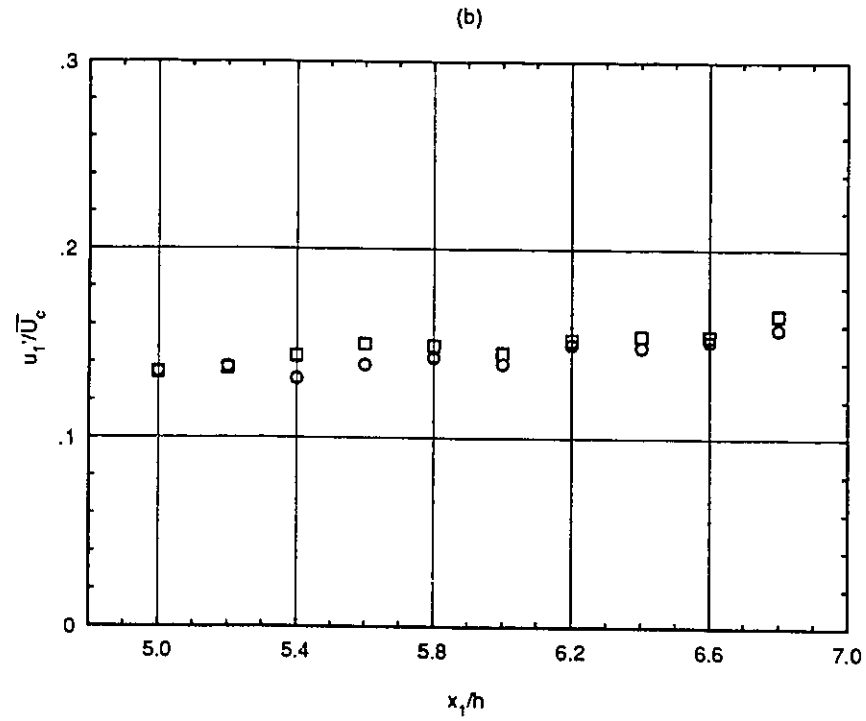
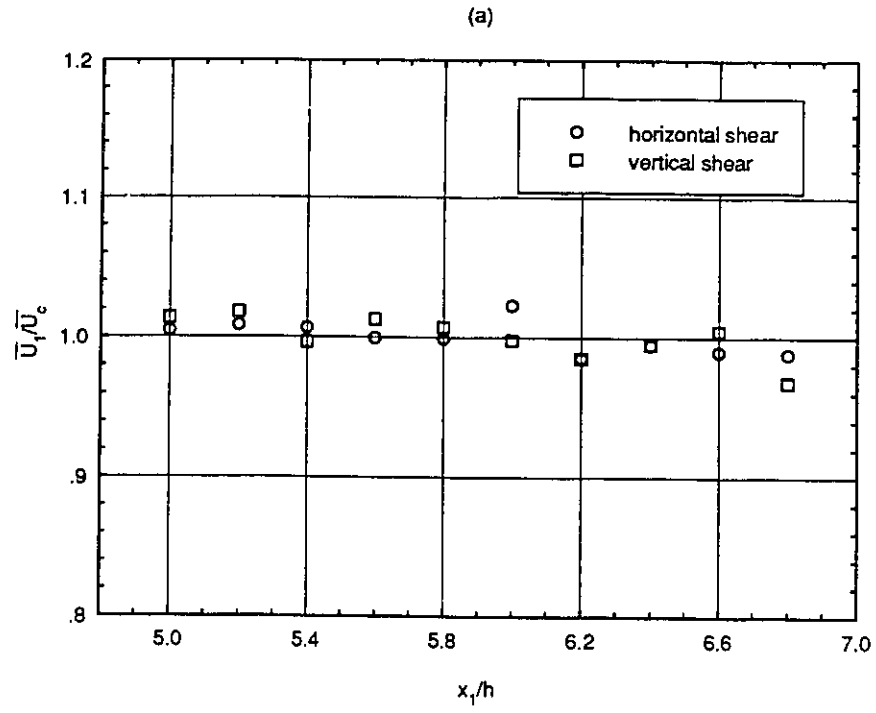


Figure 31 Comparison of streamwise velocity with orientation of shear. Flow case #3. Symbols as in (a). (a) mean velocity; (b) rms velocity.

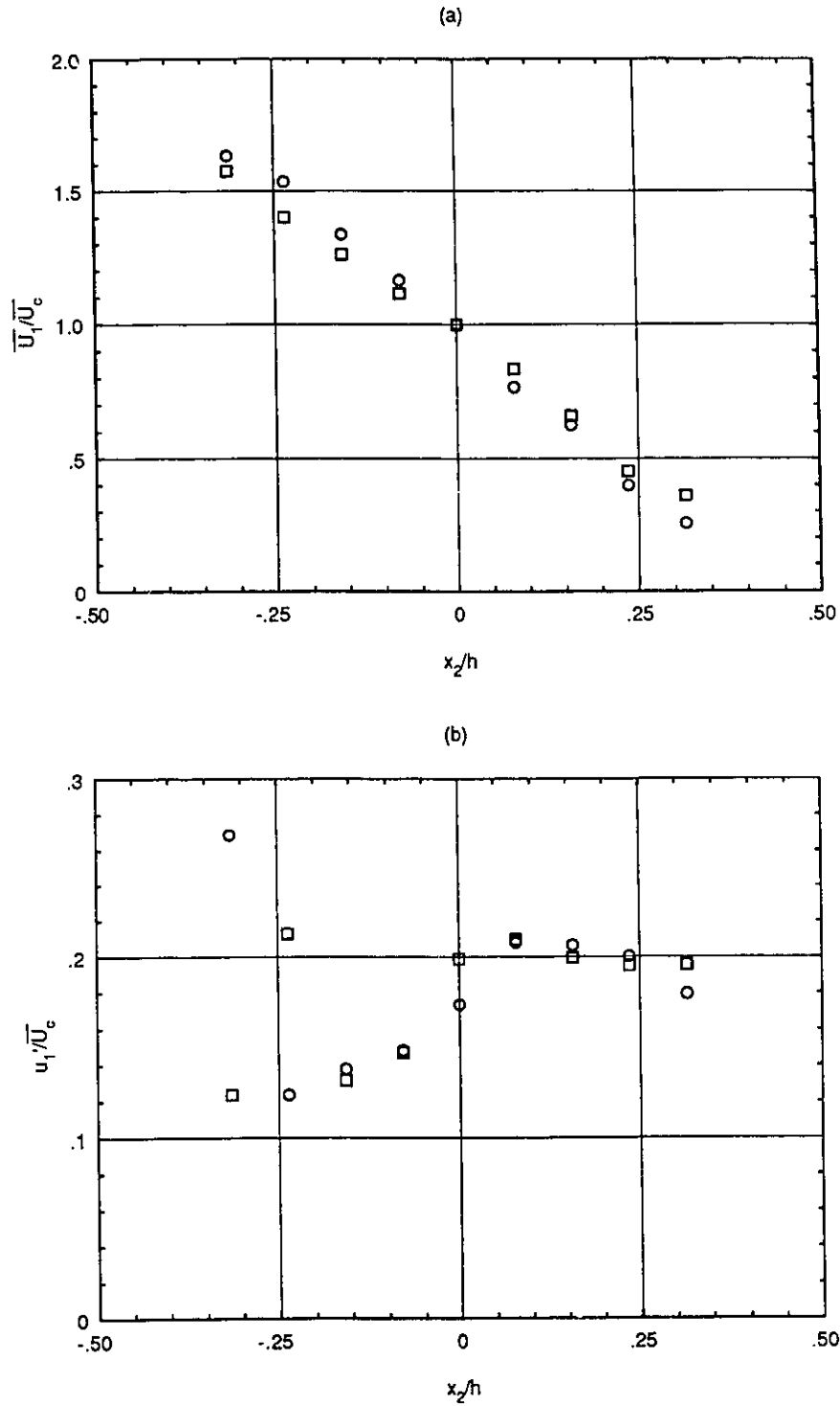


Figure 32 Comparison of streamwise velocity with orientation of shear. Flow case #3, $x_1/h=6.0$, $x_3/h=0$. Symbols as in figure 31. (a) mean velocity; (b) rms velocity.

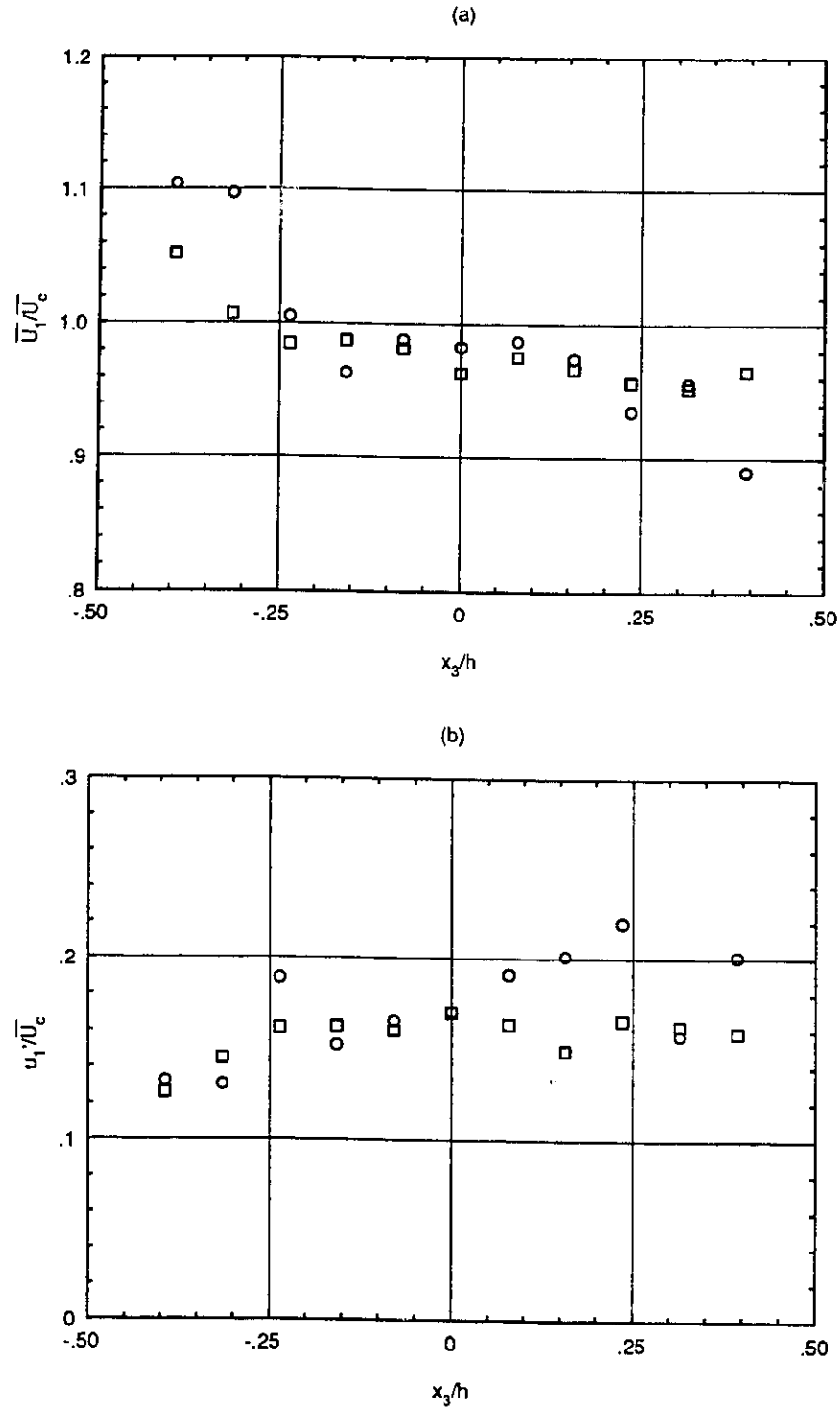


Figure 33 Comparison of streamwise velocity with orientation of shear. Flow case #3, $x_1/h=6.0$, $x_2/h=0$. Symbols as in figure 31. (a) mean velocity; (b) rms velocity.

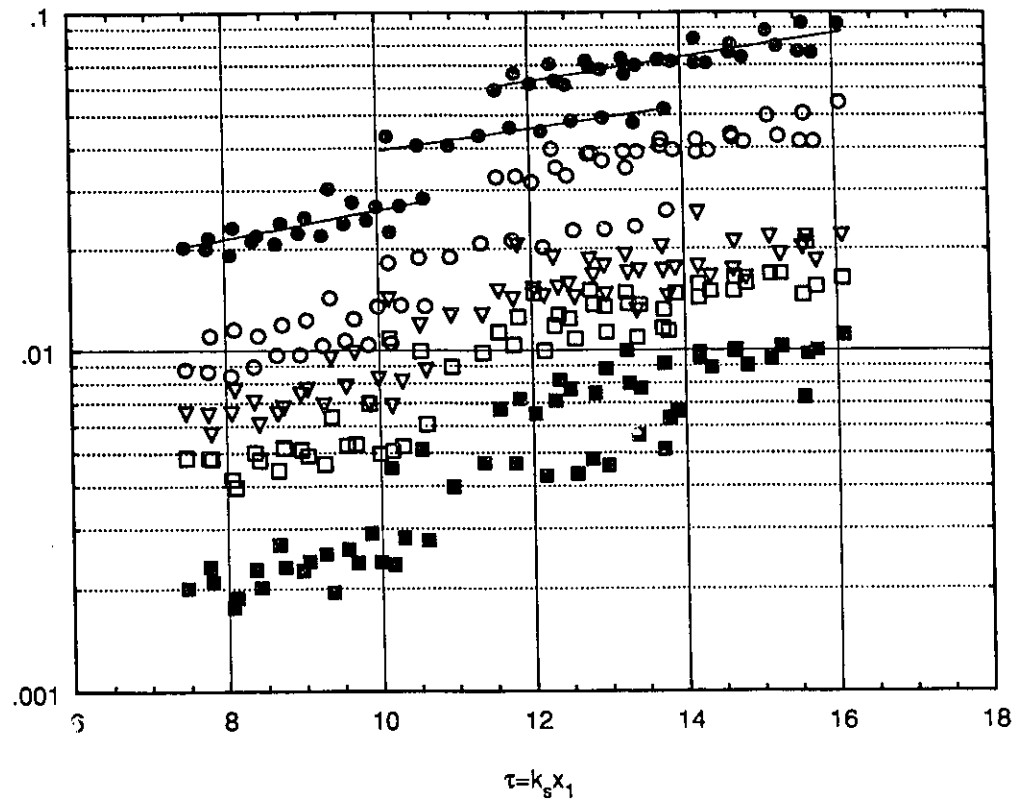


Figure 34 Downstream development of the Reynolds stresses and the turbulent kinetic energy for uniform shear flow cases #1 to #6. Symbols as in figure 29.

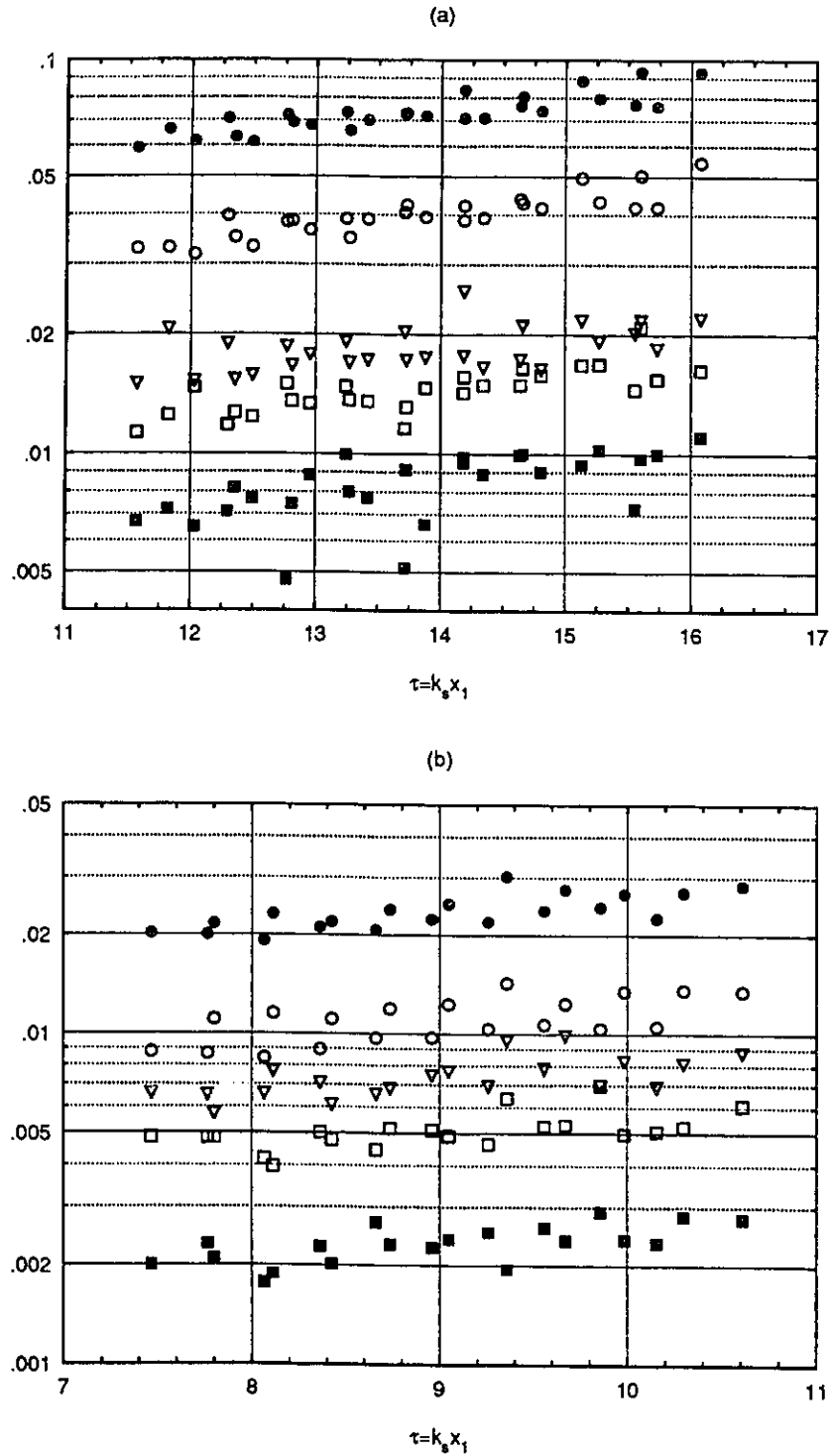


Figure 35 Downstream development of the Reynolds stresses and the turbulent kinetic energy for groups of uniform shear flows. Symbols as in figure 29. (a) Cases #2, #4 and #6; (b) Cases #1 and #5.

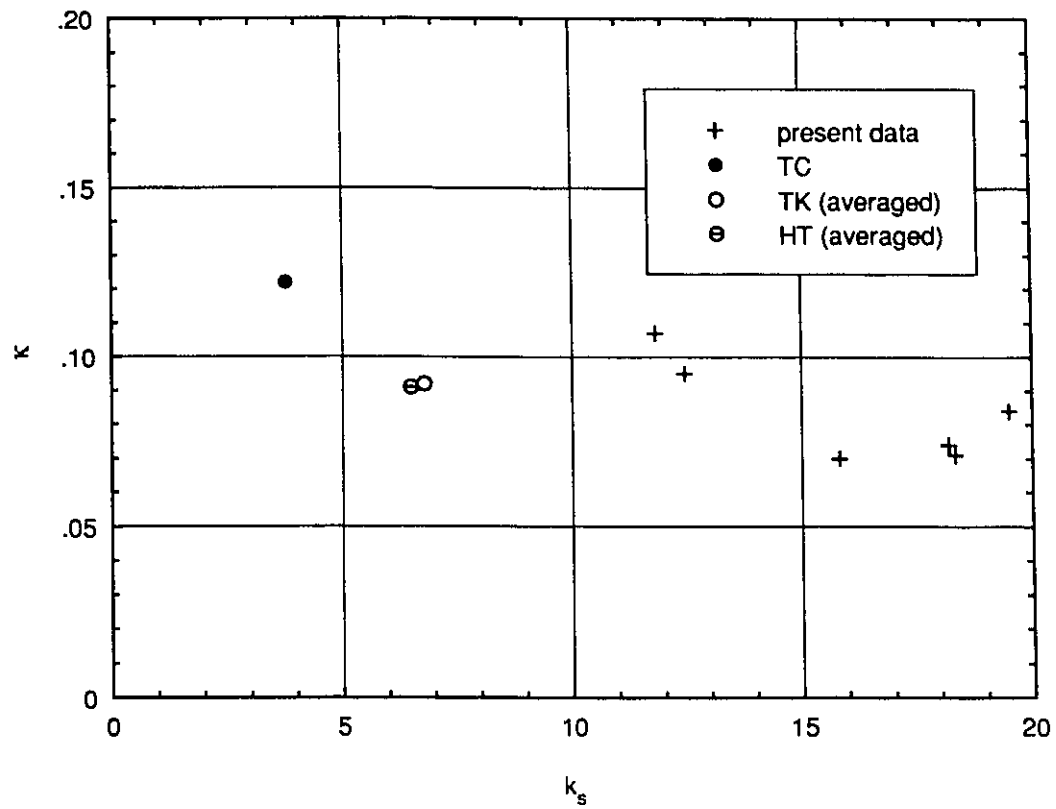


Figure 36 The exponent coefficient κ vs. k_s in uniform shear flow.

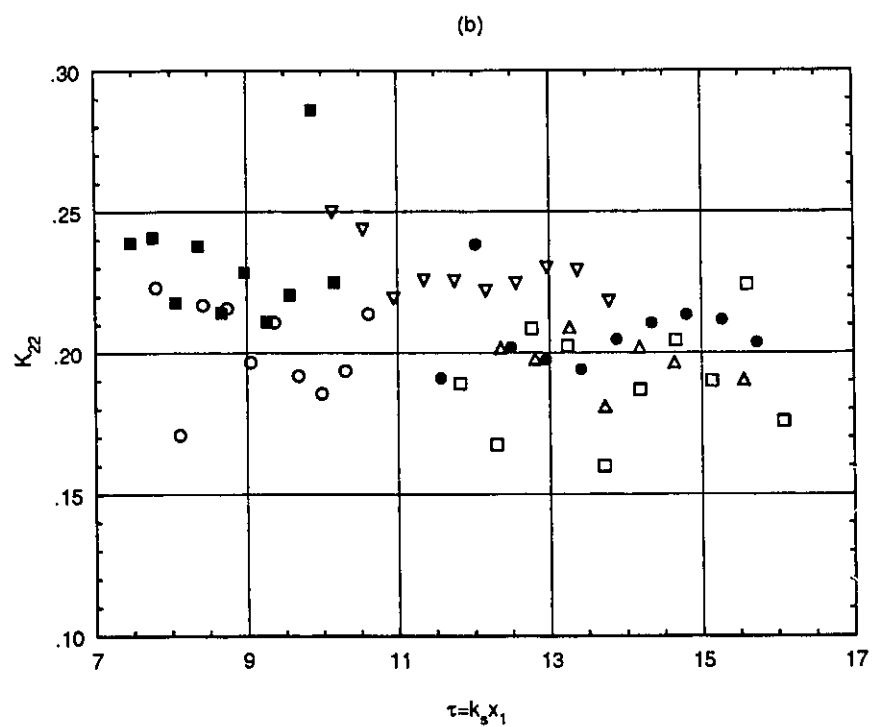
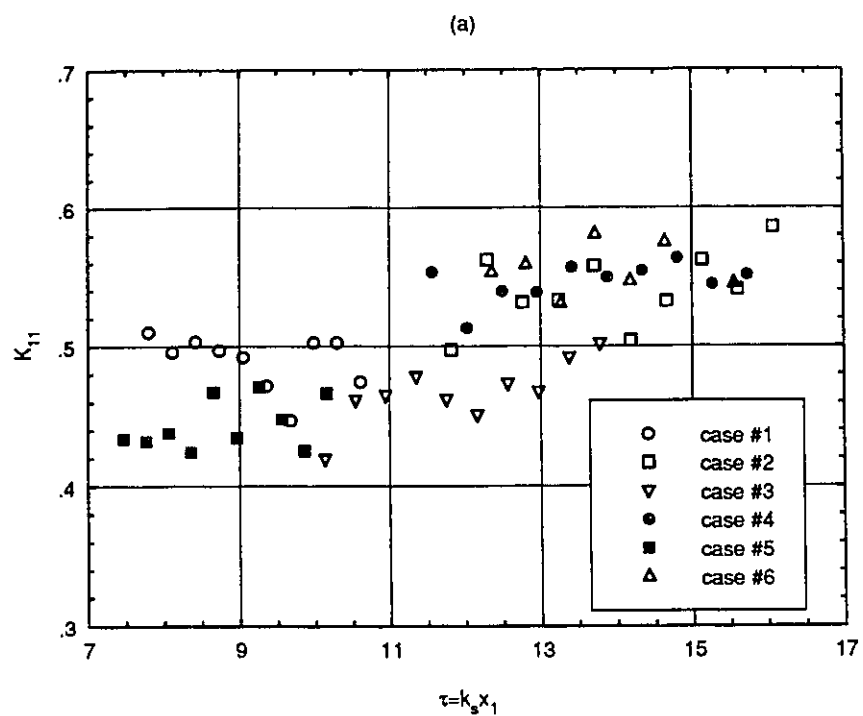


Figure 37 (a,b). For caption see next page.

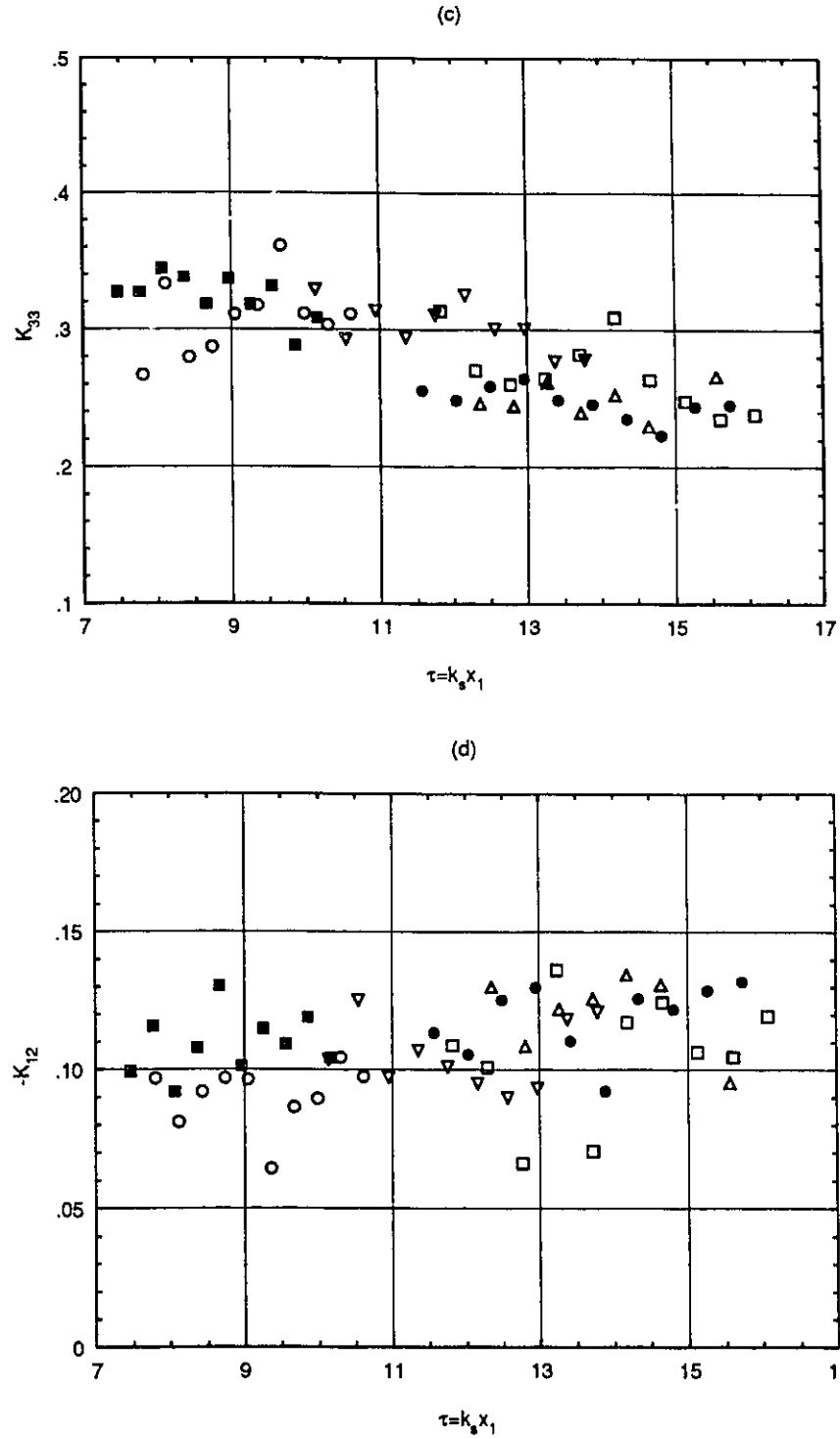


Figure 37 Downstream development of the non-dimensional Reynolds stresses for uniform shear flow cases #1 to #6. Symbols as in (a). (a) K_{11} ; (b) K_{22} ; (c) K_{33} ; (d) $-K_{12}$.

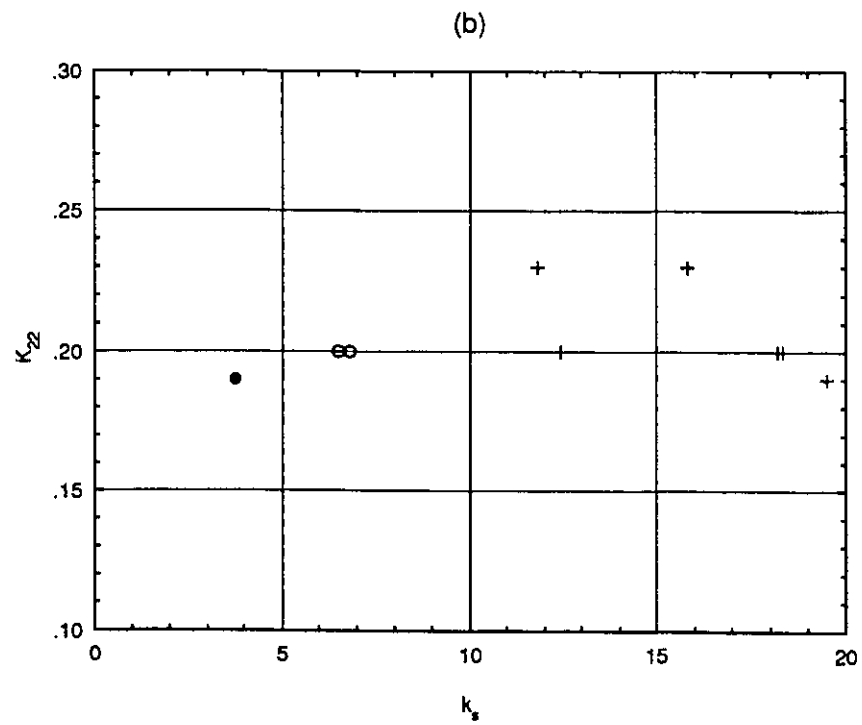
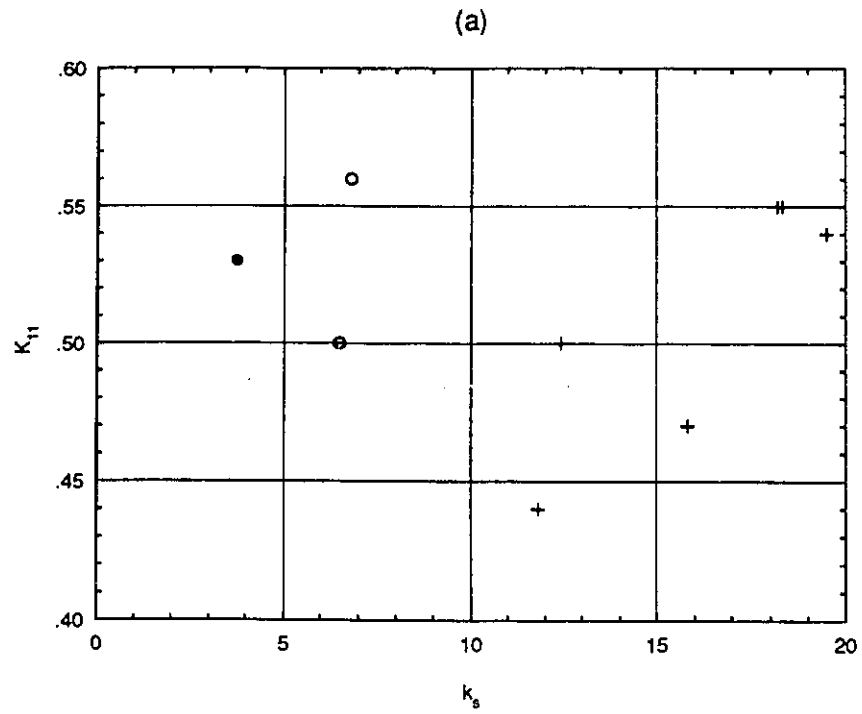


Figure 38 (a,b). For caption see next page.

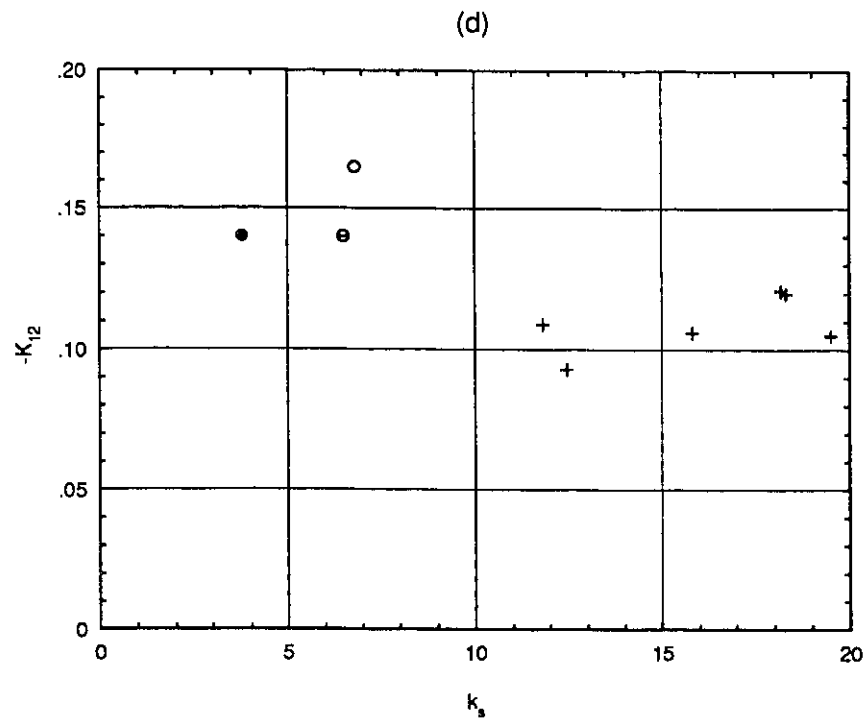
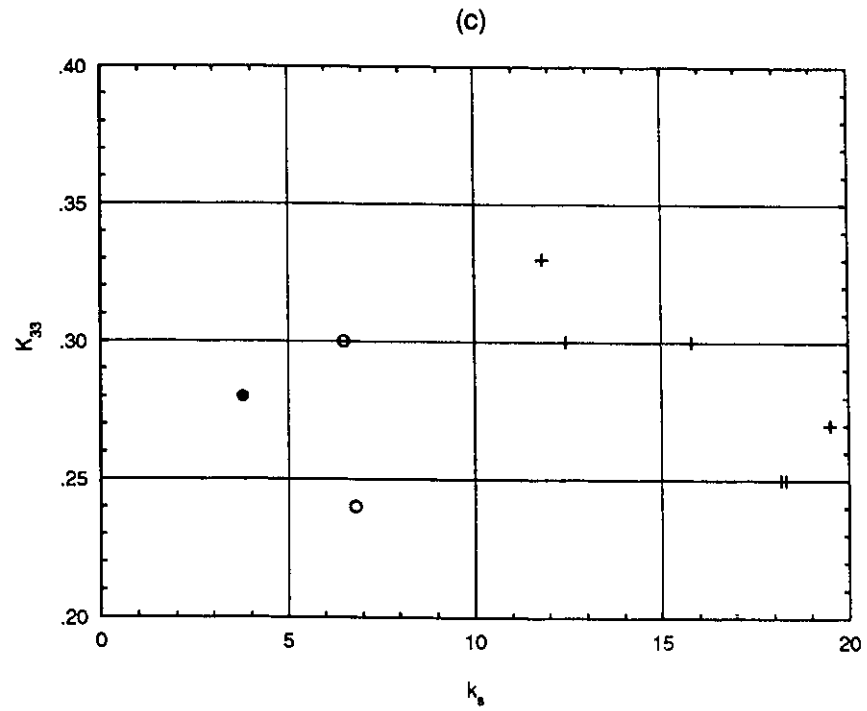


Figure 38 Non-dimensional Reynolds stresses vs. k_s in uniform shear flow. Symbols as in figure 36. (a) K_{11} ; (b) K_{22} ; (c) K_{33} ; (d) $-K_{12}$.

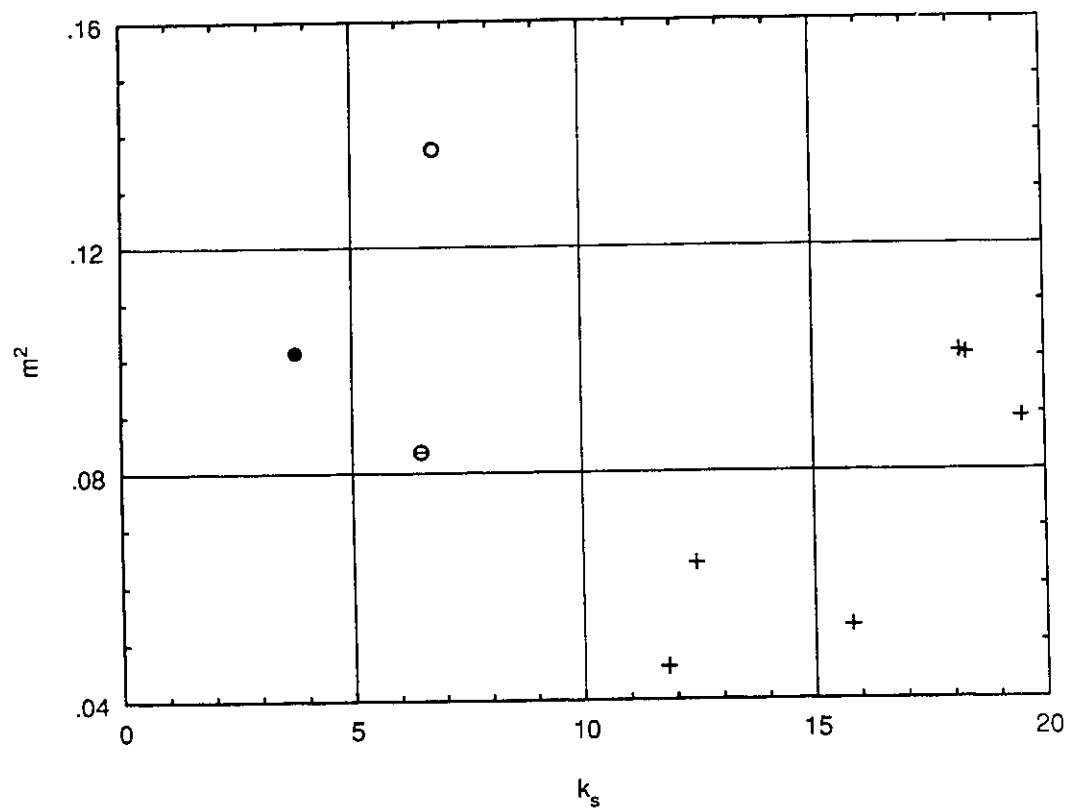


Figure 39 Total anisotropy m^2 vs. k_s in uniform shear flow. Symbols as in figure 36.

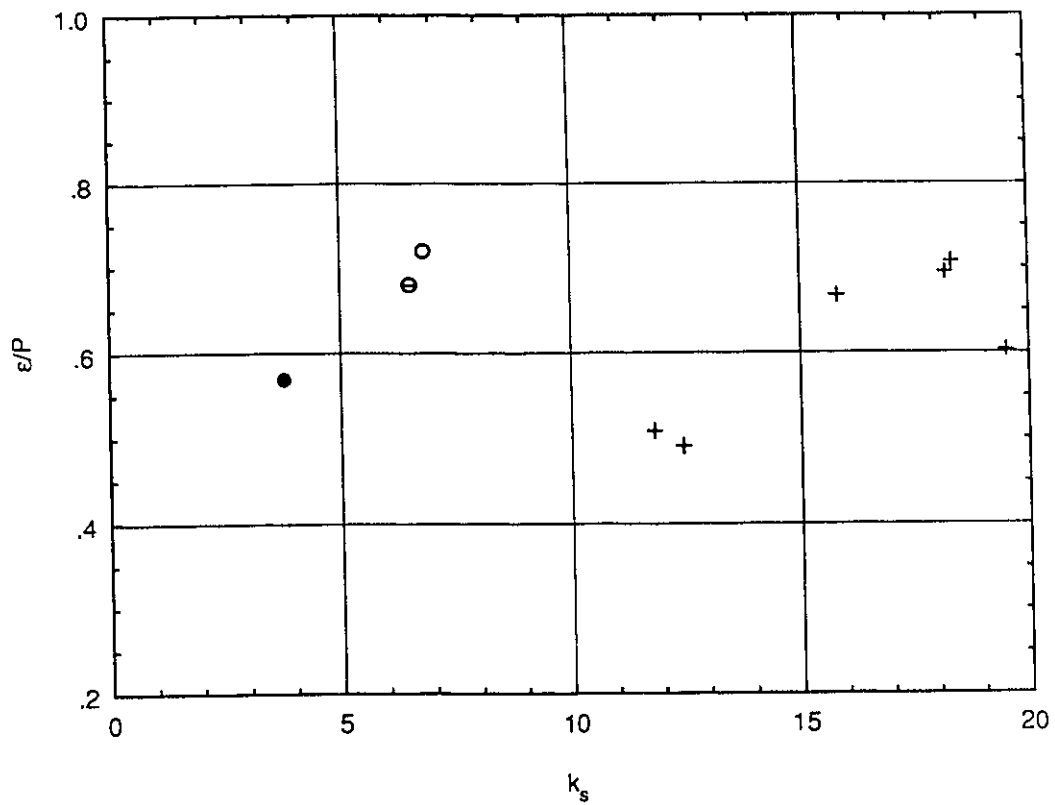


Figure 40 Rate of turbulent kinetic energy dissipation over production ratio vs. k_s in uniform shear flow. Symbols as in figure 36.

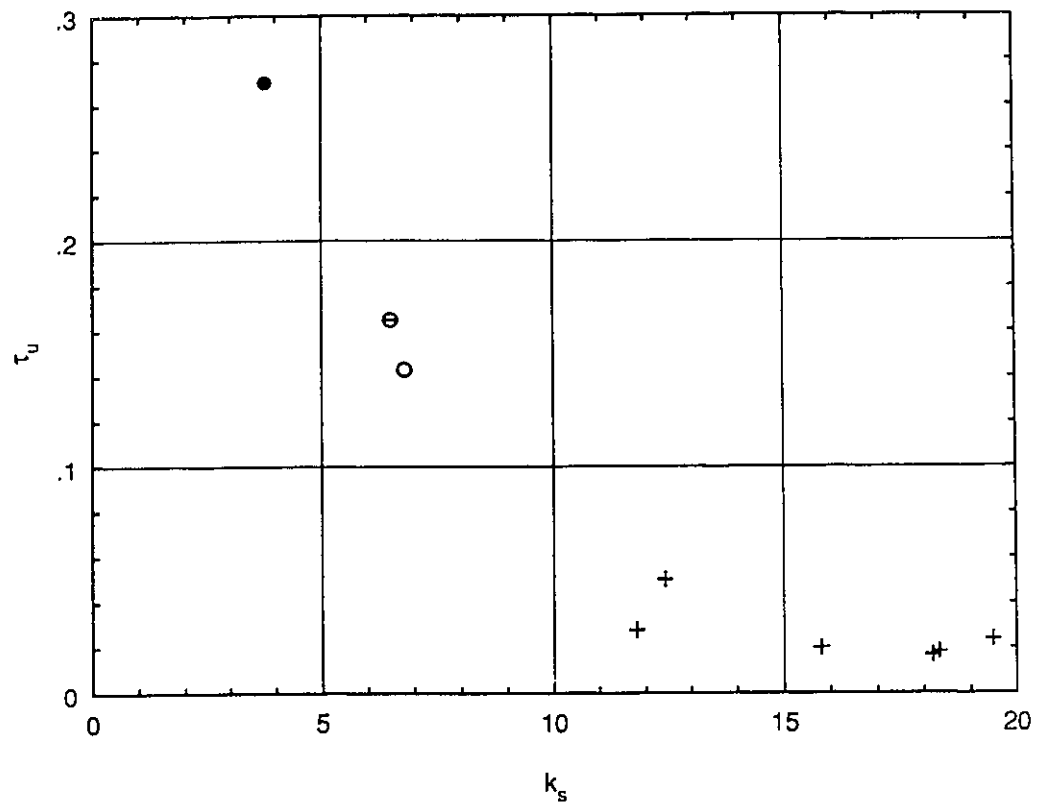


Figure 41 Turbulent timescale τ_u vs. k_s in uniform shear flow. Symbols as in figure 36.

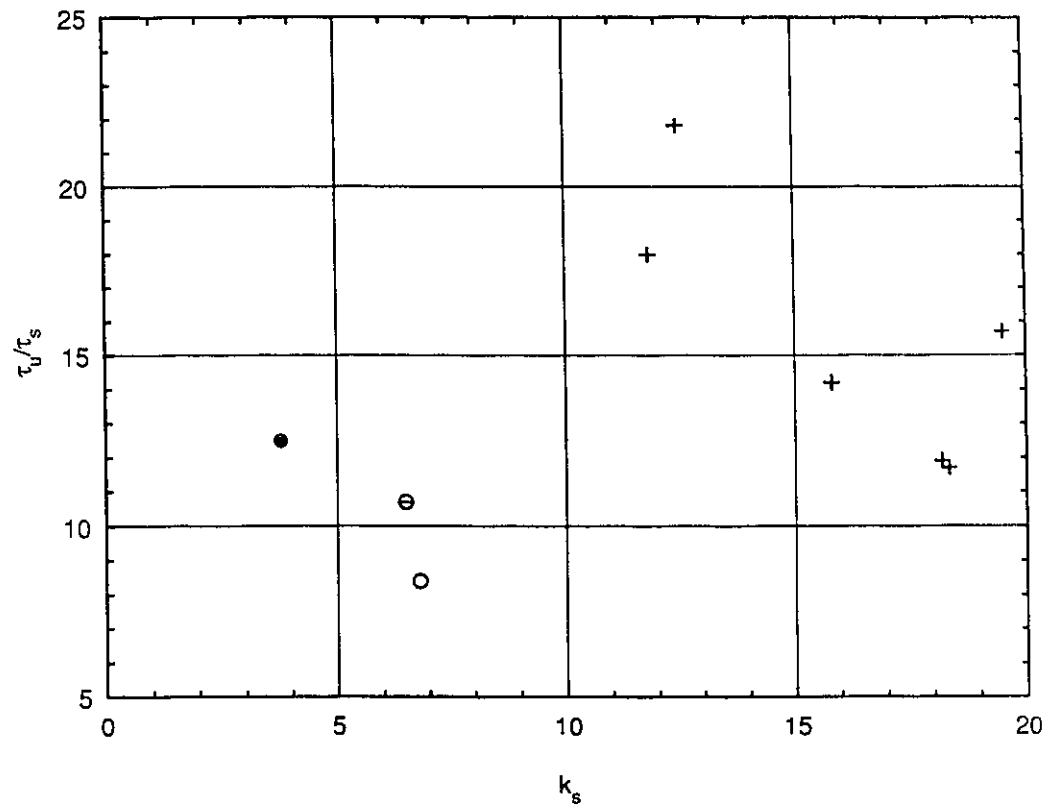


Figure 42 Timescale ratio τ_u/τ_s vs. k_s in uniform shear flow. Symbols as in figure 36.

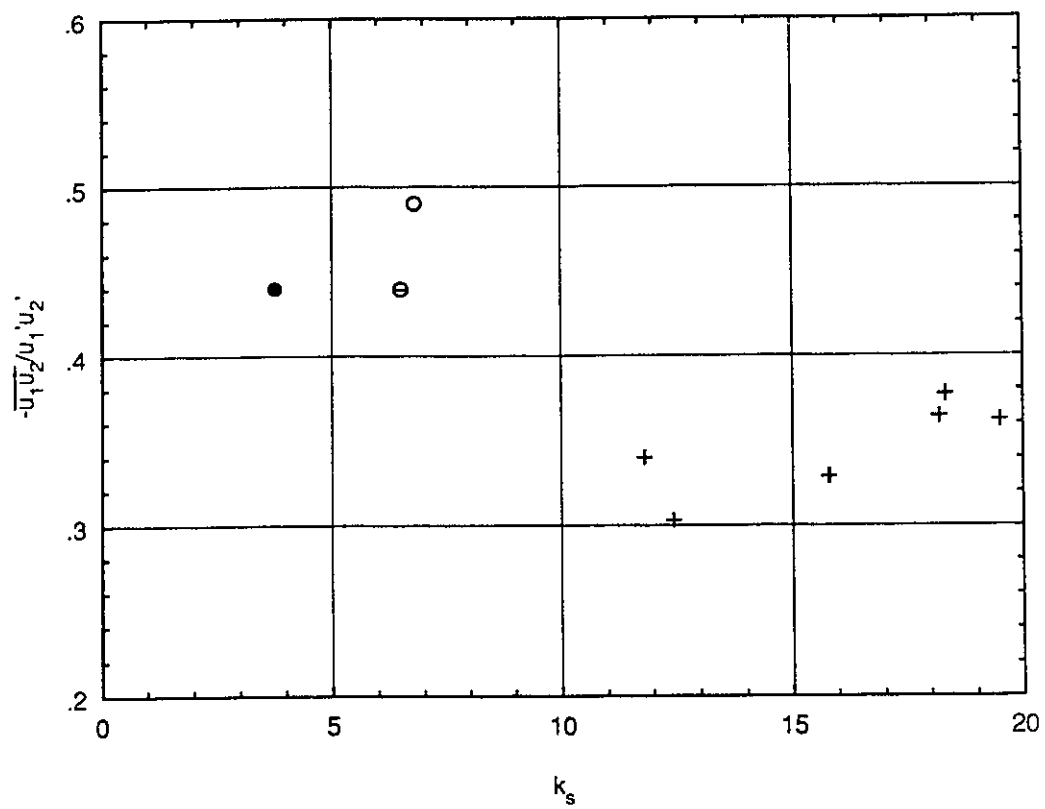


Figure 43 Reynolds stress correlation coefficient vs. k_s in uniform shear flow. Symbols as in figure 36.

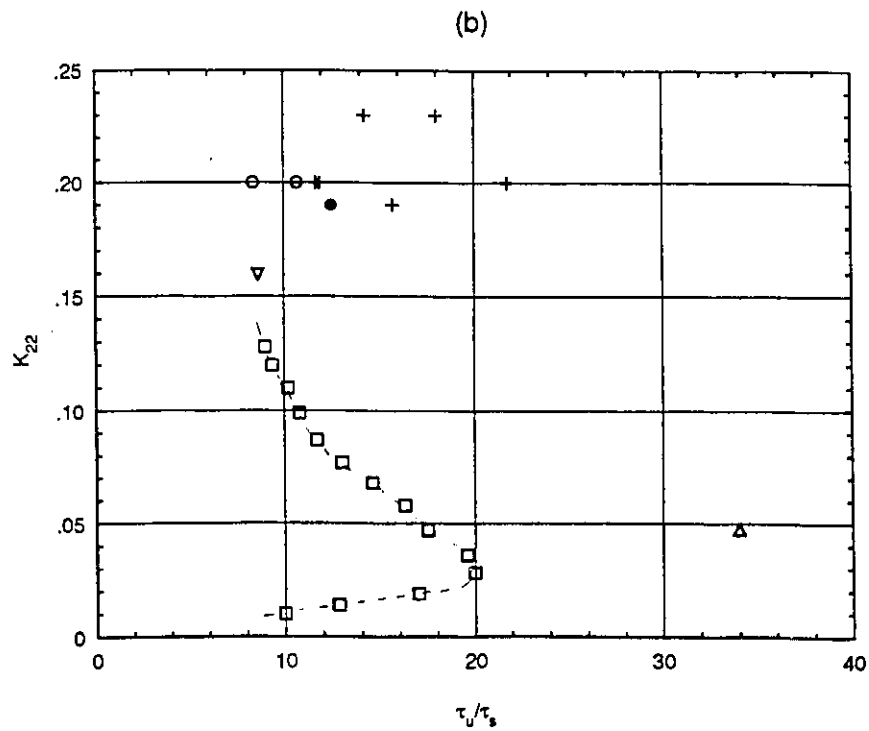
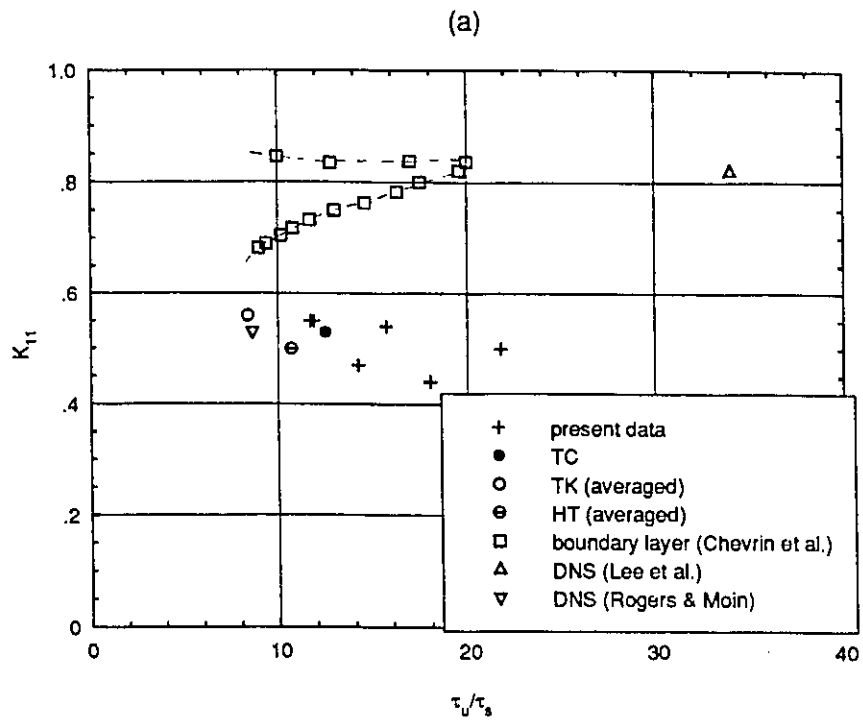


Figure 44 (a,b). For caption see next page.

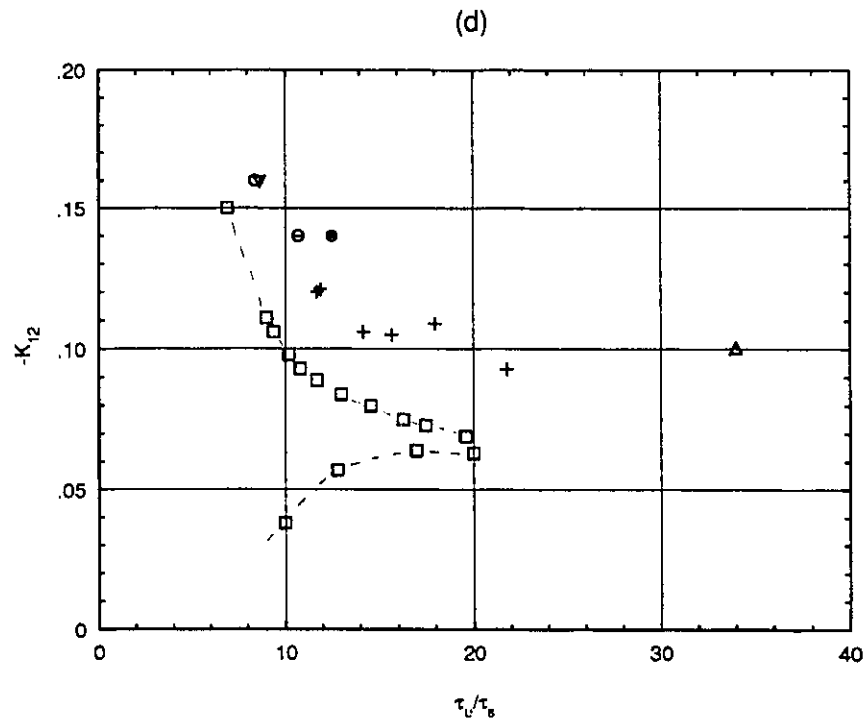
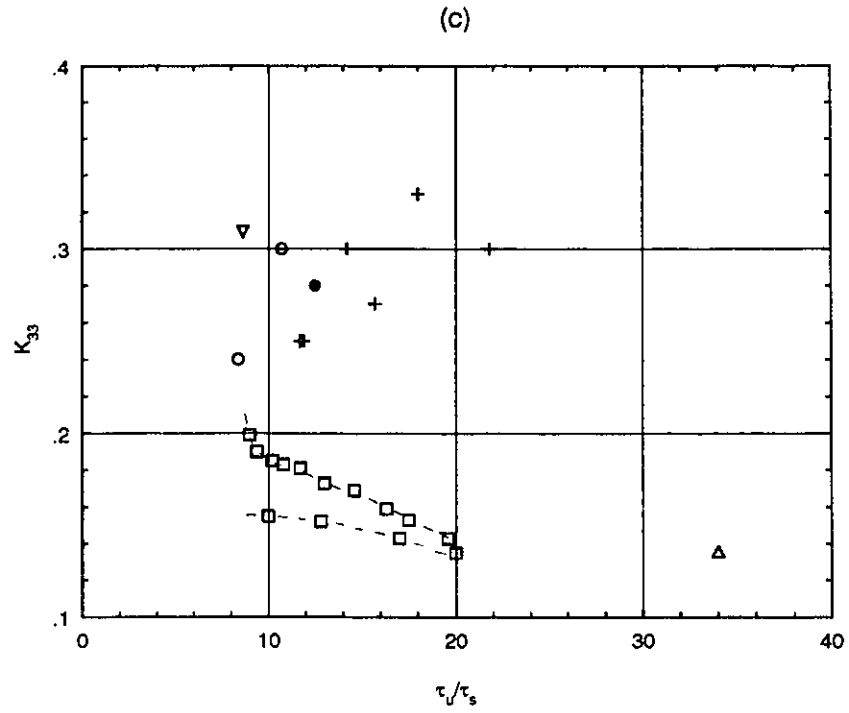


Figure 44 Non-dimensional Reynolds stresses vs. τ_u/τ_s . Symbols as in (a).
 (a) K_{11} ; (b) K_{22} ; (c) K_{33} ; (d) $-K_{12}$

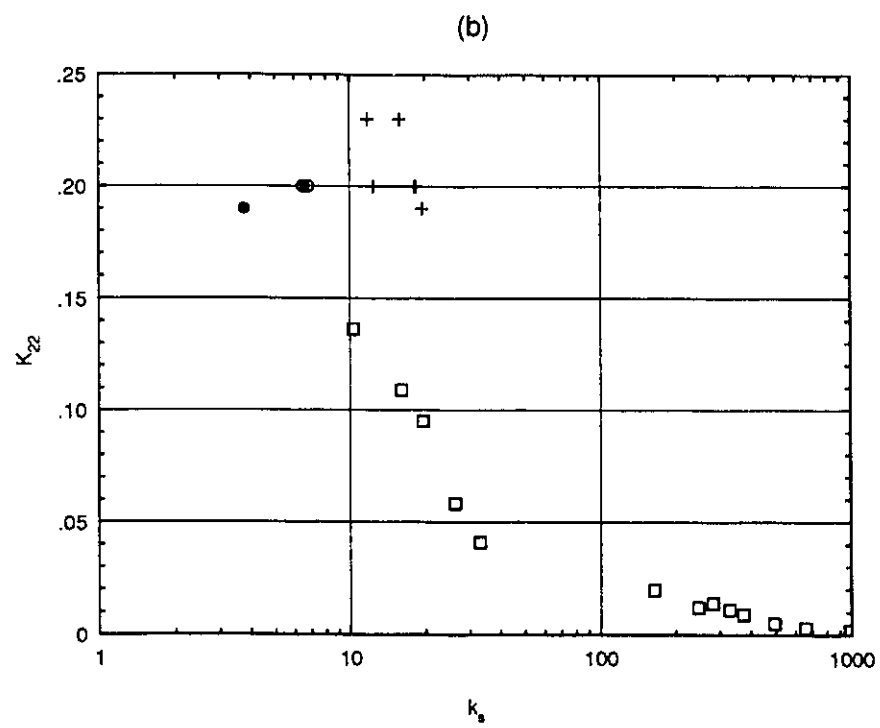
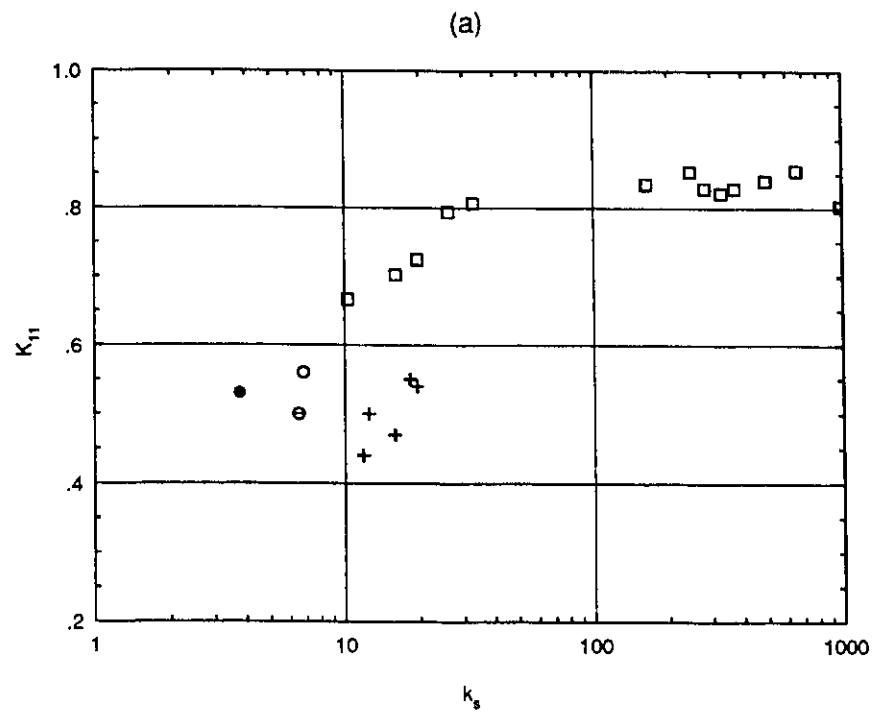


Figure 45 (a,b). For caption see next page.

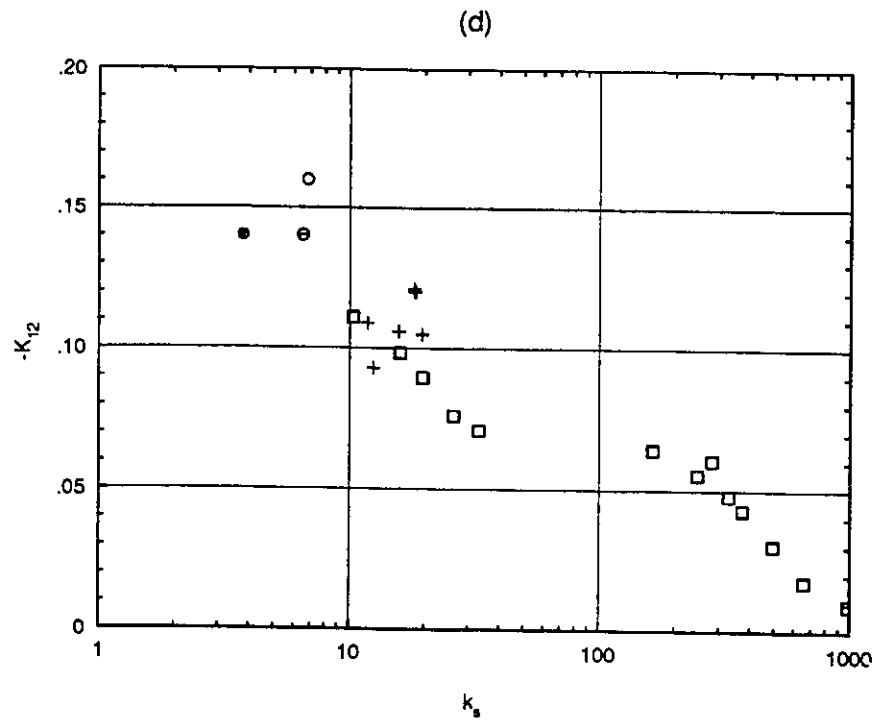
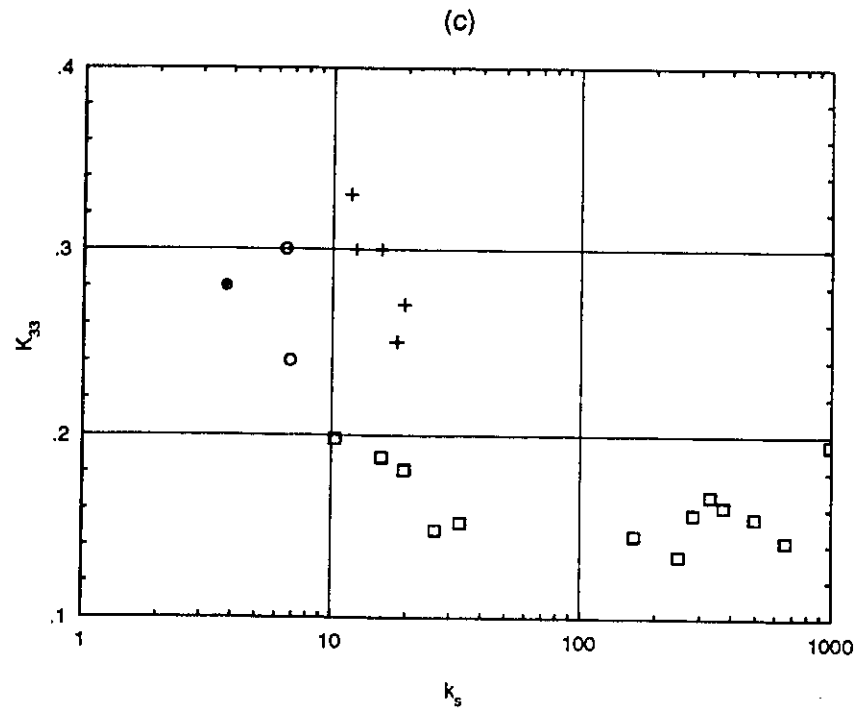


Figure 45 Non-dimensional Reynolds stresses vs. k_s . Symbols as in figure 44. (a) K_{11} ; (b) K_{22} ; (c) K_{33} ; (d) $-K_{12}$

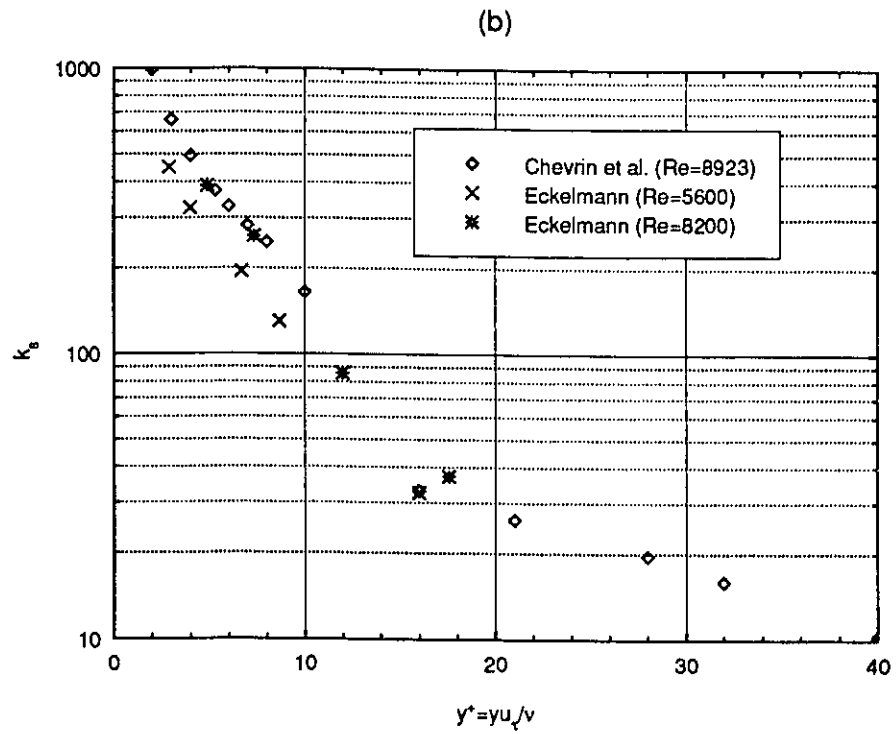
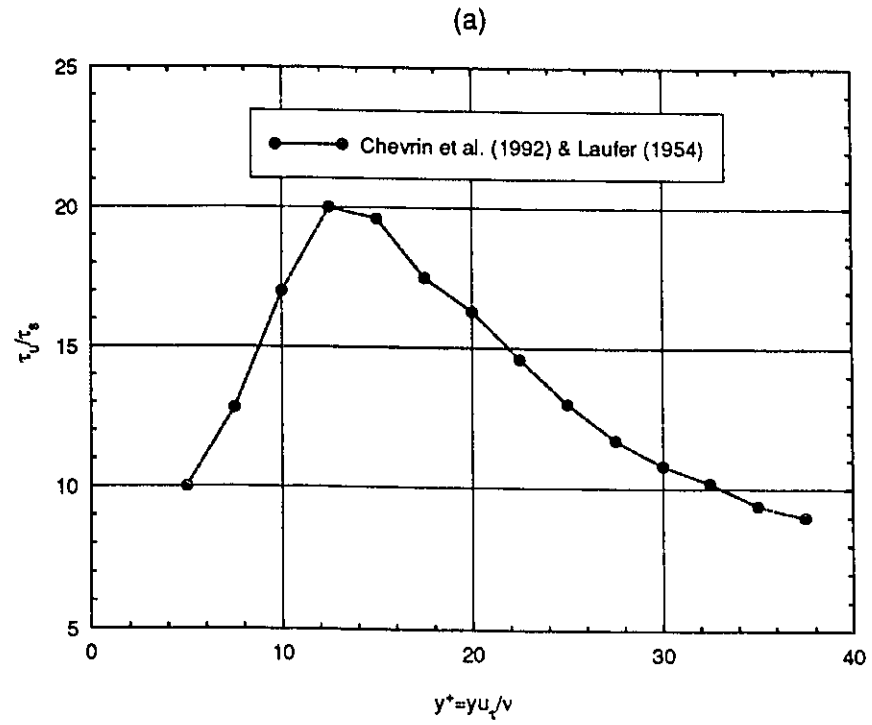


Figure 46 (a,b). For caption see next page.

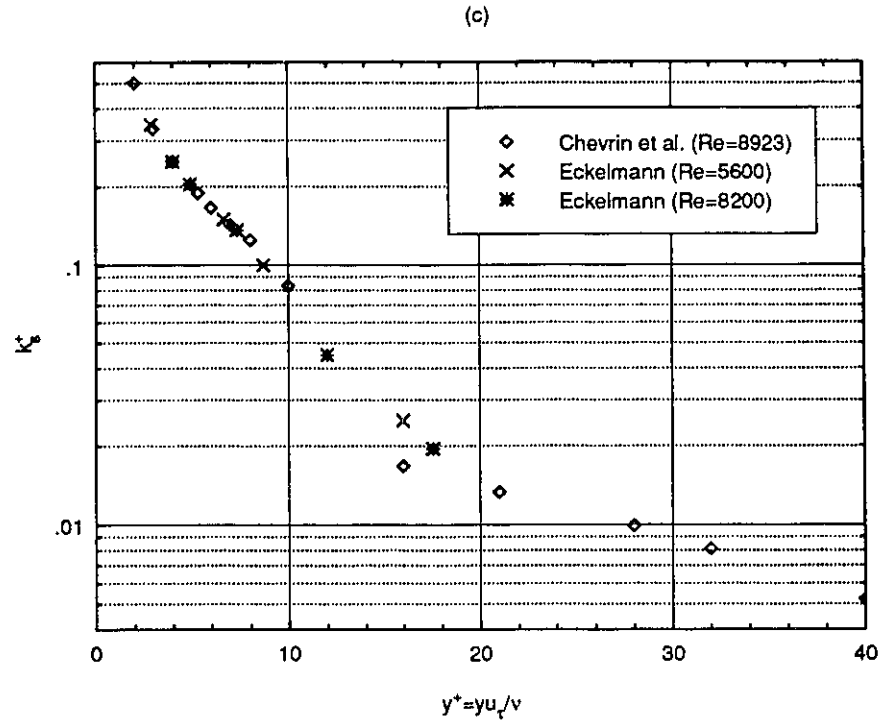


Figure 46 Variation of shear rate parameters with wall distance in boundary layer flow. (a) τ_w/τ_s vs. y^+ ; (b) k_s vs. y^+ ; (c) k_s^+ vs. y^+ .

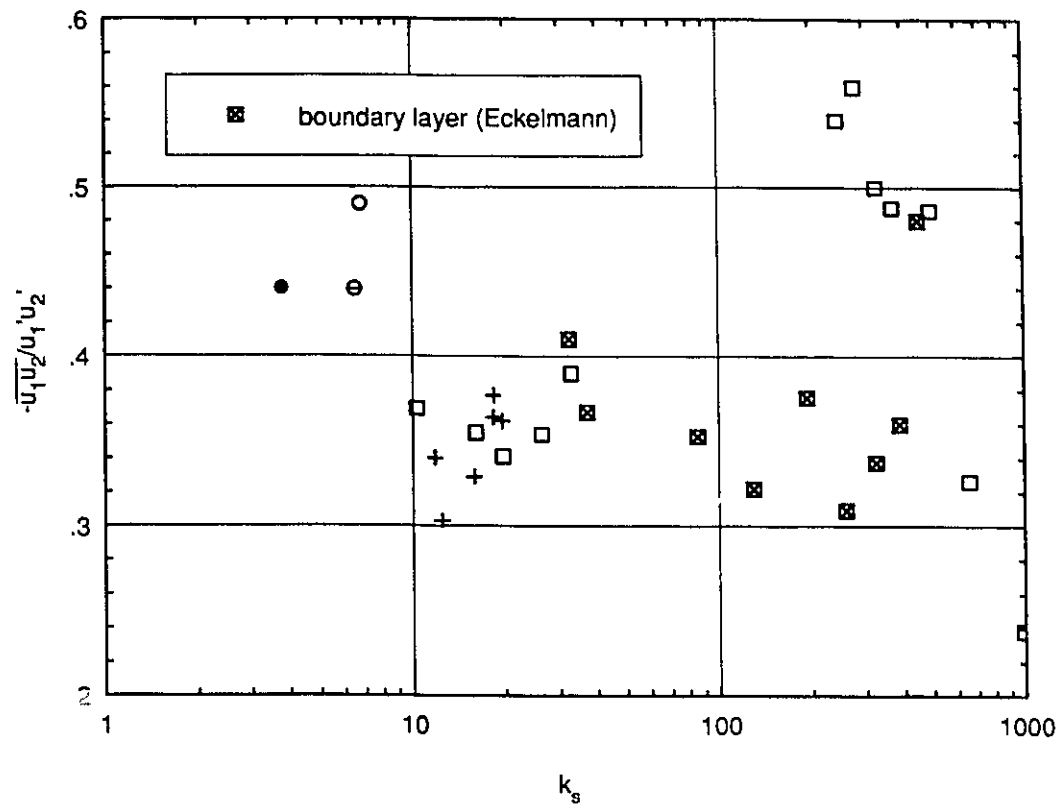


Figure 47 Reynolds stress correlation coefficient vs. k_s . Unlabelled symbols as in figure 44.

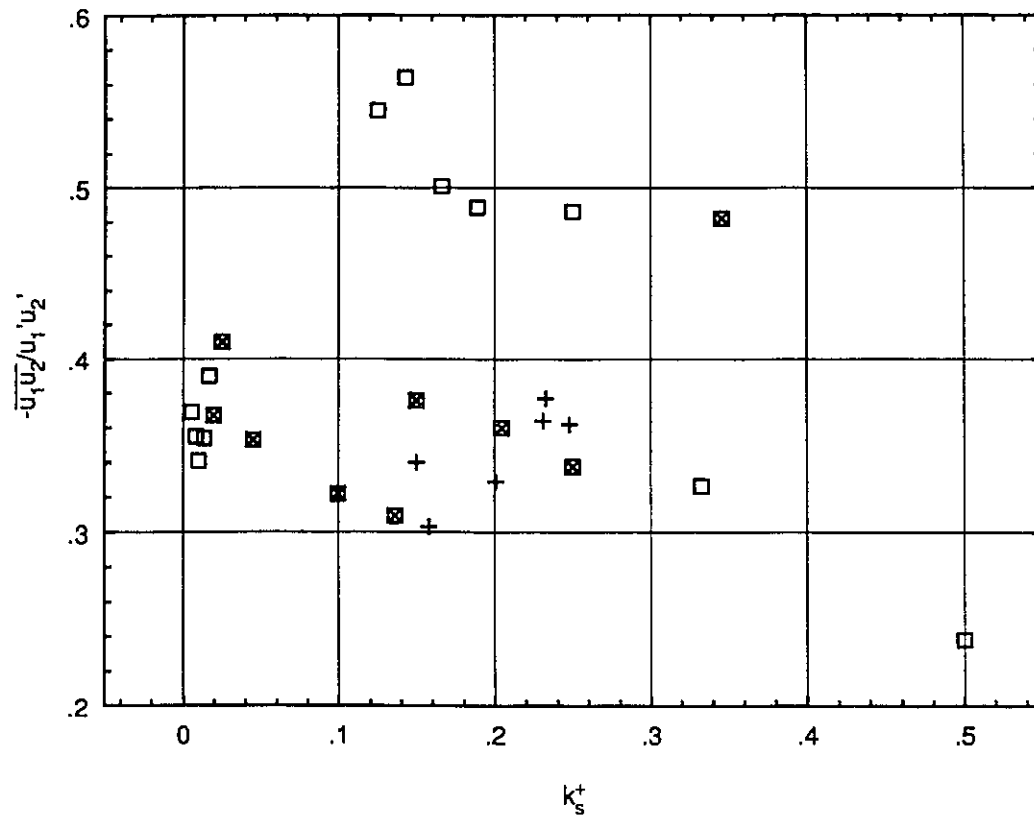


Figure 48 Reynolds stress correlation coefficient vs. k_s^+ for uniform shear flow and boundary layer flow. Symbols as in figure 44 and figure 47.

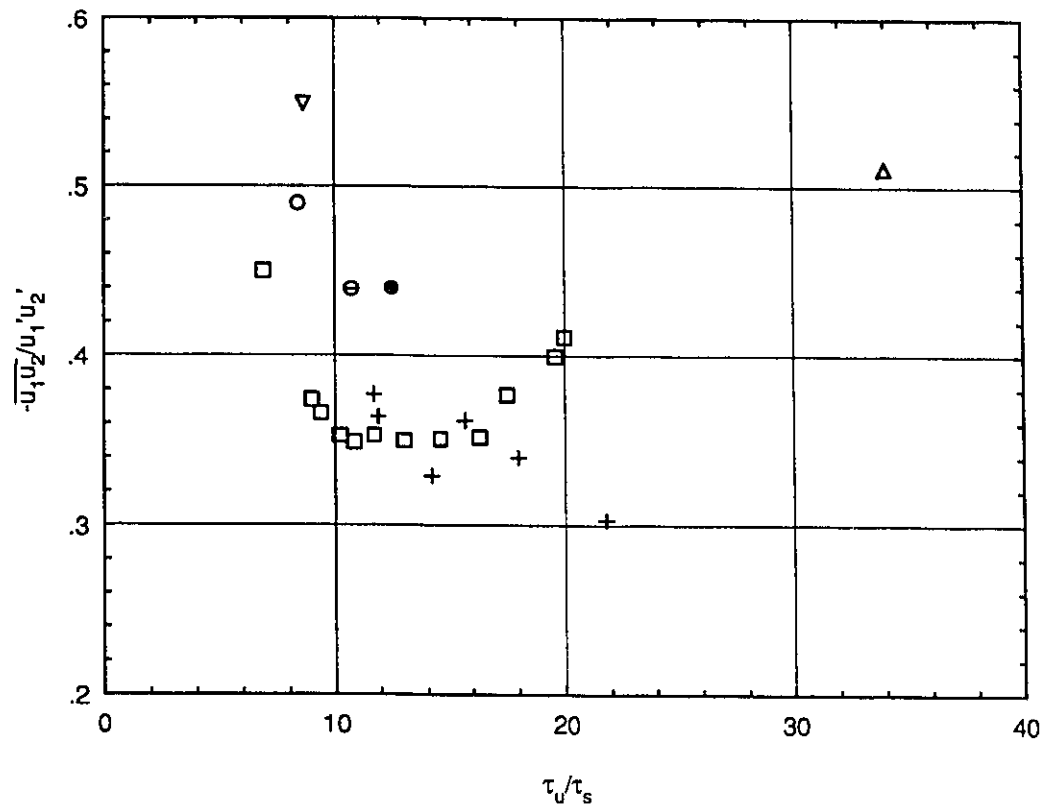


Figure 49 Reynolds stress correlation coefficient vs. τ_u/τ_s . Symbols as in figure 44.

APPENDIX A

Drawings of Shear Generator Components

The following pages contain drawings of all the components of the shear generator. These components are listed below. The drawings shown are those actually submitted to the machine shop.

Component	Page
Assembly of cover plate, spacer plate and filler blocks in shear generator frame	A2
Fully open (zero solidity) cover plate (not used in present study)	A3
Perforated cover plates #1 and #2	A4
Perforated cover plates #3 and #4 (plate #4 was not fabricated)	A5
Spacer plate (fits inside shear generator frame against downstream face)	A6
Flow separator assembly (separator plates and side plates)	A7
Individual separator plate	A8
Supporting side plates for separator plates at wide end	A9
Supporting side plates for separator plates at narrow end	A10
Solid plug for middle eight flow separator channels	A11
Solid plug for top and bottom channel	A12
Aluminum spacer blocks to reduce channel width to 12.7 cm	A13
Assembly of additional screens for each channel (up to two screens per channel)	A14
Small blocks used to clamp additional screens in each channel	A15
Additional screens for each channel	A16

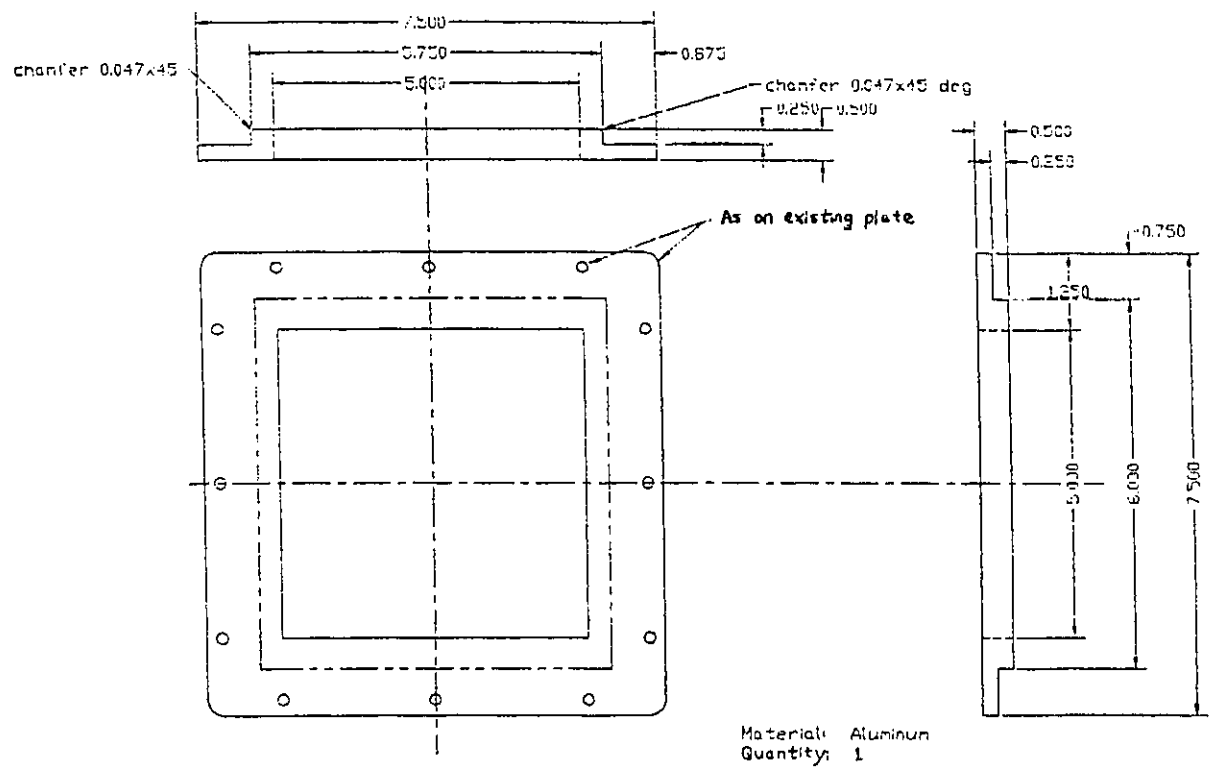


Figure A2 Fully open cover plate (not used in present study).

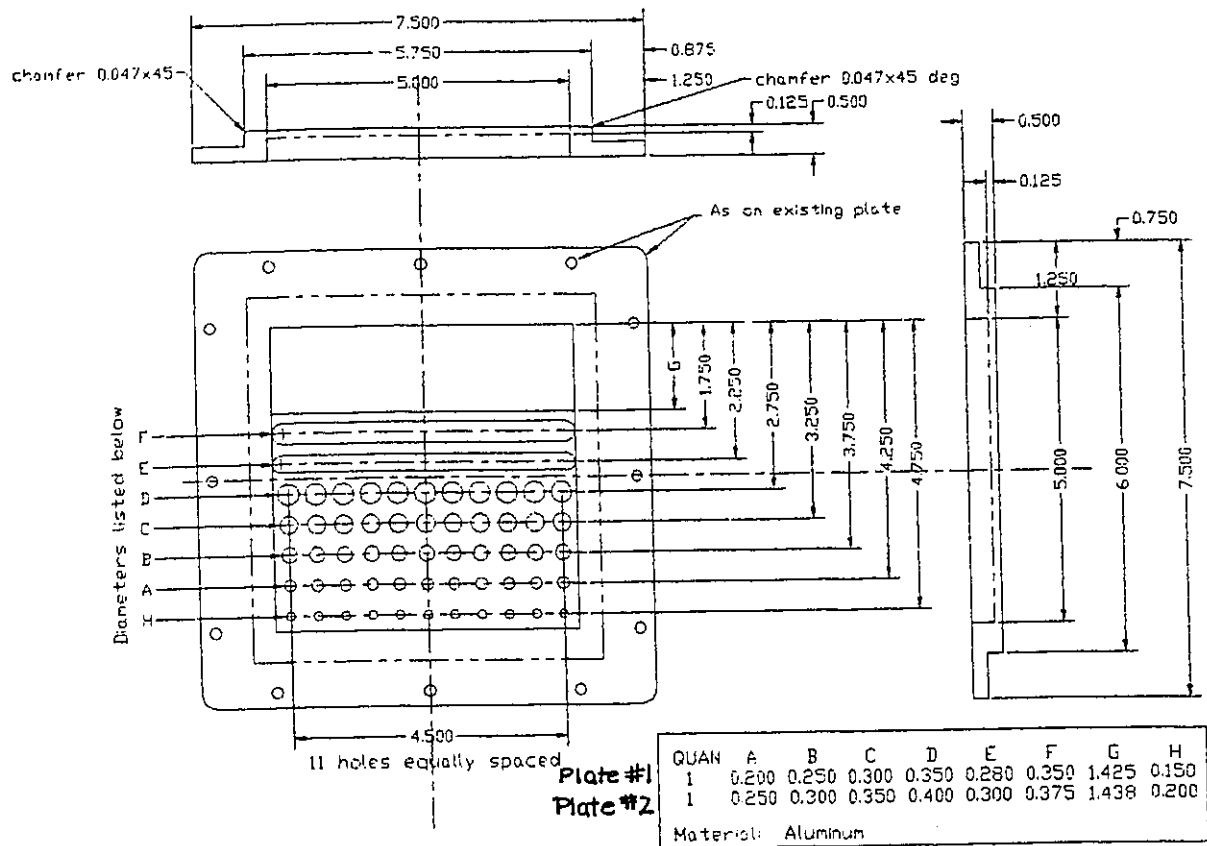


Figure A3 Perforated cover plates #1 and #2.

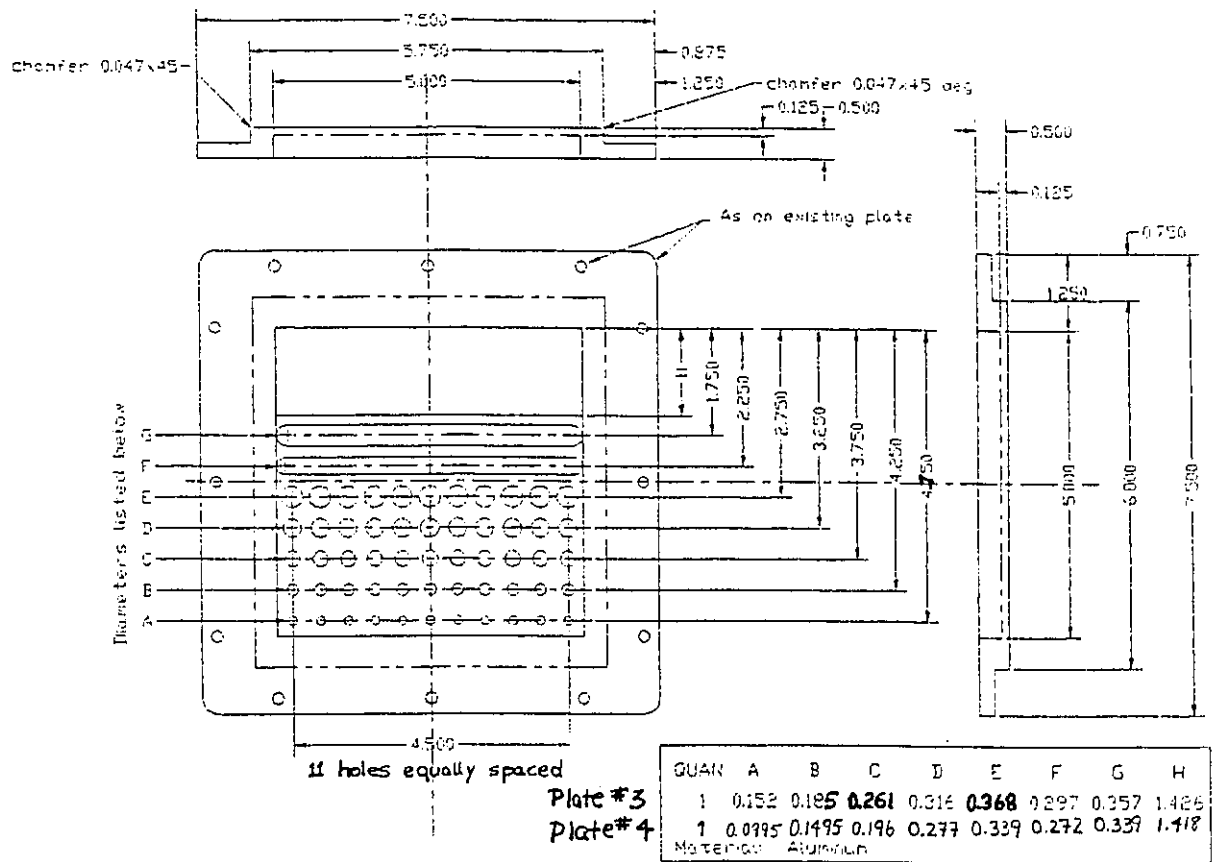


Figure A4 Perforated cover plates #3 and #4 (Plate #4 was not fabricated).

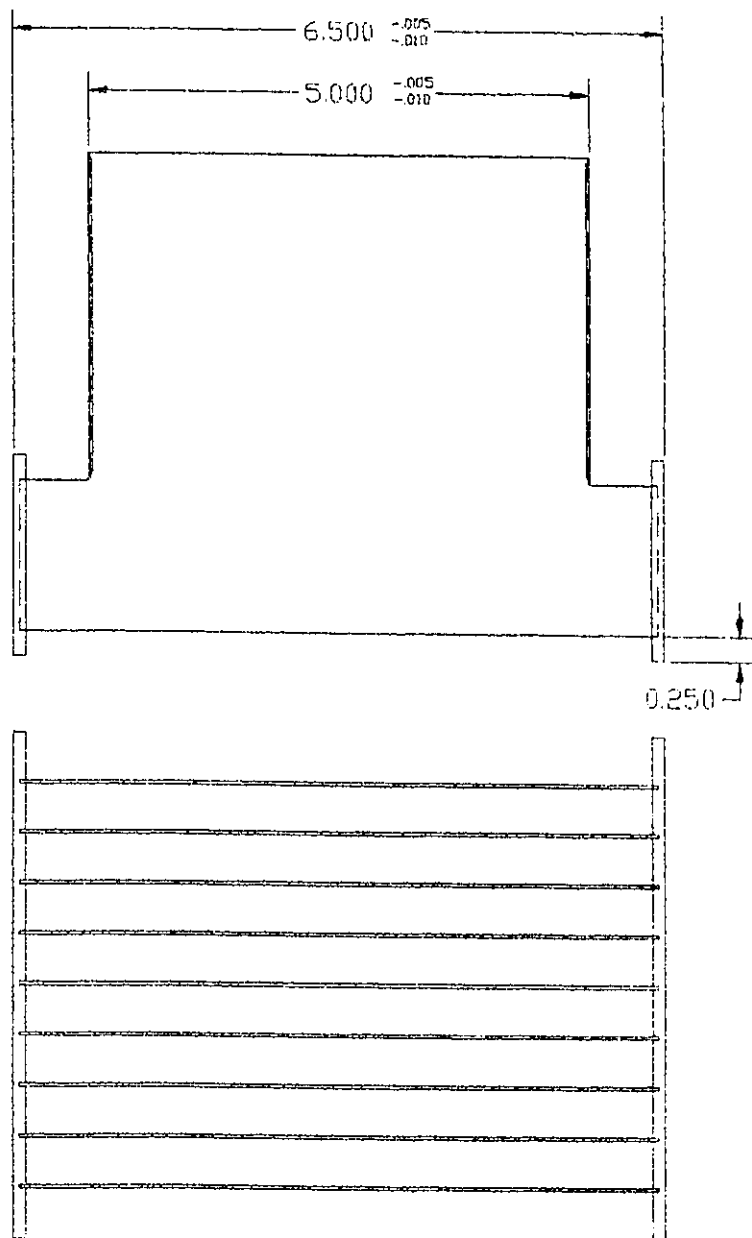


Figure A6 Flow separator assembly (separator plates and supporting side plates).

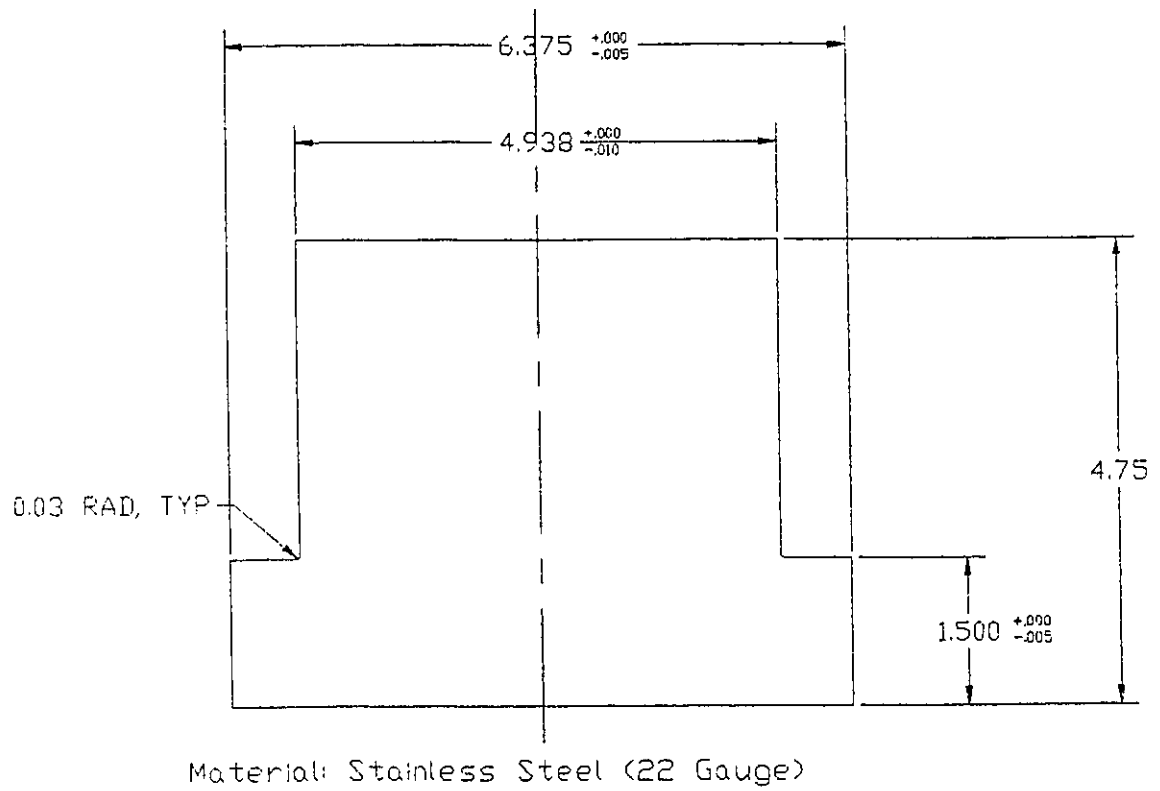


Figure A7 Individual separator plate.

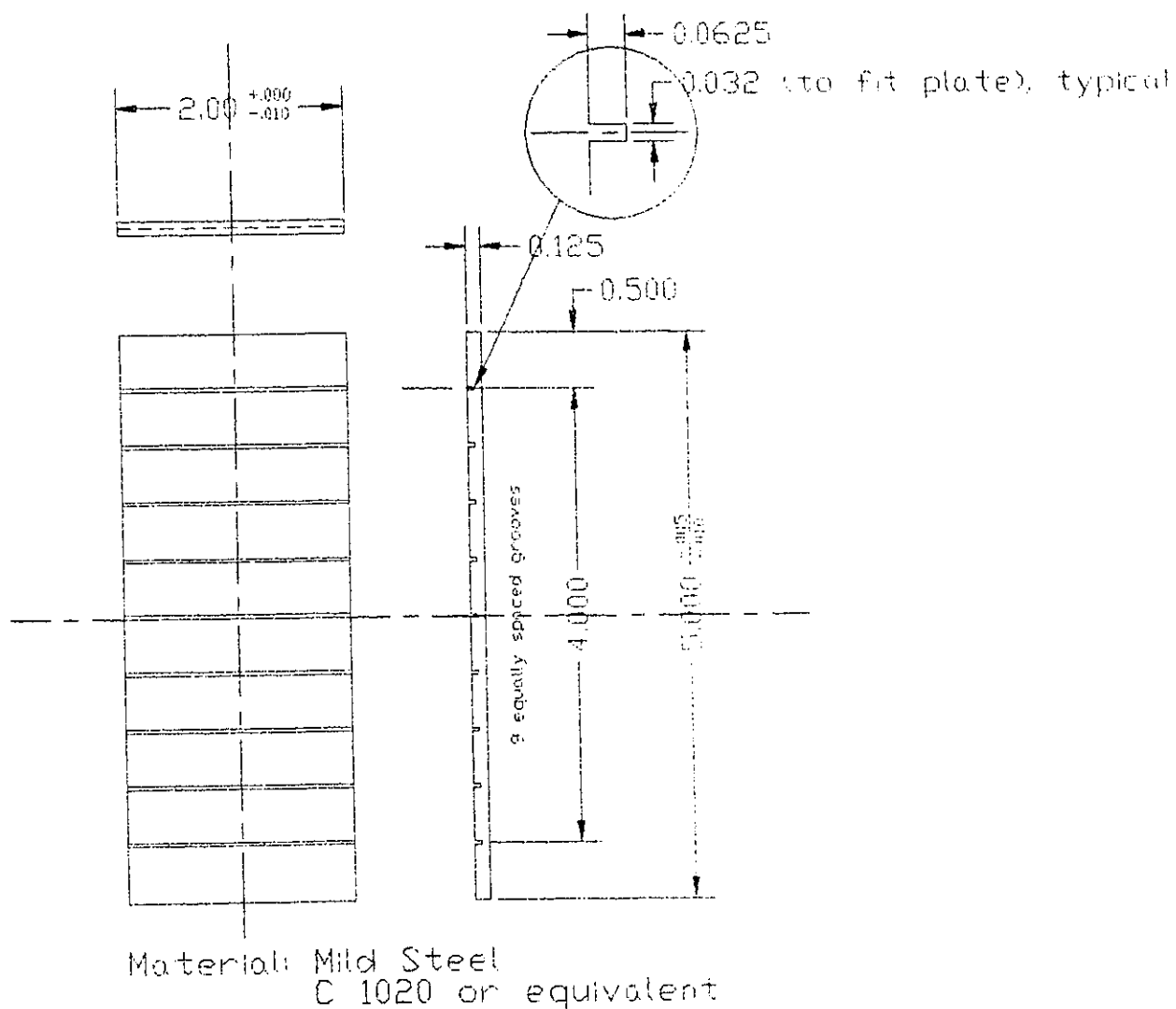


Figure A8 Supporting side plates for separator plates at wide end.

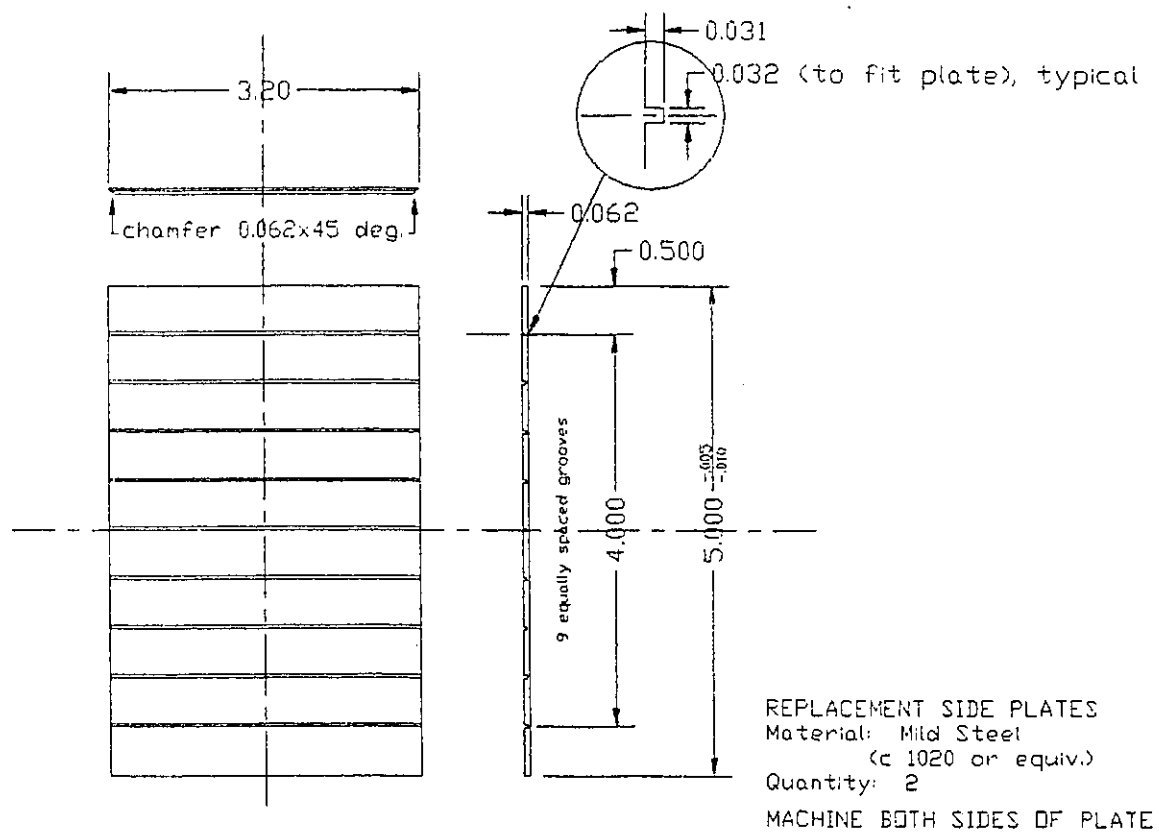
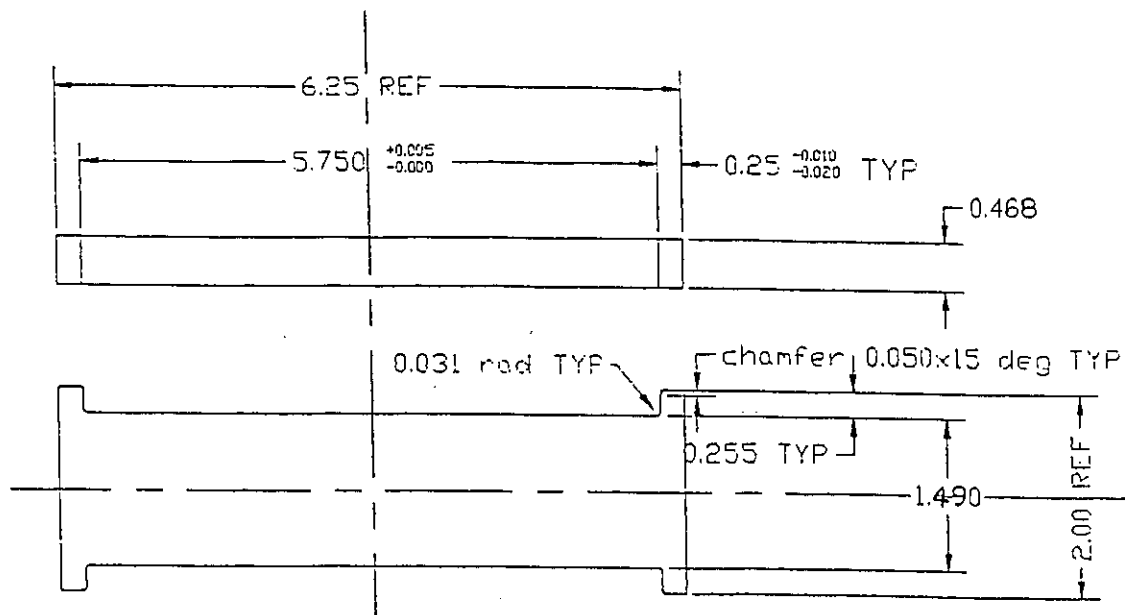


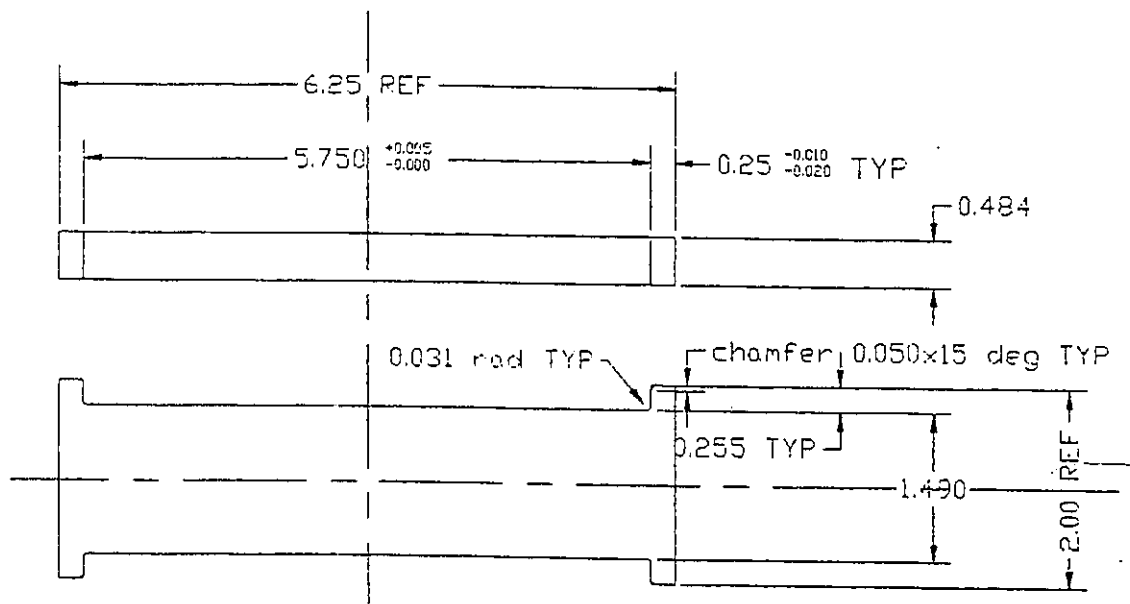
Figure A9 Supporting side plates for separator plates at narrow end.



All tolerances: $\begin{smallmatrix} +0.000 \\ -0.005 \end{smallmatrix}$ (except where specified)

Material: Aluminum

Figure A10 Solid plug for middle eight flow separator channels.



All tolerances: $\begin{smallmatrix} +0.000 \\ -0.005 \end{smallmatrix}$ (except where specified)

Material: Aluminum

Figure A11 Solid plug for top and bottom channel.

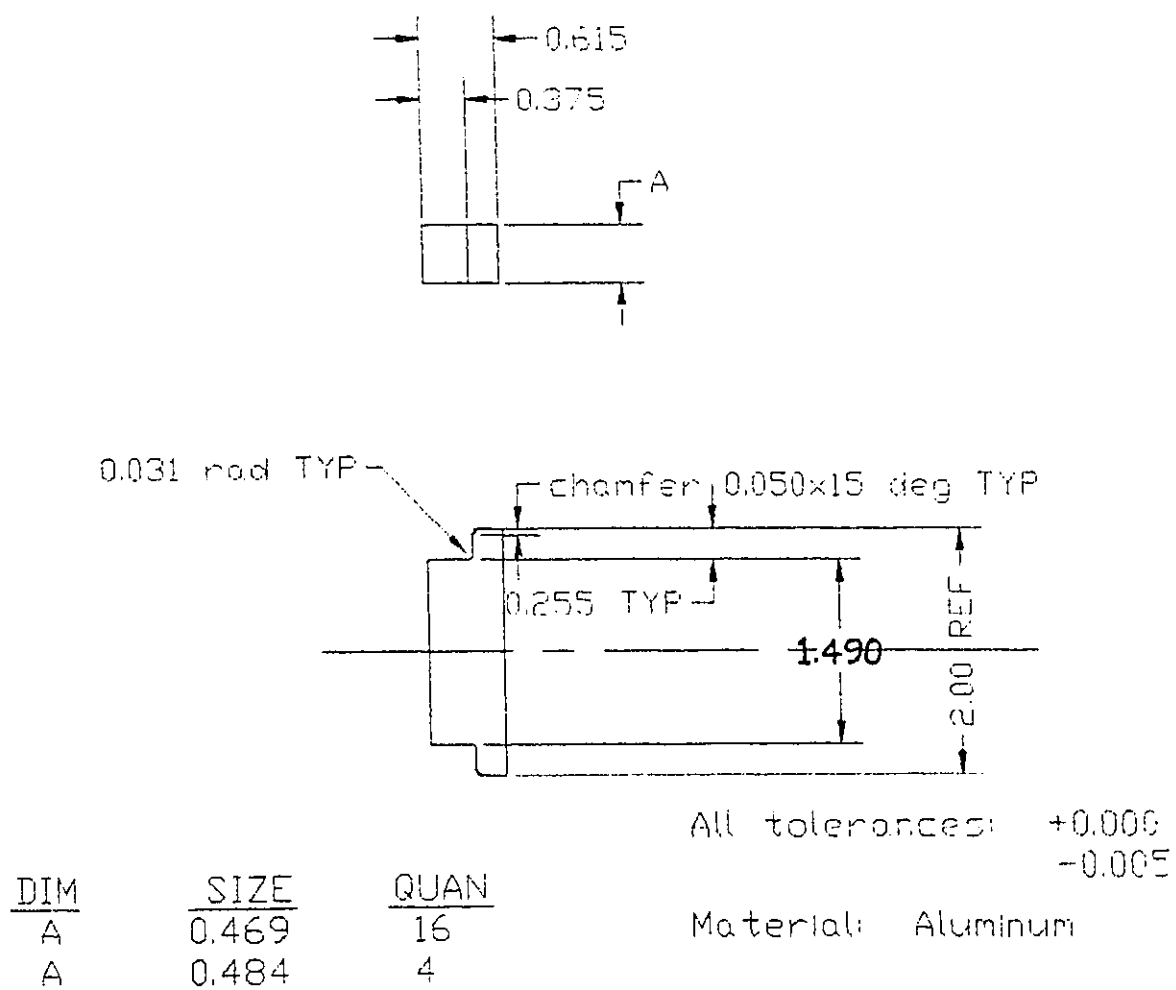
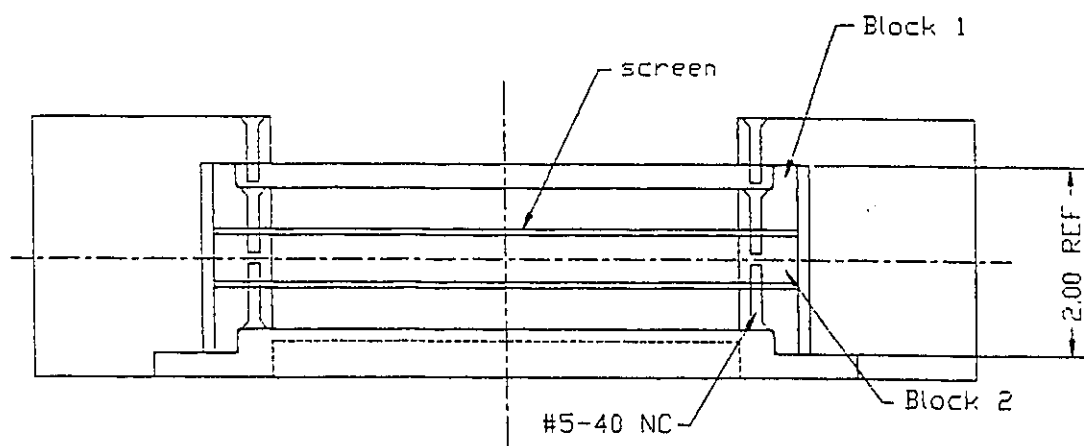


Figure A12 Aluminum spacer blocks to reduce channel width to 12.7 cm.



ASSEMBLY: BLOCK 1 AND BLOCK 2

Figure A13 Assembly of additional screens for each channel.

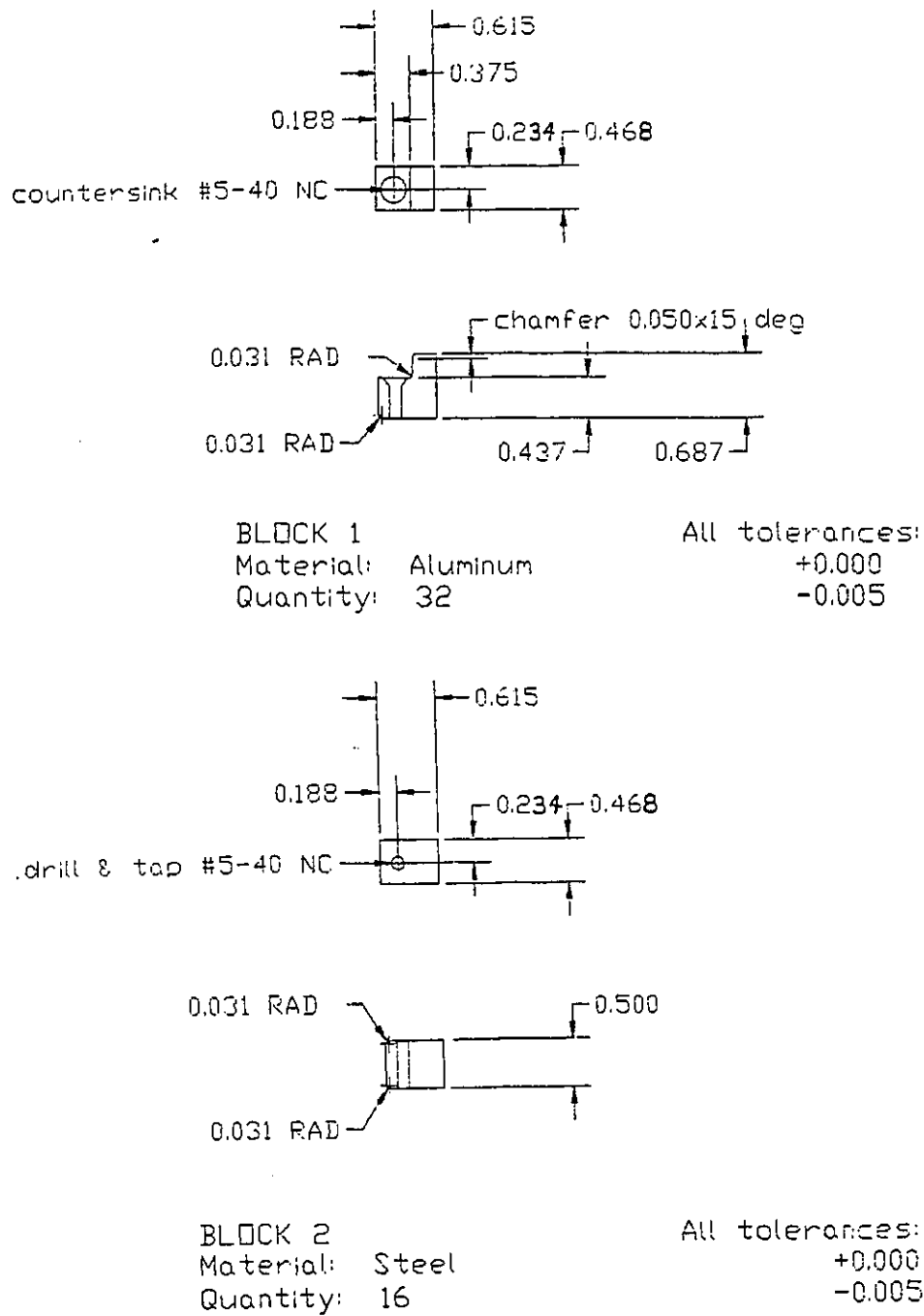


Figure A14 Small blocks used to clamp additional screens in each channel.

APPENDIX B

Set-up Parameters for the LDV System

In order to acquire data using the FLOWare software, various physical and optical parameters of the LDV system, as well as run-time specifications, must be entered in the Setup and Acquire module. The following are typical settings, which are specific to the LDV system and test conditions of the present study.

ELECTRONICS SETUP	
Dimension	2-D
Encoder mode	Disabled
Bragg cell outputs	1 on 2 off
Burst detector mode	Trigger on U1/external inhibit
Base address (HEX)	300H
Photomultipliers	55X08

TRANSMITTING OPTICS SETUP		
Parameter	U_x (U_1 in present tests)	U_y (U_2 or U_3 in tests)
Fringe spacing (μm)	2.914	3.072
Number of fringes	25	25
Wavelength (nm)	488	514.5
Gaussian beam diameter (mm)	1.35	1.35
Beam collimator expansion	1	1
Beam expander expansion	1	1
Beam separation (mm)	26.87	26.87
Lens focal length (mm)	159.9	159.9

BANDWIDTH SETUP			
Component	Bandwidth (MHz)	Gain	Optical Frequency Shift (MHz)
U _x	36.0	High	40
U _y	12.0	High	40
Burst detector bandwidth (MHz)		1.250	
CLOCK			
Transit time resolution (μsec/bit)		0.2	
Arrival time mode		1	
Arrival time resolution (μsec/bit)		1	

VALIDATION SETUP	
Signal level validation	Yes
Validation level	-3 dB
U_x velocity	Yes
U_y velocity	Yes
Accepted fringe count	0 to 150

HIGH VOLTAGE SETUP		
Component	Volts	Balance
U_x	1800	1.0
U_y	1200	0.66667

APPENDIX C

Computer Programs and Effect of Noise Elimination

The source codes of the computer programs which eliminate noise from the data and calculate turbulence statistics are included in the following pages. Also shown are the output files generated by these programs. The effect of varying the "window of data acceptance", or the limits beyond which data samples are rejected, are shown in numerical and graphical forms. Finally, selected plots of shear flow velocity time series and histograms, depicting random noise in the signal, are presented. A brief description of the information presented in this section follows.

The program "stat" is found on pages C3 to C5. For a specified downstream development data run, it reads the velocity files which are created for each measurement point by FLOWare. Each velocity file lists the values of both fluctuating velocity components, as well as the arrival time, of each valid data sample collected by the LDV system. The program "stat" calculates the mean and standard deviation of the streamwise velocity, and then discards samples for which the value of the streamwise velocity is beyond 2.5 standard deviations from the mean. With the remaining samples, it calculates various turbulence statistics at each measurement point, and outputs these in tabular form. Output files of filtered data for each flow case are shown on pages C6 to C8. For comparison, "stat" was run with the limiting number of standard deviations set to 20, so that no data samples were eliminated. These output files, representing "unfiltered" data for each flow case, appear on pages C9 to C11.

The program "stat" is compatible with FLOWare version 3. Slight modification was necessary in order to process the data of flow cases #1 and #2, since these were acquired using version 2 of FLOWare. Minor changes were also required for flow case #6, in order to accommodate the fewer measurement points.

The source code of "estat" is found on pages C12 to C14. This program performs the same elimination procedure as "stat", but for empty tunnel runs. It also calculates and outputs various turbulence statistics, which are shown in the output files on pages C15 and C16.

For each flow case, quantities such as turbulence timescales, the ratio of dissipation to production, the average Reynolds stress correlation coefficient and the average dimensionless Reynolds stress tensor, are calculated by the program "turb", whose source code is listed on pages C17 and C18. This program reads the output files of "stat". When calculating averages of the dimensionless Reynolds stress tensor and correlation coefficient over all the measurement points (usually 10) of a given downstream development run, it rejects outlying values beyond two standard deviations from the mean. The output files of this program are included on pages C19 to C22.

Before the selection of 2.5 standard deviations from the mean as the window of data acceptance, the program "stat" was run using various other limits as well. The effect of varying the window of data acceptance is demonstrated in figure C1 (pages C26-C27), using the data of flow case #3. The effect on the turbulence quantities calculated by the program "turb" are shown in the output files for flow cases #1 and #3, which are listed on pages C23 to C25. Also shown, for case #1 only, is the sensitivity of the turbulence statistics to the number of measurement points used for the least-squares fit of the exponential coefficient κ .

Figure C2 (pages C28-C30) displays velocity time series for each shear flow case. Each time series represents an arbitrarily selected measurement point taken during a downstream development data run, and depicts spurious noise as randomly occurring, large spikes. The corresponding streamwise velocity histograms are shown in figure C3 (pages C31-C33).

```

PROGRAM STATISTICS

C   *** THIS PROGRAM READS THE VELOCITY FILES FROM FLOWARE ***
C   *** AND CALCULATES THE MEAN, STANDARD DEVIATION AND ***
C   *** ELIMINATES POINTS WHICH ARE MORE THAN X TIMES THE ***
C   *** STANDARD DEVIATION FROM THE MEAN, THEN RECALCULATES ***
C   *** MEAN, RMS AND REYNOLDS STRESS VALUES. ***
C   *** THE INPUT TO THE PROGRAM CONSISTS OF: ***
C   *** LINE 1:  NUMBER OF FILES TO BE PROCESSED ***
C   *** LINE 2:  NUMBER OF STANDARD DEVIATIONS TO LIMIT ***
C   *** LINE 3:  SHEAR RATE IN INVERSE SECONDS FOR FILES ***
C   *** LINES 4 to NFIL+3:  FILENAMES (HOR. FILES FIRST) ***
C   *****

PARAMETER(LUN=9, LUNO=10, NPTS=2000)
CHARACTER INFILE*9, CHAR*30
REAL AVERAGE, STD, REYNOLDS
REAL UVEL(NPTS), VVEL(NPTS), URAW(NPTS), VRAW(NPTS)
REAL UCHOR, UCVERT, USQHOR(10), USQVER(10), USQ(10)
REAL VSQ(10), WSQ(10), TAU(10), REYN(10), UVCO(10)
REAL UMEANH(10), UMEANV(10), URMSH(10), URMSV(10)
REAL VMEAN(10), WMEAN(10), VRMS(10), WRMS(10), UV(10)
REAL QSQ(10), K11(10), K22(10), K33(10), K12(10)

WRITE(*,1)
1  FORMAT('ENTER NUMBER OF FILES TO BE PROCESSED:')
   READ(*,*) NFIL

WRITE(*,2)
2  FORMAT('ENTER NUMBER OF STANDARD DEVIATIONS TO LIMIT DATA:')
   READ(*,*) FAC

C   *** OPEN OUTPUT FILE ***
OPEN(UNIT=LUNO, FILE='output.dat', STATUS='NEW')
WRITE(LUNO,3)
3  FORMAT(T5,'TAU',T13,'u1^2/Uc^2',T24,'u2^2/Uc^2',T35,'u3^2/Uc^2',
+        T46,'q^2/Uc^2',T58,'uv/Uc^2',T69,'uv/u''v''',T82,'K11',
+        T93,'K22',T104,'K33',T115,'K12')

WRITE(*,4)
4  FORMAT('ENTER THE SHEAR RATE {du1/dx2}:')
   READ(*,*) DULY

DO 99 NF=1,NFIL

WRITE(*,5)
5  FORMAT('ENTER VELOCITY FILENAME:')
   READ(*, '(A9)') INFILE
   OPEN (UNIT=LUN, FILE=INFILE, STATUS='READONLY')

C   *** FOR NEW VERSION OF FLOWARE ONLY ***
C   ***SKIP FIRST 13 LINES OF FILE ***
DO 10 I=1,13
10  READ(LUN,*)

C   ***READ FILE PARTICULARS***
READ(LUN,12) XPOS
READ(LUN,12) YPOS
READ(LUN,12) ZPOS
12  FORMAT(17x,$5.0)

DO 13 I=1,3
13  READ(LUN,*)
C   *****

NDP=1
20  READ(LUN,*,END=199) NPT,NSTAT,ARR,TRANS,URAW(NDP),VRAW(NDP)
   NDP=NDP+1
   GO TO 20
199  NDP=NDP-1

URAWM=AVERAGE(URAW,NDP)
VRAWM=AVERAGE(VRAW,NDP)

```

```

        USTD=STD(URAW,URAWM,NDP)
        VSTD=STD(VRAW,VRAWM,NDP)
        UVRAW=REYNOLDS(URAW,URAWM,VRAW,VRAWM,NDP)

22      WRITE(*,22) INFILE, FAC
        FORMAT('FOR FILE: ',a9,' (number of std=',f5.2,',)')
25      WRITE(*,25) URAWM,USTD,VRAWM,VSTD,UVRAW
        FORMAT('U Mean = ',f8.4,tr6,'U RMS= ',f8.4,
+           /'V Mean= ',f8.4,tr6,'V RMS= ',f8.4,/'UV= ',f8.4)

C      *** GET RID OF EXTRANEIOUS POINTS ***

        NSAM=0
        DO 40 I=1,NDP
            IF(ABS(URAW(I)-URAWM).LE.(USTD*FAC)) THEN
                NSAM=NSAM+1
                UVEL(NSAM)=URAW(I)
                VVEL(NSAM)=VRAW(I)
            ENDIF
40      CONTINUE

        WRITE (*,45) NSAM, NDP
65      FORMAT('Used ',i4,' out of ',i4,' samples.')

C      *** CALCULATE NEW MEAN, RMS AND REYNOLDS STRESS ***

        UM=AVERAGE(UVEL,NSAM)
        VM=AVERAGE(VVEL,NSAM)
        UR=STD(UVEL,UM,NSAM)
        VR=STD(VVEL,VM,NSAM)
        UVR=REYNOLDS(UVEL,UM,VVEL,VM,NSAM)
        WRITE(*,25) UM, UR, VM, VR, UVR

        IF((NF.LE.10).AND.(INFILE(3:3).EQ.'H').AND.(INT(XPOS).EQ.(NF-1)))
+      THEN
            UMEANH(NF)=UM
            VMEAN(NF)=VM
            URMESH(NF)=UR
            VRMS(NF)=VR
            UV(NF)=UVR
        ELSE IF((NF.GE.11).AND.(INFILE(3:3).EQ.'V').AND.
+      (INT(XPOS).EQ.(NF-1))) THEN
            UMEANV(NF-10)=UM
            URMV(NF-10)=UR
            VMEAN(NF-10)=VM
            VRMS(NF-10)=VR
        ELSE
            TYPE *,'INPUT FILES ARE INCORRECTLY ORDERED'
            GO TO 999
        ENDIF

99      CONTINUE

C      *** CALCULATE TURBULENCE STATISTICS ***

        UCHOR=AVERAGE(UMEANH,10)
        UCVERT=AVERAGE(UMEANV,10)
        UC=(UCHOR+UCVERT)/2

        DO 200 I=1,10
            USQHOR(I)=(URMESH(I)/UCHOR)**2
            USQVER(I)=(URMSV(I)/UCVERT)**2
            USQ(I)=(USQHOR(I)+USQVER(I))/2
            VSQ(I)=(VRMS(I)/UCHOR)**2
            WSQ(I)=(VRMS(I)/UCVERT)**2
            TAU(I)=0.0254*(I+24)*DUDY/UC
            REYN(I)=UV(I)/(UCHOR**2)
            UVCO(I)=UV(I)/(URMESH(I)*VRMS(I))
            QSQ(I)=USQ(I)+VSQ(I)+WSQ(I)
            K11(I)=USQ(I)/QSQ(I)
            K22(I)=VSQ(I)/QSQ(I)
            K33(I)=WSQ(I)/QSQ(I)
            K12(I)=REYN(I)/QSQ(I)

```

```
      WRITE(LUNO,'(11F11.6)') TAU(I),USQ(I),VSQ(I),WSQ(I),OSQ(I),
      REYN(I),UVCO(I),K11(I),K22(I),K33(I),K12(I)
200 + CONTINUE

      WRITE(LUNO,210) UCHOR, UCVERT, UC, FAC
210  FORMAT('Uc (from horizontal runs)= ',F8.4,
+         'Uc (from vertical runs) =',F8.4,'Uc (avg) =',F8.4,
+         'Standard deviation factor=',F5.2)

999  STOP
      END

      REAL FUNCTION AVERAGE(X,N)

      REAL X(2000)
      SUM=0
      DO 10 I=1,N
          SUM=SUM+X(I)
10   CONTINUE
      AVERAGE=SUM/N

      RETURN
      END

      REAL FUNCTION STD(X,XM,N)

      REAL X(2000)
      SUM=0
      DO 10 I=1,N
          SUM=SUM+(X(I)-XM)**2
10   CONTINUE
      STD=SQRT(SUM/N)

      RETURN
      END

      REAL FUNCTION REYNOLDS(U,UM,V,VM,N)

      REAL U(2000), V(2000), UV(2000)
      REAL AVERAGE

      DO 10 I=1,N
          UV(I)=(U(I)-UM)*(V(I)-VM)
10   CONTINUE
      REYNOLDS=AVERAGE(UV,N)

      RETURN
      END
```

COMBINED OUTPUT FILES OF PROGRAM 'STAT' FOR ALL FLOW CASES
(DATA WAS FILTERED TO REMOVE NOISE BEYOND 2.5 STD FROM THE MEAN)

FLOW CASE #1

TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11
7.800727	0.011036	0.004825	0.005759	0.021621	0.002094	0.283462	0.51
0426	0.223188	0.266386	0.096845				
8.112756	0.011507	0.003965	0.007733	0.023205	0.001883	0.280667	0.49
5863	0.170877	0.333260	0.081138				
8.424786	0.011049	0.004764	0.006136	0.021949	0.002018	0.277702	0.50
3413	0.217039	0.279548	0.091954				
8.736814	0.011909	0.005171	0.006875	0.023955	0.002321	0.288486	0.49
7152	0.215862	0.286986	0.096902				
9.048844	0.012287	0.004906	0.007761	0.024954	0.002406	0.326567	0.49
2375	0.196610	0.311016	0.096416				
9.360872	0.014286	0.006385	0.009615	0.030287	0.001950	0.215039	0.47
1701	0.210827	0.317473	0.064390				
9.672902	0.012351	0.005301	0.009976	0.027628	0.002388	0.303227	0.44
7042	0.191865	0.361092	0.086421				
9.984931	0.013482	0.004975	0.008354	0.026811	0.002400	0.311896	0.50
2853	0.185564	0.311583	0.089496				
10.296960	0.013587	0.005231	0.008206	0.027024	0.002822	0.349318	0.50
2774	0.193576	0.303649	0.104417				
10.608990	0.013475	0.006074	0.008850	0.028398	0.002770	0.304825	0.47
4506	0.213871	0.311623	0.097530				

Uc (from horizontal runs)= 36.2725
Uc (from vertical runs) = 34.7432
Uc (avg) = 35.5078
Standard deviation factor= 2.50

FLOW CASE #2

TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11
11.822006	0.032899	0.012511	0.020734	0.066144	0.007199	0.421566	0.49
7385	0.189144	0.313470	0.108843				
12.294887	0.039671	0.011812	0.019048	0.070531	0.007113	0.352089	0.56
2456	0.167477	0.270066	0.100842				
12.767768	0.038349	0.015044	0.018759	0.072152	0.004784	0.220891	0.53
1505	0.208499	0.259996	0.066309				
13.240648	0.039010	0.014807	0.019326	0.073143	0.009966	0.459869	0.53
3340	0.202434	0.264226	0.136249				
13.713528	0.040548	0.011622	0.020492	0.072661	0.005128	0.266376	0.55
8041	0.159944	0.282016	0.070578				
14.186408	0.042249	0.015658	0.025890	0.083797	0.009818	0.418938	0.50
4181	0.186856	0.308963	0.117163				
14.659288	0.042915	0.016473	0.021224	0.080612	0.010033	0.413665	0.53
2362	0.204350	0.263287	0.124456				
15.132168	0.049700	0.016801	0.021925	0.088425	0.009409	0.340634	0.56
2052	0.189997	0.247951	0.106404				
15.605049	0.050452	0.020923	0.021904	0.093278	0.009750	0.327332	0.54
0870	0.224307	0.234824	0.104529				
16.077930	0.054430	0.016319	0.022133	0.092881	0.011090	0.395909	0.58
6015	0.175692	0.238292	0.119404				

Uc (from horizontal runs)= 36.5436
Uc (from vertical runs) = 34.8522
Uc (avg) = 35.6979
Standard deviation factor= 2.50

FLOW CASE #3

TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11
10.134602	0.018216	0.010872	0.014339	0.043427	0.004520	0.320895	0.41
9466	0.250350	0.330184	0.104089				

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10.539986	0.018838	0.009961	0.011998	0.040797	0.005126	0.373213	0.46
1750	0.244152	0.294097	0.125651				
10.945371	0.018929	0.008952	0.012811	0.040691	0.003974	0.319509	0.46
5182	0.219991	0.314827	0.097668				
11.350754	0.020816	0.009844	0.012852	0.043512	0.004676	0.339789	0.47
8386	0.226244	0.295370	0.107466				
11.756138	0.021204	0.010369	0.014308	0.045881	0.004659	0.321081	0.46
2158	0.225987	0.311855	0.101552				
12.161522	0.020220	0.009971	0.014620	0.044811	0.004280	0.307713	0.45
1226	0.222514	0.326260	0.095515				
12.566906	0.022725	0.010811	0.014489	0.048024	0.004344	0.279596	0.47
3191	0.225114	0.301695	0.090462				
12.972291	0.022880	0.011289	0.014769	0.048937	0.004591	0.291463	0.46
7531	0.230675	0.301794	0.093821				
13.377674	0.023383	0.010917	0.013212	0.047513	0.005645	0.356395	0.49
2149	0.229778	0.278073	0.118804				
13.783059	0.026115	0.011378	0.014530	0.052022	0.006324	0.375657	0.50
1993	0.218709	0.279298	0.121568				

Uc (from horizontal runs)= 44.0625

Uc (from vertical runs) = 44.3084

Uc (avg) = 44.1855

Standard deviation factor= 2.50

FLOW CASE #4

TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11
	K22	K33	K12				
11.567563	0.032755	0.011299	0.015112	0.059166	0.006712	0.347713	0.55
3605	0.190974	0.255421	0.113436				
12.030265	0.031689	0.014724	0.015338	0.061751	0.006515	0.297784	0.51
3169	0.238449	0.248382	0.105507				
12.492969	0.033109	0.012390	0.015865	0.061363	0.007685	0.380809	0.53
9554	0.201908	0.258537	0.125246				
12.955671	0.036602	0.013424	0.017949	0.067974	0.008830	0.402587	0.53
8462	0.197488	0.264050	0.129899				
13.418373	0.038994	0.013589	0.017415	0.069998	0.007731	0.345286	0.55
7077	0.194128	0.248794	0.110450				
13.881075	0.039478	0.014698	0.017640	0.071815	0.006618	0.273736	0.54
9718	0.204658	0.245624	0.092158				
14.343779	0.039315	0.014930	0.016663	0.070908	0.008910	0.371484	0.55
4450	0.210551	0.235000	0.125658				
14.806481	0.041714	0.015799	0.016509	0.074022	0.009023	0.357930	0.56
3542	0.213434	0.223024	0.121894				
15.269183	0.043329	0.016851	0.019404	0.079585	0.010240	0.384515	0.54
4445	0.211735	0.243820	0.128672				
15.731887	0.041875	0.015465	0.018616	0.075956	0.010020	0.391464	0.55
1303	0.203609	0.245088	0.131924				

Uc (from horizontal runs)= 38.6136

Uc (from vertical runs) = 38.7882

Uc (avg) = 38.7009

Standard deviation factor= 2.50

FLOW CASE #5

TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11
	K22	K33	K12				
7.467881	0.008787	0.004840	0.006621	0.020248	0.002010	0.307686	0.43
3978	0.239022	0.327000	0.099270				
7.766596	0.008668	0.004832	0.006556	0.020056	0.002324	0.372138	0.43
2201	0.240921	0.326878	0.115882				
8.065312	0.008410	0.004184	0.006607	0.019201	0.001767	0.305890	0.43
8004	0.217903	0.344093	0.092018				
8.364027	0.008953	0.005020	0.007134	0.021108	0.002276	0.352017	0.42
4153	0.237847	0.338000	0.107813				
8.662743	0.009698	0.004446	0.006606	0.020750	0.002702	0.416435	0.46
7385	0.214266	0.318349	0.130223				
8.961457	0.009724	0.005112	0.007534	0.022370	0.002268	0.325274	0.43

4702	0.228504	0.336794	0.101401				
9.260173	0.010354	0.004640	0.006994	0.021987	0.002525	0.373662	0.47
0888	0.211019	0.318093	0.114855				
9.558887	0.010675	0.005256	0.007908	0.023839	0.002607	0.355530	0.44
7772	0.220492	0.331736	0.109356				
9.857603	0.010387	0.006989	0.007041	0.024418	0.002906	0.338363	0.42
5403	0.286231	0.288366	0.118999				
10.156319	0.010519	0.005076	0.006962	0.022557	0.002352	0.329691	0.46
6343	0.225022	0.308635	0.104250				

Uc (from horizontal runs)= 54.9790

Uc (from vertical runs) = 54.8978

Uc (avg) = 54.9384

Standard deviation factor= 2.50

FLOW CASE #6

TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11
K22	K33	K12					
12.353723	0.034958	0.012698	0.015481	0.063136	0.008176	0.402343	0.55
3685	0.201120	0.245194	0.129496				
12.811269	0.038593	0.013606	0.016813	0.069011	0.007458	0.333193	0.55
9224	0.197152	0.243624	0.108075				
13.268813	0.034889	0.013700	0.017127	0.065715	0.007983	0.373398	0.53
0904	0.208477	0.260619	0.121480				
13.726357	0.042368	0.013160	0.017401	0.072929	0.009130	0.380204	0.58
0943	0.180453	0.238603	0.125196				
14.183905	0.038798	0.014281	0.017832	0.070911	0.009502	0.402067	0.54
7140	0.201387	0.251473	0.133996				
14.641448	0.043888	0.014945	0.017445	0.076279	0.009946	0.411267	0.57
5368	0.195930	0.228701	0.130391				
15.556540	0.041872	0.014584	0.020341	0.076796	0.007278	0.337274	0.54
5235	0.189899	0.264866	0.094774				

Uc (from horizontal runs)= 36.2697

Uc (from vertical runs) = 35.4650

Uc (avg) = 35.8674

Standard deviation factor= 2.50

COMBINED OUTPUT FILES OF PROGRAM "STAT" FOR ALL FLOW CASES
(DATA WAS NOT FILTERED TO REMOVE NOISE)

FLOW CASE #1

TAU	$u1^2/Uc^2$	$u2^2/Uc^2$	$u3^2/Uc^2$	q^2/Uc^2	uv/Uc^2	$uv/u'v'$	K11
K22	K33	K12					
7.816626	0.013362	0.004831	0.006998	0.025192	0.002039	0.248347	0.53
0424	0.191788	0.277788	0.080939				
8.129291	0.013926	0.004026	0.007872	0.025824	0.002136	0.281161	0.53
9263	0.155911	0.304826	0.082722				
8.441956	0.013470	0.004860	0.006225	0.024556	0.002191	0.265882	0.54
8559	0.197920	0.253521	0.089220				
8.754621	0.014306	0.005219	0.006918	0.026443	0.002565	0.284375	0.54
1012	0.197371	0.261617	0.097014				
9.067286	0.014315	0.004962	0.007885	0.027162	0.002563	0.311485	0.52
7028	0.182669	0.290303	0.094347				
9.379951	0.020302	0.006479	0.009649	0.036431	0.002210	0.214247	0.55
7282	0.177847	0.264871	0.060676				
9.692616	0.015807	0.005334	0.010035	0.031175	0.002525	0.296568	0.50
7036	0.171085	0.321878	0.081004				
10.005280	0.016671	0.005029	0.008361	0.030060	0.002580	0.300983	0.55
4571	0.167288	0.278142	0.085835				
10.317945	0.016459	0.005339	0.008310	0.030108	0.003273	0.351878	0.54
6675	0.177335	0.275990	0.108712				
10.630611	0.015046	0.006185	0.009015	0.030247	0.003133	0.320278	0.49
7457	0.204480	0.298063	0.103596				

Uc (from horizontal runs)= 36.2266

Uc (from vertical runs) = 34.6446

Uc (avg) = 35.4356

Standard deviation factor=20.00

FLOW CASE #2

TAU	$u1^2/Uc^2$	$u2^2/Uc^2$	$u3^2/Uc^2$	q^2/Uc^2	uv/Uc^2	$uv/u'v'$	K11
K22	K33	K12					
11.909085	0.040905	0.012540	0.021127	0.074572	0.007198	0.386207	0.54
8530	0.168160	0.283310	0.096523				
12.385449	0.046904	0.012050	0.019386	0.078339	0.007631	0.364049	0.59
8725	0.153819	0.247456	0.097412				
12.861814	0.046154	0.015236	0.019050	0.080440	0.005482	0.222077	0.57
3774	0.189405	0.236821	0.068150				
13.338177	0.044401	0.015181	0.019490	0.079072	0.011140	0.479147	0.56
1529	0.191986	0.246485	0.140880				
13.814540	0.049300	0.012005	0.020896	0.082201	0.006190	0.295421	0.59
9757	0.146041	0.254202	0.075306				
14.290903	0.048032	0.015906	0.026288	0.090225	0.010684	0.427132	0.53
2352	0.176289	0.291359	0.118410				
14.767267	0.050986	0.016722	0.021603	0.089310	0.011021	0.413763	0.57
0882	0.187233	0.241885	0.123403				
15.243629	0.055958	0.017014	0.022206	0.095178	0.010078	0.347788	0.58
7937	0.178756	0.233308	0.105881				
15.719994	0.060533	0.021329	0.022130	0.103992	0.011443	0.344189	0.58
2089	0.205104	0.212806	0.110036				
16.196358	0.061519	0.017135	0.022410	0.101064	0.013342	0.433764	0.60
8710	0.169545	0.221745	0.132012				

Uc (from horizontal runs)= 36.2892

Uc (from vertical runs) = 34.5846

Uc (avg) = 35.4369

Standard deviation factor=20.00

FLOW CASE #3

TAU	$u1^2/Uc^2$	$u2^2/Uc^2$	$u3^2/Uc^2$	q^2/Uc^2	uv/Uc^2	$uv/u'v'$	K11
K22	K33	K12					
10.220633	0.026842	0.011341	0.014521	0.052703	0.004031	0.231355	0.50

9302	0.215183	0.275515	0.076491				
10.629458	0.025154	0.010406	0.012353	0.047914	0.006262	0.384839	0.52
4992	0.217185	0.257823	0.130686				
11.038284	0.023812	0.009316	0.013029	0.046158	0	0.333897	0.51
5889	0.201833	0.282279	0.102631				
11.447108	0.028885	0.010057	0.013190	0.052133	0.005516	0.343940	0.55
4074	0.192909	0.253017	0.105804				
11.855934	0.027106	0.010828	0.014573	0.052507	0.005622	0.336725	0.51
6238	0.206220	0.277542	0.107069				
12.264758	0.024445	0.010457	0.014771	0.049673	0.004498	0.278472	0.49
2124	0.210511	0.297365	0.090560				
12.673585	0.028616	0.011232	0.014748	0.054595	0.005558	0.303585	0.52
4149	0.205723	0.270128	0.101798				
13.082411	0.031125	0.011654	0.014933	0.057712	0.005300	0.298240	0.53
9312	0.201941	0.258747	0.091836				
13.491235	0.028228	0.011298	0.013596	0.053122	0.006448	0.356923	0.53
1385	0.212678	0.255937	0.121384				
13.900061	0.034933	0.011716	0.014798	0.061446	0.007203	0.357549	0.56
8507	0.190667	0.240826	0.117230				

Uc (from horizontal runs)= 43.6842
 Uc (from vertical runs) = 43.9429
 Uc (avg) = 43.8135
 Standard deviation factor=20.00

FLOW CASE #4

TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11
K22	K33	K12					
11.640886	0.039730	0.011674	0.015306	0.066710	0.007710	0.363300	0.59
5563	0.174995	0.229441	0.115574				
12.106522	0.036410	0.015117	0.015539	0.067066	0.007484	0.312042	0.54
2899	0.225410	0.231691	0.111596				
12.572158	0.038803	0.012748	0.016355	0.067906	0.008631	0.395489	0.57
1418	0.187735	0.240847	0.127097				
13.037793	0.041334	0.014166	0.018372	0.073872	0.008908	0.368931	0.55
9542	0.191760	0.248698	0.120593				
13.503428	0.046101	0.013724	0.017574	0.077398	0.008059	0.337980	0.59
5631	0.177315	0.227054	0.104128				
13.969063	0.047413	0.015087	0.017795	0.080295	0.007807	0.293630	0.59
0481	0.187895	0.221624	0.097229				
14.434699	0.050154	0.015408	0.016819	0.082382	0.008598	0.319379	0.60
8807	0.187034	0.204158	0.104370				
14.900334	0.049426	0.016198	0.016741	0.082365	0.010119	0.359898	0.60
0080	0.196663	0.203257	0.122856				
15.365970	0.050585	0.017368	0.019565	0.087519	0.011454	0.393545	0.57
7993	0.198450	0.223557	0.130873				
15.831606	0.047103	0.015783	0.018769	0.081655	0.010801	0.393283	0.57
6848	0.193290	0.229861	0.132277				

Uc (from horizontal runs)= 38.3592
 Uc (from vertical runs) = 38.5550
 Uc (avg) = 38.4571
 Standard deviation factor=20.00

FLOW CASE #5

TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11
K22	K33	K12					
7.490888	0.017432	0.004850	0.006643	0.028925	0.002363	0.233264	0.60
2663	0.167666	0.229671	0.081697				
7.790524	0.012124	0.004920	0.006572	0.023616	0.002533	0.361269	0.51
3385	0.208346	0.278269	0.107256				
8.090159	0.011817	0.004216	0.006669	0.022702	0.001520	0.219385	0.52
0539	0.185689	0.293771	0.066945				
8.389795	0.011984	0.005118	0.007161	0.024263	0.002504	0.344537	0.49
3925	0.210939	0.295136	0.103207				
8.689430	0.014807	0.004538	0.006605	0.025951	0.003030	0.359069	0.57
0590	0.174887	0.254522	0.116748				

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8.989066	0.012333	0.005222	0.007562	0.025117	0.002607	0.333184	0.49		
1015	0.207924	0.301062	0.103787						
9.288702	0.012151	0.004695	0.007126	0.023972	0.002740	0.378329	0.50		
6873	0.195868	0.297258	0.114294						
9.588337	0.014157	0.005279	0.007955	0.027391	0.002852	0.351917	0.51		
6838	0.192726	0.290436	0.104111						
9.887973	0.012236	0.007095	0.007117	0.026449	0.003275	0.346613	0.46		
2646	0.268267	0.269087	0.123819						
10.187608	0.014491	0.005187	0.006984	0.026662	0.002172	0.267624	0.54		
3485	0.194558	0.261956	0.081473						
Uc (from horizontal runs)= 54.8093									
Uc (from vertical runs) = 54.7300									
Uc (avg) = 54.7697									
Standard deviation factor=20.00									
FLOW CASE #6									
TAU	u1^2/Uc^2	u2^2/Uc^2	u3^2/Uc^2	q^2/Uc^2	uv/Uc^2	uv/u'v'	K11		
K22	K33	K12							
12.409109	0.039273	0.013109	0.015479	0.067861	0.009118	0.418093	0.57		
8728	0.193172	0.228099	0.134355						
12.868706	0.044873	0.013703	0.017079	0.075655	0.007758	0.338649	0.59		
3126	0.181122	0.225752	0.102541						
13.328301	0.040822	0.013848	0.017322	0.071991	0.008886	0.389781	0.56		
7034	0.192354	0.240612	0.123426						
13.787898	0.049924	0.013417	0.017857	0.081197	0.010218	0.396434	0.61		
4846	0.165238	0.219916	0.125843						
14.247496	0.043455	0.014476	0.018003	0.075934	0.010395	0.412006	0.57		
2273	0.190643	0.237085	0.136896						
14.707090	0.056634	0.015024	0.017595	0.089252	0.010227	0.397420	0.63		
4538	0.168326	0.197135	0.114585						
15.626285	0.049818	0.014762	0.020624	0.085204	0.008155	0.349995	0.58		
4692	0.173251	0.242057	0.095706						
Uc (from horizontal runs)= 36.1274									
Uc (from vertical runs) = 35.2872									
Uc (avg) = 35.7073									
Standard deviation factor=20.00									

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PROGRAM STATISTICS

C   *** THIS PROGRAM READS THE VELOCITY FILES FROM FLOWARE ***
C   *** AND CALCULATES THE MEAN, STANDARD DEVIATION AND ***
C   *** ELIMINATES POINTS WHICH ARE MORE THAN X TIMES THE ***
C   *** STANDARD DEVIATION FROM THE MEAN, THEN RECALCULATES ***
C   *** MEAN, RMS AND REYNOLDS STRESS VALUES. ***
C   *** THE INPUT TO THE PROGRAM CONSISTS OF: ***
C   *** LINE 1:  NUMBER OF FILES TO BE PROCESSED ***
C   *** LINE 2:  NUMBER OF STANDARD DEVIATIONS TO LIMIT ***
C   *** LINES 3 to NFIL+2:  FILENAMES ***
C   *** THIS PROGRAM IS FOR EMPTY TUNNEL RUNS ***
C   .....

PARAMETER(LUN=9, LUNO=10, NPTS=2000)
CHARACTER INFILE*9, CHAR*30
REAL AVERAGE, STD, REYNOLDS
REAL UVEL(NPTS), VVEL(NPTS), URAW(NPTS), VRAW(NPTS)
REAL USQ(11), UNOR(11), VNOR(11)
REAL VSQ(11), VVCO(11)
REAL UMEAN(11), URMS(11), UVSQ(11)
REAL VMEAN(11), VRMS(11), UV(11)

WRITE(*,1)
1  FORMAT('ENTER NUMBER OF FILES TO BE PROCESSED:')
   READ(*,*) NFIL

WRITE(*,2)
2  FORMAT('ENTER NUMBER OF STANDARD DEVIATIONS TO LIMIT DATA:')
   READ(*,*) FAC

C   *** OPEN OUTPUT FILE ***
OPEN(UNIT=LUNO, FILE='output.dat', STATUS='NEW')
WRITE(LUNO,3)
3  FORMAT(T5,'U mean',T13,'V mean',T24,'U/Uav',T35,'V/Uav',
+        T46,'u rms',T58,'v rms',T69,'uv',T82,'uv/u''v'',
+        T93,'u1^2/Uav^2',T104,'u2^2/Uav^2',T115,'uv/Uav^2')

DO 99 NF=1,NFIL

   WRITE(*,5)
5  FORMAT('ENTER VELOCITY FILENAME:')
   READ(*, '(A9)') INFILE
   OPEN (UNIT=LUN, FILE=INFILE, STATUS='READONLY')

C   *** NEW VERSION OF FLOWARE ONLY ***
C   ***SKIP FIRST 13 LINES OF FILE ***
DO 10 I=1,13
10  READ(LUN,*)

C   ***READ FILE PARTICULARS***
READ(LUN,12) XPOS
READ(LUN,12) YPOS
READ(LUN,12) ZPOS
12  FORMAT(17X,f5.0)

DO 13 I=1,3
13  READ(LUN,*)
C   .....

C   *** OLD VERSION OF FLOWARE ONLY ***
DO 13 I=1,2
C   13   READ(LUN,*)
C   .....

NDP=1
20  READ(LUN,*,END=199) NPT,NSTAT,ARR,TRANS,URAW(NDP),VRAW(NDP)
    NDP=NDP+1
    GO TO 20
199  NDP=NDP-1

URAWM=AVERAGE(URAW,NDP)

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VRAWM=AVERAGE(VRAW,NDP)
USTD=STD(URAW,URAWM,NDP)
VSTD=STD(VRAW,VRAWM,NDP)
UVRW=REYNOLDS(URAW,URAWM,VRAW,VRAWM,NDP)

WRITE(*,22) INFILE, FAC
FORMAT('FOR FILE: ',a9,' (number of std=',f5.2,')')
WRITE(*,25) URAWM,USTD,VRAWM,VSTD,UVRW
25  FORMAT('U Mean = ',f8.4,tr6,'U RMS= ',f8.4,
+      /'V Mean= ',f8.4,tr6,'V RMS= ',f8.4,/'UV= ',f8.4)

C      *** GET RID OF EXTRANEIOUS POINTS ***

NSAM=0
DO 40 I=1,NDP
    IF (ABS(URAW(I)-URAWM).LE.(USTD*FAC)) THEN
        NSAM=NSAM+1
        UVEL(NSAM)=URAW(I)
        VVEL(NSAM)=VRAW(I)
    ENDIF
40  CONTINUE

WRITE (*,45) NSAM, NDP
45  FORMAT('Used ',i4,' out of ',i4,' samples.')

C      *** CALCULATE NEW MEAN, RMS AND REYNOLDS STRESS ***

UM=AVERAGE(UVEL,NSAM)
VM=AVERAGE(VVEL,NSAM)
UR=STD(UVEL,UM,NSAM)
VR=STD(VVEL,VM,NSAM)
UVR=REYNOLDS(UVEL,UM,VVEL,VM,NSAM)
WRITE(*,25) UM, UR, VM, VR, UVR

UMEAN(NF)=UM
VMEAN(NF)=VM
URMS(NF)=UR
VRMS(NF)=VR
UV(NF)=UVR
UVCO(NF)=UVR/(UR*VR)

99  CONTINUE

C      *** CALCULATE TURBULENCE STATISTICS ***

UAV=AVERAGE(UMEAN,NFIL)

DO 200 I=1,NFIL
    USQ(I)=(URMS(I)/UAV)**2
    VSQ(I)=(VRMS(I)/UAV)**2
    UVSQ(I)=UV(I)/(UAV**2)
    UVCO(I)=UV(I)/(URMS(I)*VRMS(I))
    UNOR(I)=UMEAN(I)/UAV
    VNOR(I)=VMEAN(I)/UAV
    WRITE(LUNO,'(11F11.6)') UMEAN(I),VMEAN(I),UNOR(I),VNOR(I),URMS(I),
+      VRMS(I),UV(I),UVCO(I),USQ(I),VSQ(I),UVSQ(I)
200  CONTINUE

WRITE(LUNO,210) UAV, FAC
210  FORMAT('Uave = ',F8.4,/'Standard deviation factor=',F5.2)

999  STOP
END

REAL FUNCTION AVERAGE(X,N)

REAL X(2000)
SUM=0
DO 10 I=1,N
    SUM=SUM+X(I)
10  CONTINUE
AVERAGE=SUM/N

```

```
      RETURN
      END

      REAL FUNCTION STD(X,XM,N)

      REAL X(2000)
      SUM=0
      DO 10 I=1,N
         SUM=SUM+(X(I)-XM)**2
10      CONTINUE
      STD=SQRT(SUM/N)

      RETURN
      END

      REAL FUNCTION REYNOLDS(U,UM,V,VM,N)

      REAL U(2000), V(2000), UV(2000)
      REAL AVERAGE

      DO 10 I=1,N
         UV(I)=(U(I)-UM)*(V(I)-VM)
10      CONTINUE
      REYNOLDS=AVERAGE(UV,N)

      RETURN
      END
```

COMBINED OUTPUT FILES OF PROGRAM "ESTAT" FOR THE EMPTY TUNNEL RUNS AT THE BASE MACH NUMBER OF EACH OF SHEAR FLOW CASES #1 TO #5. (DATA WAS FILTERED TO REMOVE NOISE BEYOND 2.5 STANDARD DEVIATIONS FROM THE MEAN)

BASE FLOW (ie. without shear generator) FOR CASE #1

U mean	V mean	U/Uav	V/Uav	u rms	v rms	uv	uv/
u'v'	u1^2/Uav^2	u2^2/Uav^2	uv/Uav^2	x1/h			
36.341770	0.350499	1.005540	0.009698	2.946980	1.512339	-0.136032	-0.03
0522	0.006649	0.001751	-0.000104	5.2			
36.132298	0.388235	0.999744	0.010742	2.614659	2.149419	-0.014282	-0.00
2541	0.005234	0.003537	-0.000011	6.0			
35.950603	0.075338	0.994717	0.002085	2.216023	1.781451	0.191310	0.04
8461	0.003760	0.002430	0.000146	6.8			

Uave = 36.1416

Standard deviation factor= 2.50

BASE FLOW FOR CASE #1 (TRANSVERSE PROFILE)

U mean	V mean	U/Uav	V/Uav	u rms	v rms	uv	uv/
u'v'	u1^2/Uav^2	u2^2/Uav^2	uv/Uav^2	x2/h			
35.230499	-0.062762	0.985244	-0.001755	2.750170	1.221629	0.303391	0.09
0303	0.005915	0.001167	0.000237	-0.394			
36.018749	0.121386	1.007288	0.003395	2.115444	1.218019	0.117301	0.04
5525	0.003500	0.001160	0.000092	-0.315			
36.061348	0.145400	1.008479	0.004066	1.914308	1.215534	-0.083031	-0.03
5683	0.002866	0.001156	-0.000065	-0.236			
35.611031	-0.026128	0.995886	-0.000731	1.666650	0.920381	0.075487	0.04
9211	0.002172	0.000662	0.000059	-0.157			
35.999538	0.201938	1.006751	0.005647	1.946752	1.003026	-0.207744	-0.10
6391	0.002964	0.000787	-0.000162	-0.079			
35.972149	0.449829	1.005985	0.012580	1.945108	0.809019	0.077896	0.04
9501	0.002959	0.000512	0.000061	0.00			
35.575546	0.575530	0.994894	0.016095	2.139173	0.988620	-0.042153	-0.01
9932	0.003579	0.000764	-0.000033	0.079			
35.518978	0.466972	0.993312	0.013059	1.883070	1.181808	-0.225947	-0.10
1530	0.002773	0.001092	-0.000177	0.157			
35.807724	0.404696	1.001387	0.011318	1.600407	0.845935	0.077201	0.05
7024	0.002003	0.000560	0.000060	0.236			
35.785866	0.372691	1.000775	0.010423	1.642926	0.784546	0.018222	0.01
4137	0.002111	0.000481	0.000014	0.315			

Uave = 35.7581

Standard deviation factor= 2.50

BASE FLOW FOR CASE #2 (TRANSVERSE PROFILE)

U mean	V mean	U/Uav	V/Uav	u rms	v rms	uv	uv/
u'v'	u1^2/Uav^2	u2^2/Uav^2	uv/Uav^2	x2/h			
37.103764	0.065829	0.981679	0.001742	2.076870	0.914520	-0.249876	-0.13
1560	0.003019	0.000585	-0.000175	-0.394			
39.687187	0.346466	1.050030	0.009167	3.931475	0.991886	-1.600657	-0.41
0470	0.010820	0.000689	-0.001120	-0.315			
38.726563	0.041576	1.024614	0.001100	2.441271	0.686842	0.054932	0.03
2761	0.004172	0.000330	0.000038	-0.236			
37.086472	0.044379	0.981221	0.001174	1.652070	1.255559	0.177556	0.08
5328	0.001911	0.001111	0.000124	-0.157			
37.527992	0.197925	0.992903	0.005237	1.900843	1.720447	-0.036974	-0.01
1306	0.002529	0.002072	-0.000026	-0.079			
38.300652	0.318749	1.013346	0.008433	2.680934	1.266886	-0.380389	-0.11
1997	0.005031	0.001124	-0.000266	0.00			
37.746361	0.538006	0.998680	0.014234	2.198468	1.452021	0.534069	0.16
7303	0.003383	0.001476	0.000374	0.079			
37.506233	0.584723	0.992327	0.015470	1.798202	0.925604	0.024809	0.01
4906	0.002263	0.000600	0.000017	0.157			
37.487408	0.385120	0.991829	0.010189	1.807654	1.243530	0.072116	0.03
2082	0.002287	0.001082	0.000050	0.236			

```

37.570316 0.522302 0.994023 0.013815 1.626445 0.916986 -0.095204 -0.06
3834 0.001852 0.000589 -0.000067 0.315
37.015678 0.424229 0.979348 0.011224 2.252499 1.244031 1.723540 0.61
5072 0.003552 0.001083 0.001206 0.394

```

Uave = 37.7962
Standard deviation factor= 2.50

BASE FLOW FOR CASE #3

U mean	V mean	U/Uav	V/Uav	u rms	v rms	uv	uv/
u'v'	u1^2/Uav^2	u2^2/Uav^2	uv/Uav^2	x1/h			
45.351044	1.085343	0.995375	0.023821	1.950820	1.543598	0.020881	0.00
6934	0.001833	0.001148	0.000010	5.2			
45.574722	0.800040	1.000285	0.017559	2.168008	1.370411	0.216562	0.07
2890	0.002264	0.000905	0.000104	6.0			
45.759472	0.845578	1.004340	0.018559	2.744058	1.247436	-0.193404	-0.05
6501	0.003627	0.000750	-0.000093	6.8			

Uave = 45.5617
Standard deviation factor= 2.50

BASE FLOW FOR CASE #4

U mean	V mean	U/Uav	V/Uav	u rms	v rms	uv	uv/
u'v'	u1^2/Uav^2	u2^2/Uav^2	uv/Uav^2	x1/h			
40.552662	0.277360	1.003689	0.006865	1.074310	0.765359	0.118027	0.14
3545	0.000707	0.000359	0.000072	5.2			
40.242901	0.586796	0.996023	0.014523	1.431256	1.429196	-0.050452	-0.02
4665	0.001255	0.001251	-0.000031	6.0			
40.415234	0.364513	1.000288	0.009022	1.445764	0.958999	-0.011068	-0.00
7983	0.001280	0.000563	-0.000007	6.8			

Uave = 40.4036
Standard deviation factor= 2.50

BASE FLOW FOR CASE #5

U mean	V mean	U/Uav	V/Uav	u rms	v rms	uv	uv/
u'v'	u1^2/Uav^2	u2^2/Uav^2	uv/Uav^2	x1/h			
55.611984	0.609032	0.997366	0.010923	2.918607	1.222719	0.205412	0.05
7560	0.002740	0.000481	0.000066	5.2			
55.799770	0.953201	1.000734	0.017095	2.253664	1.775951	-0.132072	-0.03
2998	0.001634	0.001014	-0.000042	6.0			
55.864731	0.751386	1.001899	0.013476	2.264894	1.324962	-0.099205	-0.03
3058	0.001650	0.000565	-0.000032	6.8			

Uave = 55.7588
Standard deviation factor= 2.50

```

PROGRAM TURBULENCE

C *** This program reads the output files from stat.f and ***
C *** calculates averaged values of K11, K22, K33, K12, & ***
C *** Reynolds stress correlation coefficient, while eli- ***
C *** minating points which are further than X standard ***
C *** deviation from the mean, where X is input by the ***
C *** user. It then prompts the user to input kappa and ***
C *** the shear rate, and calculates eps/P, q^2/eps, and ***
C *** the ratio of turbulence timescale to shear timescale ***
C *** NOTE: input file must have the form xxxxxx.ext ***
C *** output file will be called xxxxxx.out ***
C *****

PARAMETER(LUN=8, LUNO=9, NPTS=10)
REAL UVCO(NPTS), K11(NPTS), K22(NPTS), K33(NPTS), K12(NPTS)
REAL AVERAGE, STD, NEWAVG, K11M, K22M, K33M, K12M, UVCOM
CHARACTER FILEN*10

WRITE(*,10)
10 FORMAT('ENTER THE INPUT FILE NAME (xxxxxx.ext):')
READ(*, '(A10)') FILEN
OPEN(UNIT=LUN, FILE=FILEN, STATUS='READONLY')
READ(LUN,*)
WRITE(*,15)
15 FORMAT('ENTER THE NUMBER OF ST.DEV. TO LIMIT DATA:')
READ(*,*) FAC

20 DO 20 I=1,NPTS
READ(LUN, '(66X,5F11.6)') UVCO(I), K11(I), K22(I), K33(I), K12(I)

K11M=NEWAVG(K11,NPTS,FAC)
K22M=NEWAVG(K22,NPTS,FAC)
K33M=NEWAVG(K33,NPTS,FAC)
K12M=NEWAVG(K12,NPTS,FAC)
UVCOM=NEWAVG(UVCO,NPTS,FAC)

WRITE(*,30)
30 FORMAT('ENTER KAPPA AND THE SHEAR RATE IN INVERSE SEC.:')
READ(*,*) XKAPPA, DUDY

EOVERP=1.0-(0.5*XKAPPA/K12M)
TAUU=1.0/(EOVERP*K12M*DUDY)
TAUS=1.0/DUDY
TUTS=TAUU/TAUS

FILEN(8:10)='out'
OPEN(UNIT=LUNO, FILE=FILEN, STATUS='NEW')
WRITE(LUNO,35) XKAPPA
35 FORMAT('kappa=',F11.6)
WRITE(LUNO,40) K11M,K22M,K33M,K12M,UVCOM, EOVERP,TAUU,TAUS,TUTS
40 FORMAT('K11=',F11.6,/'K22=',F11.6,/'K33=',F11.6,/'K12=',F11.6,
+      /'REYNOLDS STRESS CORRELATION COEFFICIENT=',F11.6,
+      /'EPSILON/P=',F11.6,/'TAU U=',F11.6,/'TAU S=',F11.6,
+      /'TAU U/TAU S=',F11.6)
WRITE(LUNO,50) FAC
50 FORMAT('Used points within',F4.1,' sigma from the mean.')

STOP
END

REAL FUNCTION AVERAGE(X,N)

REAL X(20)
SUM=0
DO 10 I=1,N
SUM=SUM+X(I)
10 AVERAGE=SUM/N

RETURN
END

```

```
REAL FUNCTION STD(X,XM,N)

REAL X(20)
SUM=0
DO 10 I=1,N
SUM=SUM+(X(I)-XM)**2
STD=SQRT(SUM/N)

RETURN
END

REAL FUNCTION NEWAVG(X,N,FAC)

REAL X(20), XNEW(20)

XM=AVERAGE(X,N)
XDEV=STD(X,XM,N)
NP=0
DO 10 I=1,N
IF(ABS(X(I)-XM).LE.(XDEV*FAC)) THEN
NP=NP+1
XNEW(NP)=X(I)
ENDIF
CONTINUE
TYPE *, 'Used ',NP,' out of ',N,' points.'
NEWAVG=AVERAGE(XNEW,NP)

RETURN
END
```

OUTPUT OF PROGRAM "TURB" FOR ALL FLOW CASES
(DATA WAS FILTERED TO REMOVE NOISE BEYOND 2.5 STD FROM THE MEAN)
(WHEN AVERAGING, POINTS BEYOND 2.0 STD WERE REJECTED)

FLOW CASE #1

kappa= 0.095140

K11= 0.494563

K22= 0.201928

K33= 0.302392

K12= 0.093458

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.302906

EPSILON/P= 0.490999

TAU U= 0.049960

TAU S= 0.002293

TAU U/TAU S= 21.792351

Used points within 2.0 sigma from the mean.

FLOW CASE #2

kappa= 0.083790

K11= 0.540821

K22= 0.190870

K33= 0.268309

K12= 0.105478

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.361727

EPSILON/P= 0.602807

TAU U= 0.023665

TAU S= 0.001505

TAU U/TAU S= 15.727547

Used points within 2.0 sigma from the mean.

FLOW CASE #3

kappa= 0.070320

K11= 0.472518

K22= 0.227018

K33= 0.303345

K12= 0.105660

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.328531

EPSILON/P= 0.667233

TAU U= 0.020114

TAU S= 0.001418

TAU U/TAU S= 14.184477

Used points within 2.0 sigma from the mean.

FLOW CASE #4

kappa= 0.074270

K11= 0.550240

K22= 0.203165

K33= 0.249413

K12= 0.121410

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.364397

EPSILON/P= 0.694134

TAU U= 0.016831

TAU S= 0.001418

TAU U/TAU S= 11.865975

Used points within 2.0 sigma from the mean.

FLOW CASE #5

kappa= 0.107400

K11= 0.444083

K22= 0.226111

K33= 0.327731
K12= 0.109407
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.340028
EPSILON/P= 0.509171
TAU U= 0.027784
TAU S= 0.001548
TAU U/TAU S= 17.951164

Used points within 2.0 sigma from the mean.

FLOW CASE #6
kappa= 0.070570

K11= 0.556071
K22= 0.196345
K33= 0.247583
K12= 0.120487
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.377107
EPSILON/P= 0.707146
TAU U= 0.018166
TAU S= 0.001548
TAU U/TAU S= 11.736835

Used points within 2.0 sigma from the mean.

OUTPUT OF PROGRAM *TURB* FOR ALL FLOW CASES
(DATA WAS NOT FILTERED TO REMOVE NOISE)
(WHEN AVERAGING, POINTS BEYOND 2.0 STD WERE REJECTED)

FLOW CASE #1
kappa= 0.082590

K11= 0.534931
K22= 0.182369
K33= 0.282700
K12= 0.091488
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.287520
EPSILON/P= 0.548628
TAU U= 0.045675
TAU S= 0.002293
TAU U/TAU S= 19.923225

Used points within 2.0 sigma from the mean.

FLOW CASE #2
kappa= 0.081900

K11= 0.576428
K22= 0.176634
K33= 0.246938
K12= 0.106801
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.387940
EPSILON/P= 0.616578
TAU U= 0.022849
TAU S= 0.001505
TAU U/TAU S= 15.185731

Used points within 2.0 sigma from the mean.

FLOW CASE #3
kappa= 0.072410

K11= 0.527597
K22= 0.205485
K33= 0.266918
K12= 0.104549
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.332686
EPSILON/P= 0.653703
TAU U= 0.020749
TAU S= 0.001418
TAU U/TAU S= 14.631882

Used points within 2.0 sigma from the mean.

FLOW CASE #4
kappa= 0.079890

K11= 0.586263
K22= 0.188349
K33= 0.226019
K12= 0.116659
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.353748
EPSILON/P= 0.657593
TAU U= 0.018490
TAU S= 0.001418
TAU U/TAU S= 13.035380

Used points within 2.0 sigma from the mean.

FLOW CASE #5
kappa= 0.065060

K11= 0.513255
K22= 0.193178

K33= 0.282389
K12= 0.100334
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.319519
EPSILON/P= 0.675782
TAU U= 0.022827
TAU S= 0.001548
TAU U/TAU S= 14.748455

Used points within 2.0 sigma from the mean.

FLOW CASE #6
kappa= 0.095460

K11= 0.592177
K22= 0.180587
K33= 0.232253
K12= 0.119050
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.386054
EPSILON/P= 0.599077
TAU U= 0.021701
TAU S= 0.001548
TAU U/TAU S= 14.021256

Used points within 2.0 sigma from the mean.

OUTPUTS OF PROGRAM "TURB" FOR CASE #1 USING FIRST 3.0 AND THEN
2.5 STANDARD DEVIATIONS TO FILTER DATA (ALSO SHOWS EFFECT OF
OMITTING CERTAIN POINTS WHEN FITTING KAPPA)

USING DATA WITHIN 3 STD FROM THE MEAN:

kappa= 0.094170 (using all points on downstream profile for fit)

K11= 0.508043

K22= 0.196719

K33= 0.294196

K12= 0.095550

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.309122

EPSILON/P= 0.507220

TAU U= 0.047303

TAU S= 0.002293

TAU U/TAU S= 20.633589

Used points within 2.0 sigma from the mean.

kappa= 0.087630 (using last 8 points on downstream profile for fit)

K11= 0.508043

K22= 0.196719

K33= 0.294196

K12= 0.095550

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.309122

EPSILON/P= 0.541443

TAU U= 0.044313

TAU S= 0.002293

TAU U/TAU S= 19.329401

Used points within 2.0 sigma from the mean.

USING DATA WITHIN 2.5 STD FROM THE MEAN:

kappa= 0.095140 (using all points on downstream profile for fit)

K11= 0.494563

K22= 0.201928

K33= 0.302392

K12= 0.093458

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.302906

EPSILON/P= 0.490999

TAU U= 0.049960

TAU S= 0.002293

TAU U/TAU S= 21.792351

Used points within 2.0 sigma from the mean.

kappa= 0.088380 (using last 8 points on downstream profile for fit)

K11= 0.494563

K22= 0.201928

K33= 0.302392

K12= 0.093458

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.302906

EPSILON/P= 0.527166

TAU U= 0.046532

TAU S= 0.002293

TAU U/TAU S= 20.297289

Used points within 2.0 sigma from the mean.

OUTPUTS OF PROGRAM "TURB" FOR FLOW CASE #3
(SHOWS EFFECT OF VARYING WINDOW OF DATA ACCEPTANCE)

USING ALL DATA:
kappa= 0.072410

K11= 0.527597
K22= 0.205485
K33= 0.266918
K12= 0.104549

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.332686
EPSILON/P= 0.653703
TAU U= 0.020749
TAU S= 0.001418
TAU U/TAU S= 14.631882

Used points within 2.0 sigma from the mean.

USING DATA WITHIN 3 STD OF THE MEAN (99.20%):
kappa= 0.065880

K11= 0.490846
K22= 0.220571
K33= 0.292076
K12= 0.106531

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.336846
EPSILON/P= 0.690795
TAU U= 0.019269
TAU S= 0.001418
TAU U/TAU S= 13.588538

Used points within 2.0 sigma from the mean.

USING DATA WITHIN 2.75 STD OF THE MEAN (98.86%):
kappa= 0.067330

K11= 0.483353
K22= 0.223472
K33= 0.296395
K12= 0.107812

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.332939
EPSILON/P= 0.687743
TAU U= 0.019125
TAU S= 0.001418
TAU U/TAU S= 13.486739

Used points within 2.0 sigma from the mean.

USING DATA WITHIN 2.5 STD OF THE MEAN (98.29%):
kappa= 0.070320

K11= 0.472618
K22= 0.227018
K33= 0.303345
K12= 0.105660

REYNOLDS STRESS CORRELATION COEFFICIENT= 0.328531
EPSILON/P= 0.667233
TAU U= 0.020114
TAU S= 0.001418
TAU U/TAU S= 14.184477

Used points within 2.0 sigma from the mean.

USING DATA WITHIN 2.25 STD OF THE MEAN (97.43%):
kappa= 0.068870

K11= 0.458752
K22= 0.232066

K33= 0.311962
K12= 0.103896
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.324739
EPSILON/P= 0.668562
TAU U= 0.020415
TAU S= 0.001418
TAU U/TAU S= 14.396630

Used points within 2.0 sigma from the mean.

USING DATA WITHIN 2 STD OF THE MEAN (95.96%):
kappa= 0.067520

K11= 0.434327
K22= 0.242052
K33= 0.323621
K12= 0.101412
REYNOLDS STRESS CORRELATION COEFFICIENT= 0.317200
EPSILON/P= 0.667101
TAU U= 0.020961
TAU S= 0.001418
TAU U/TAU S= 14.781484

Used points within 2.0 sigma from the mean.

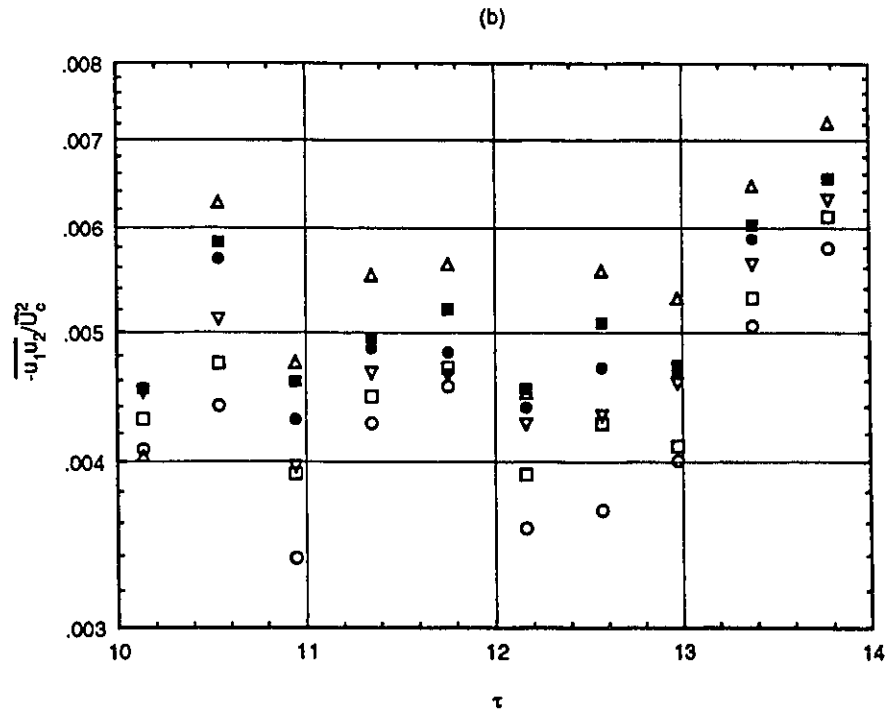
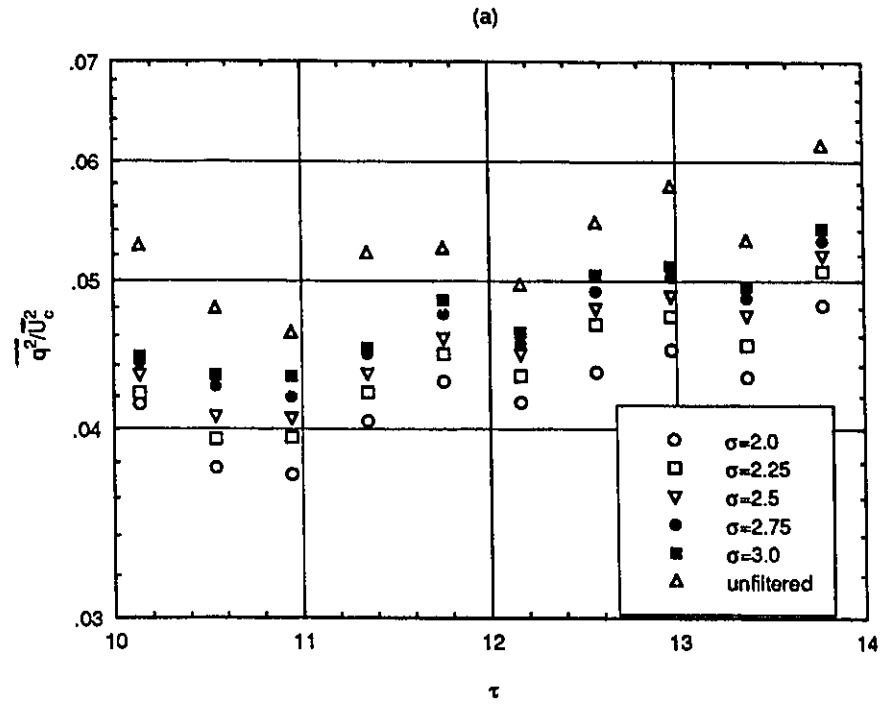


Figure C1 (a,b). For caption see next page.

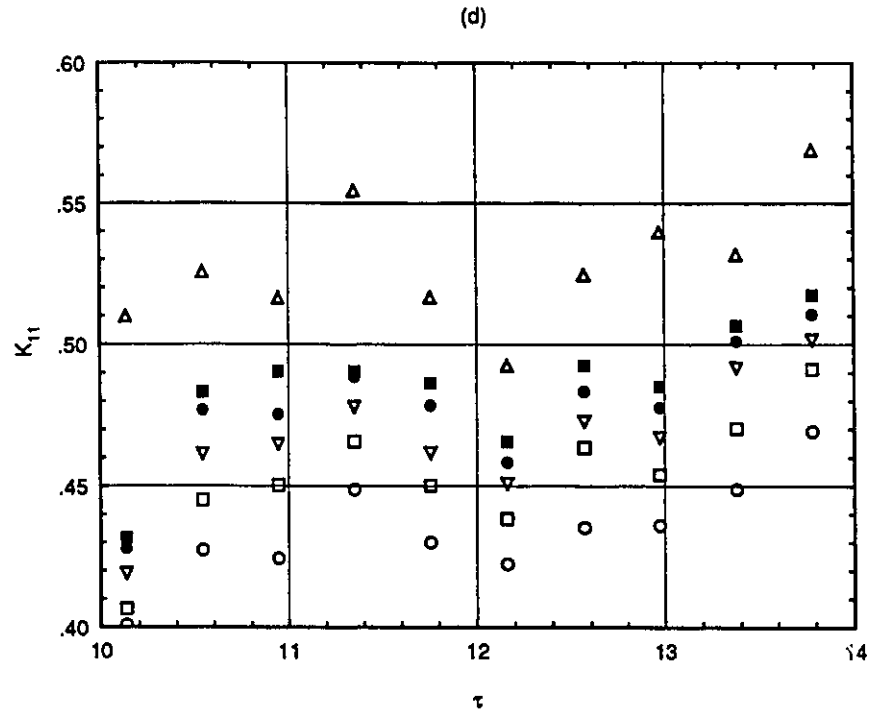
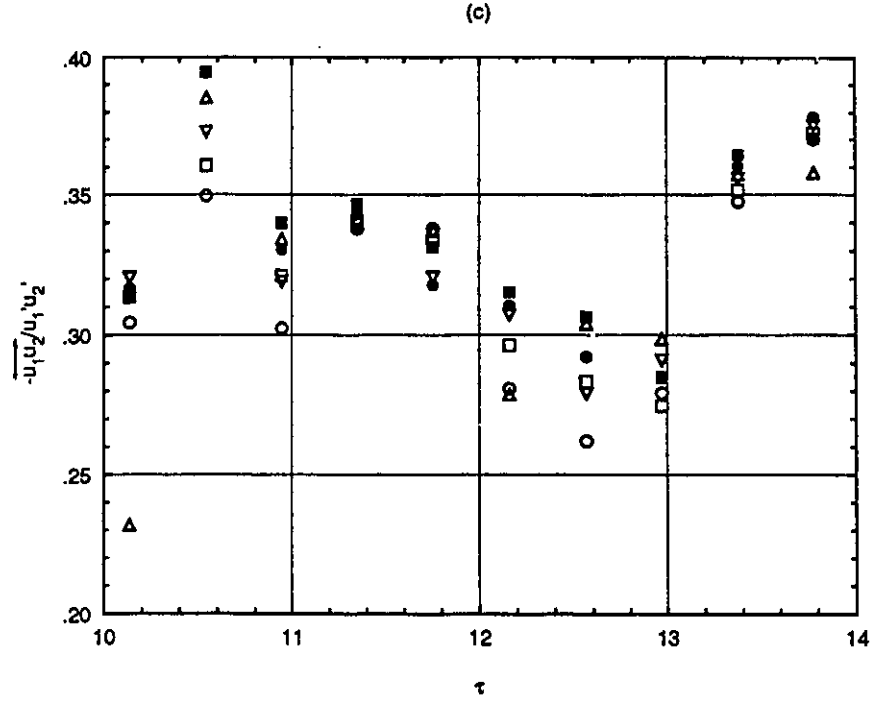


Figure C1 Effect of varying the window of data acceptance for flow case #3.
 (a) $q^2/\bar{U}_c^2$; (b) $-\overline{u_1 u_2}/\bar{U}_c^2$; (c) $-\overline{u_1 u_2}/u_1' u_2'$; (d) K_{11} .

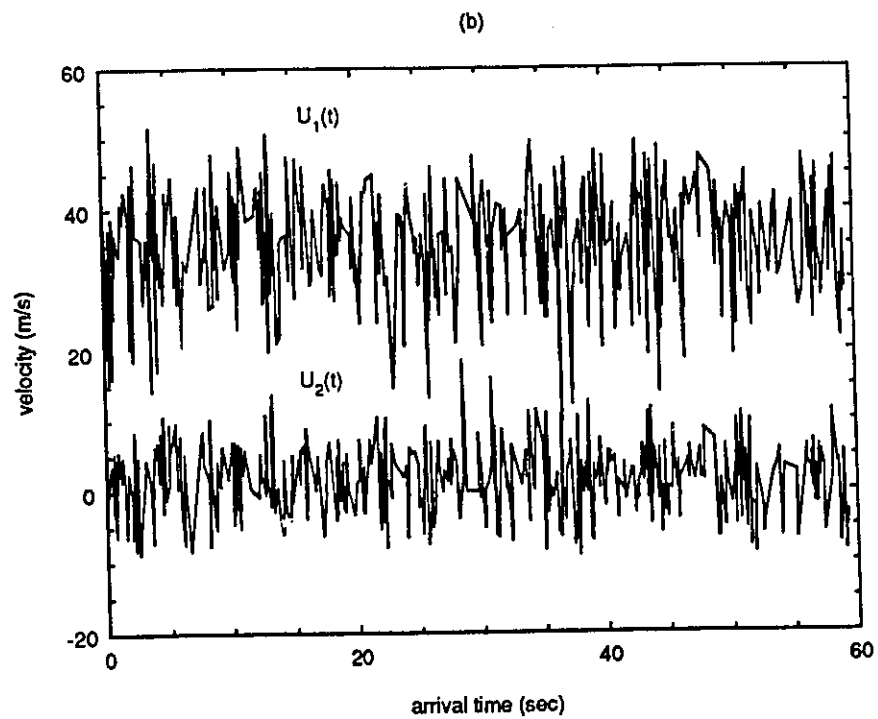
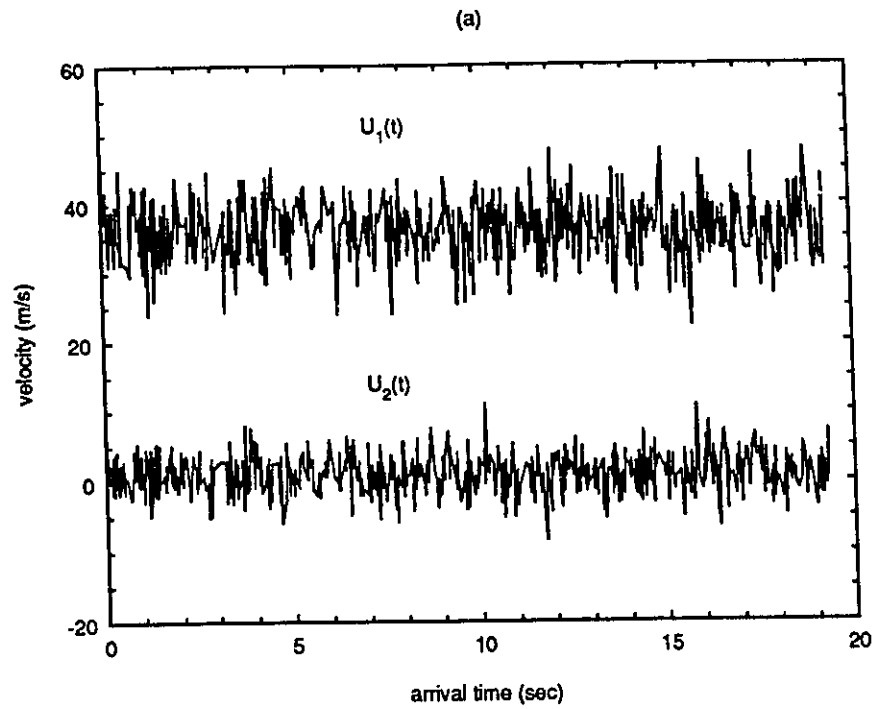


Figure C2 (a,b). For caption see page after next.

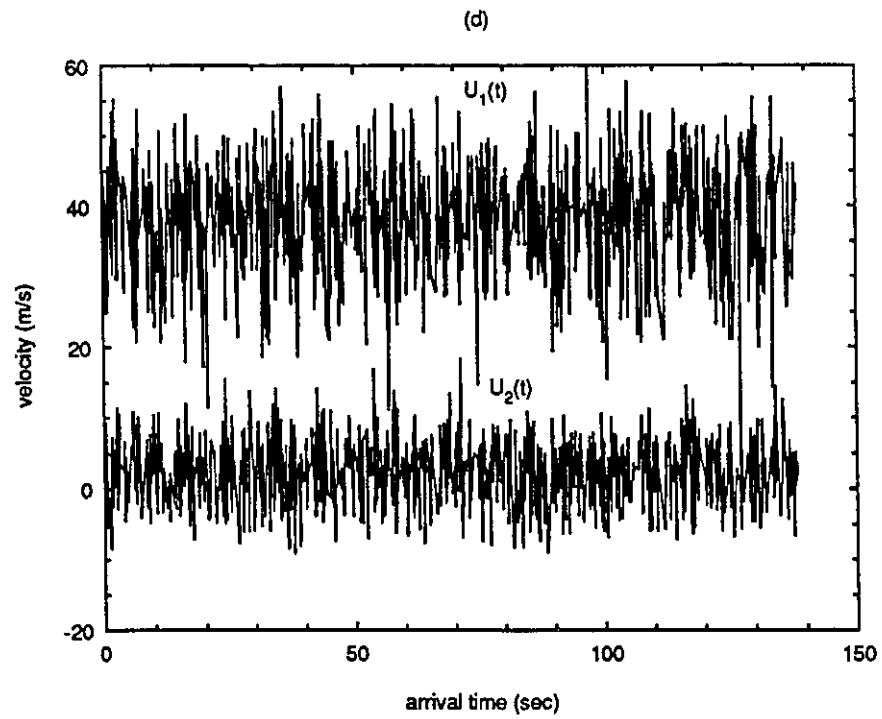
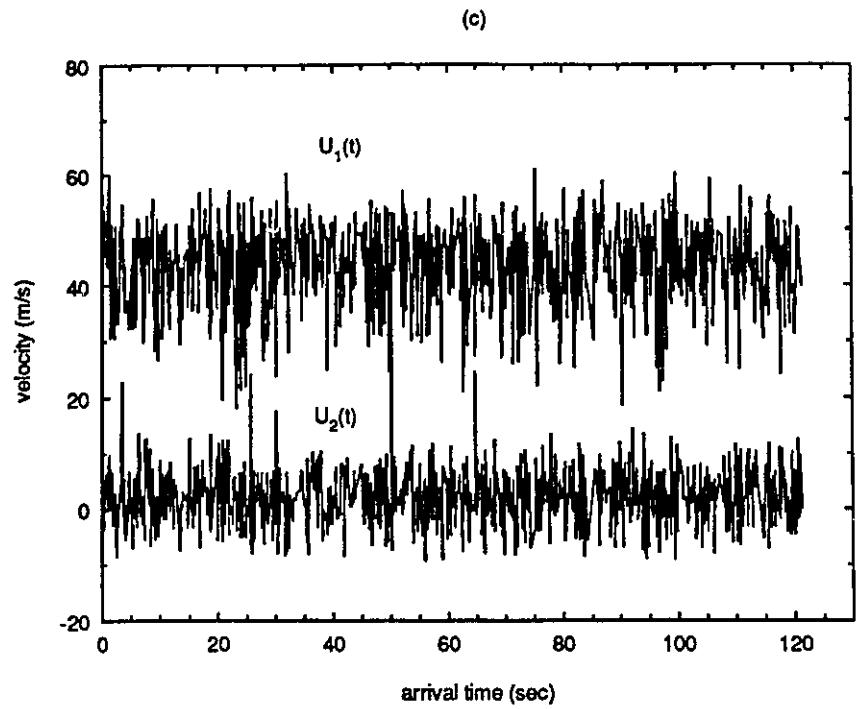


Figure C2 (c,d). For caption see next page.

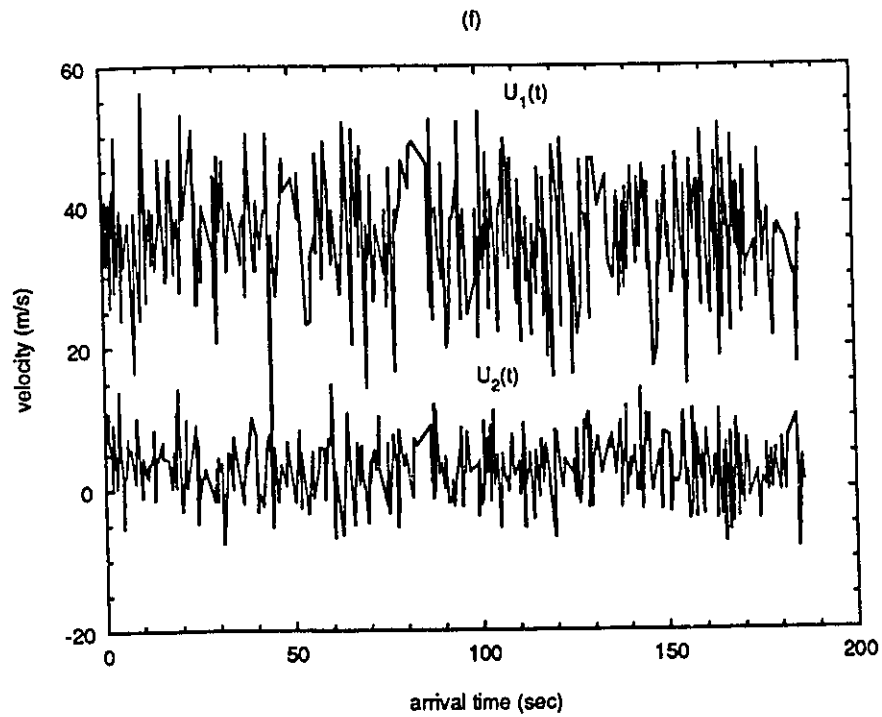
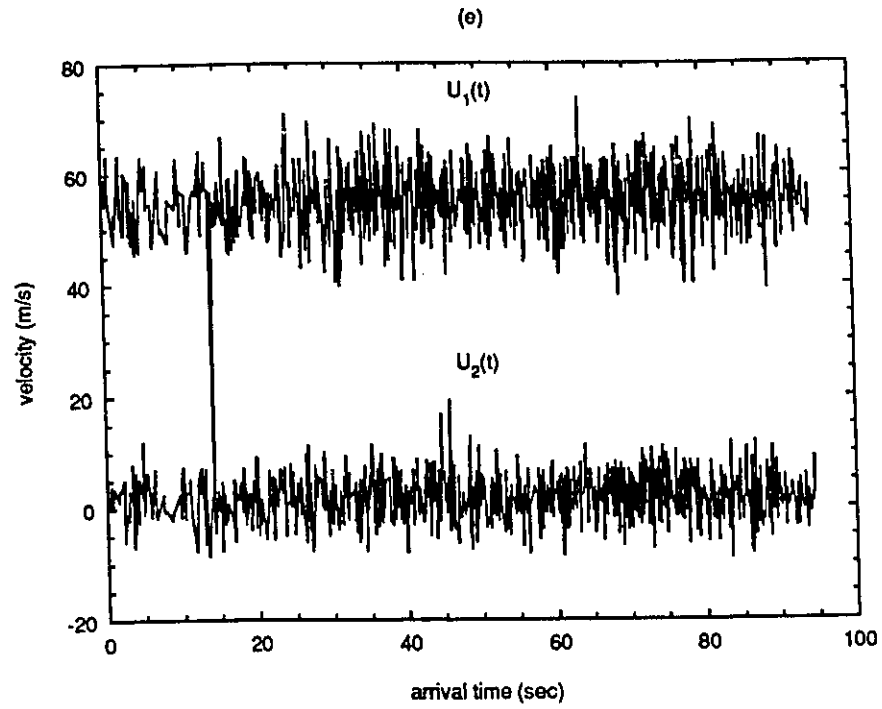
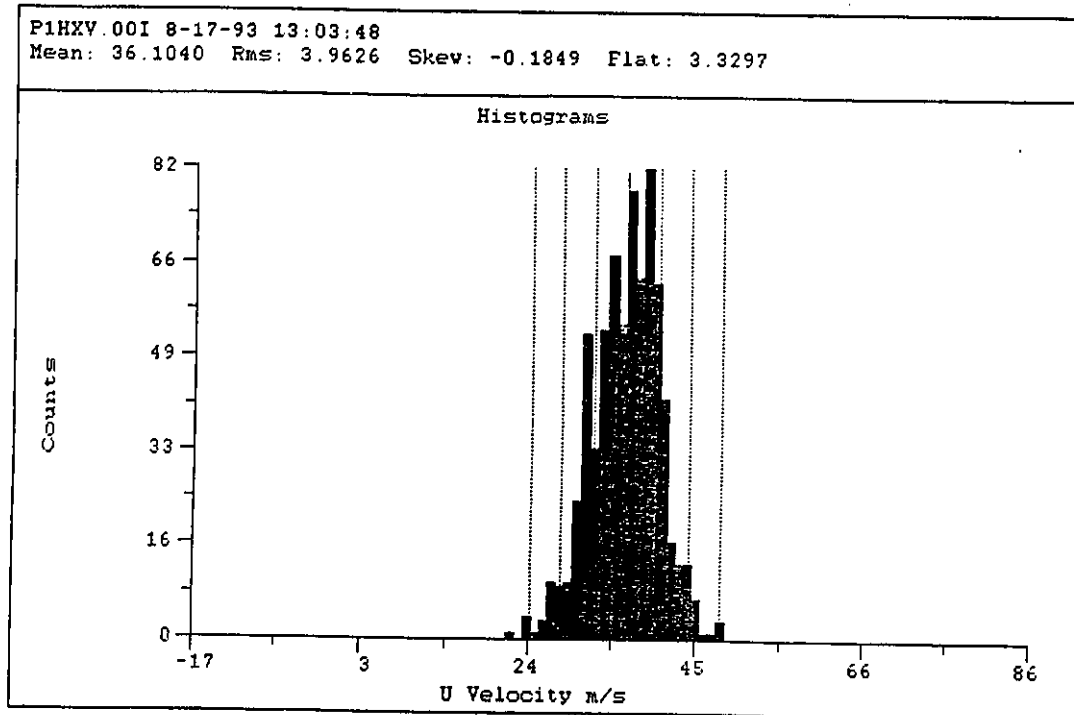


Figure C2 Time series. (a) Case #1, $x_1/h=6.4$; (b) Case #2, $x_1/h=6.2$; (c) Case #3, $x_1/h=6.4$; (d) Case #4, $x_1/h=5.8$; (e) Case #5, $x_1/h=5.6$; (f) Case #6, $x_1/h=6.0$.

(a)



(b)

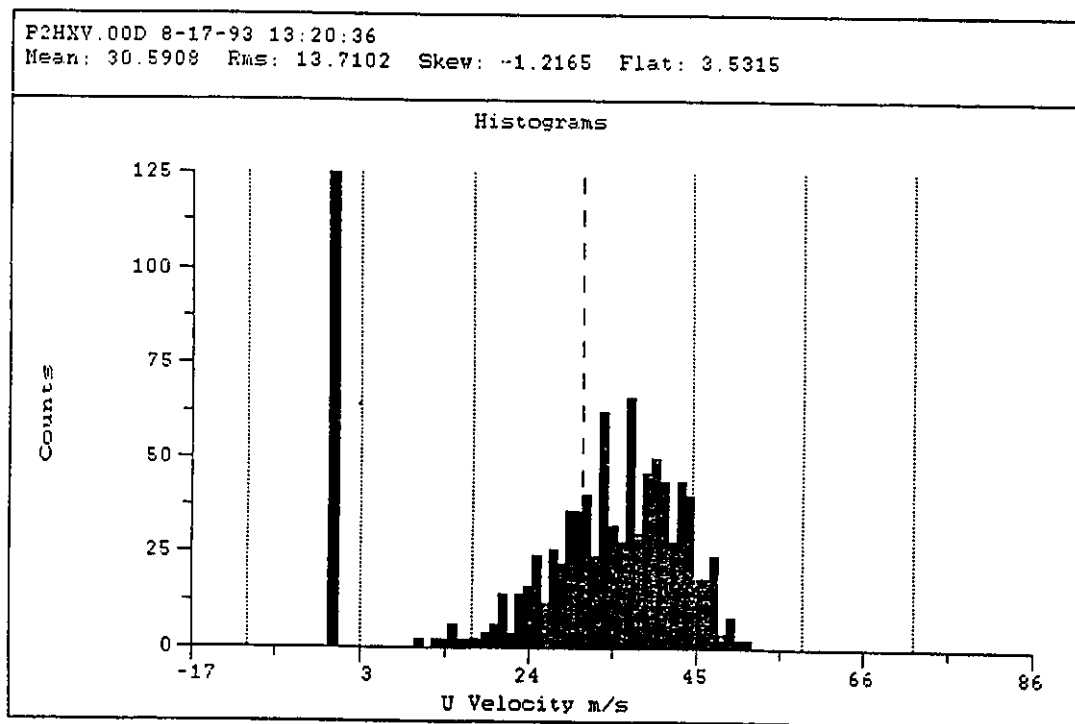
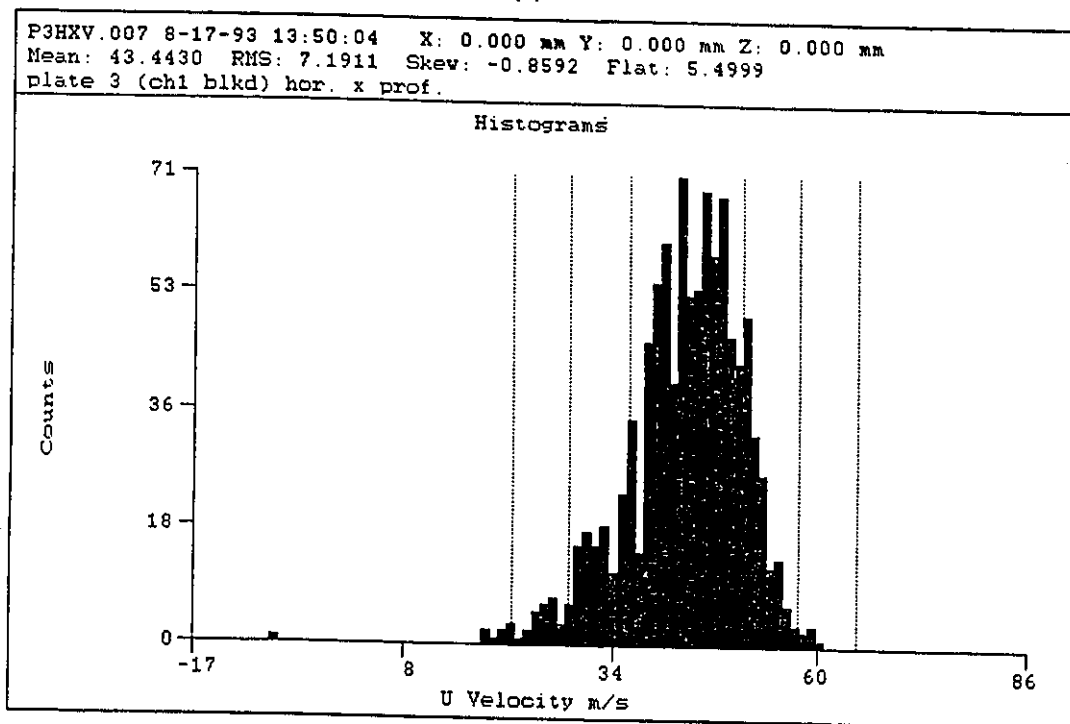


Figure C3 (a,b). For caption see page after next.

(c)



(d)

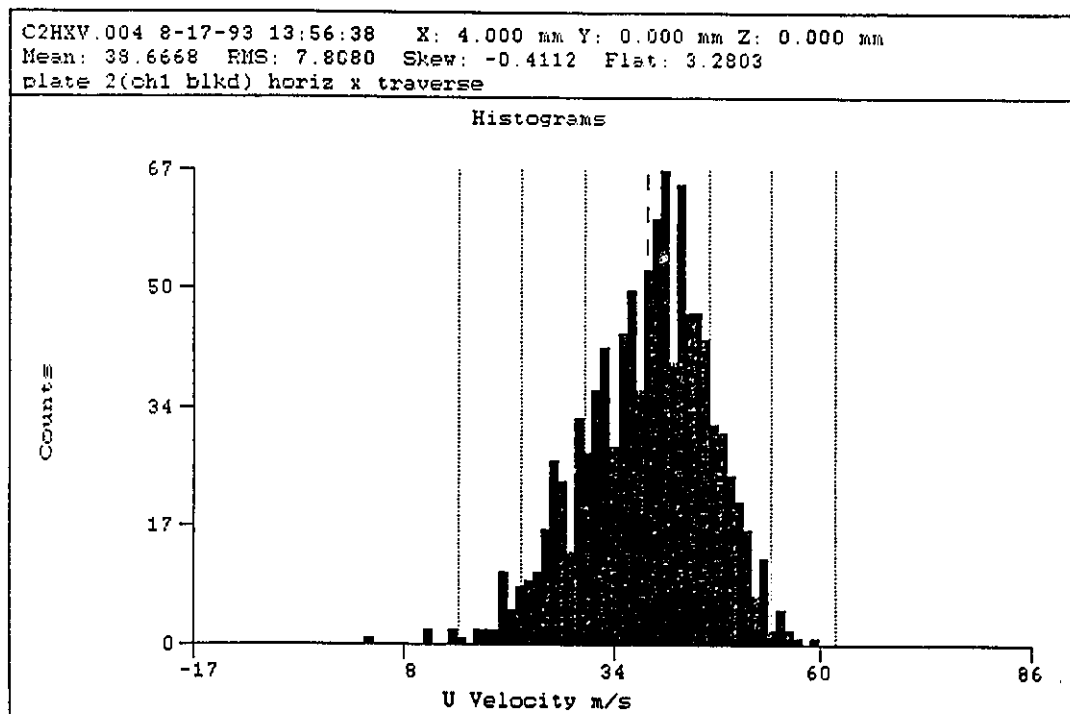
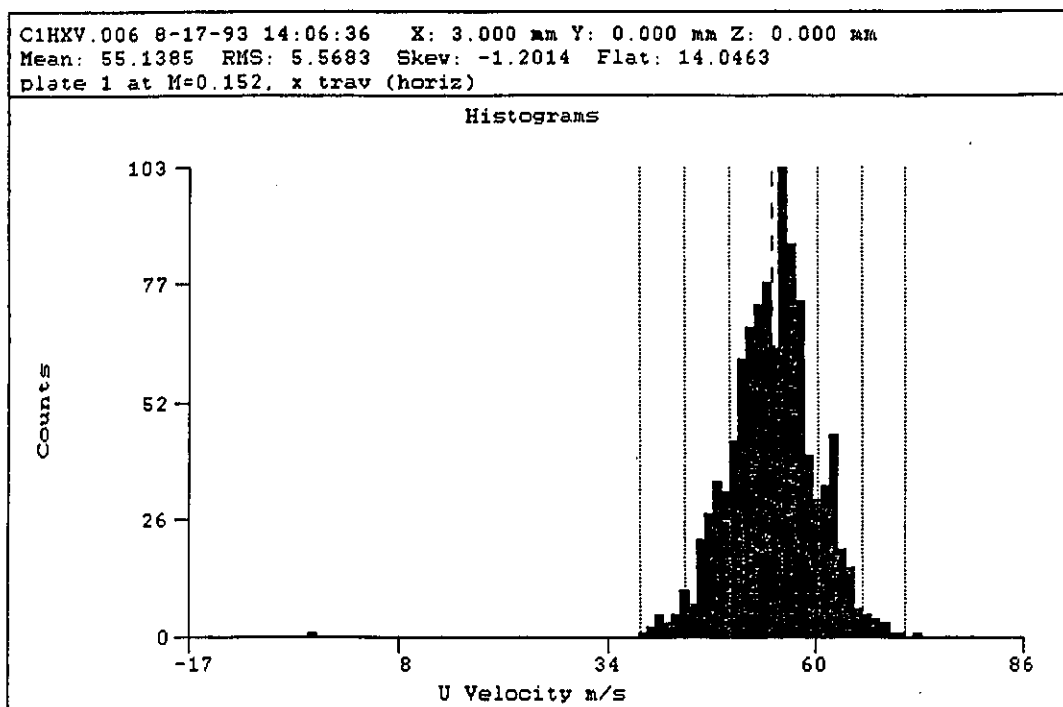


Figure C3 (c,d). For caption see next page.

(e)



(f)

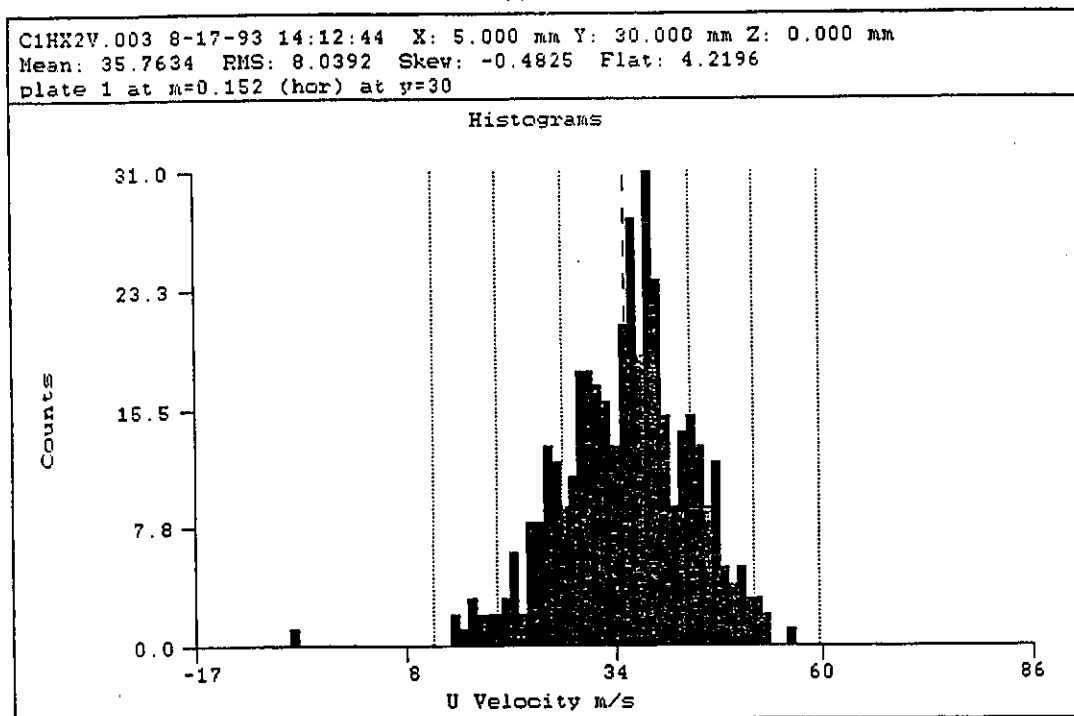


Figure C3 Histograms. (a) Case #1, $x_1/h=6.4$; (b) Case #2, $x_1/h=6.2$; (c) Case #3, $x_1/h=6.4$; (d) Case #4, $x_1/h=5.8$; (e) Case #5, $x_1/h=5.6$; (f) Case #6, $x_1/h=6.0$.