

Turbulence measurements using a small electro-magnetic current meter in open channel flows

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**Hydraulics Research Station
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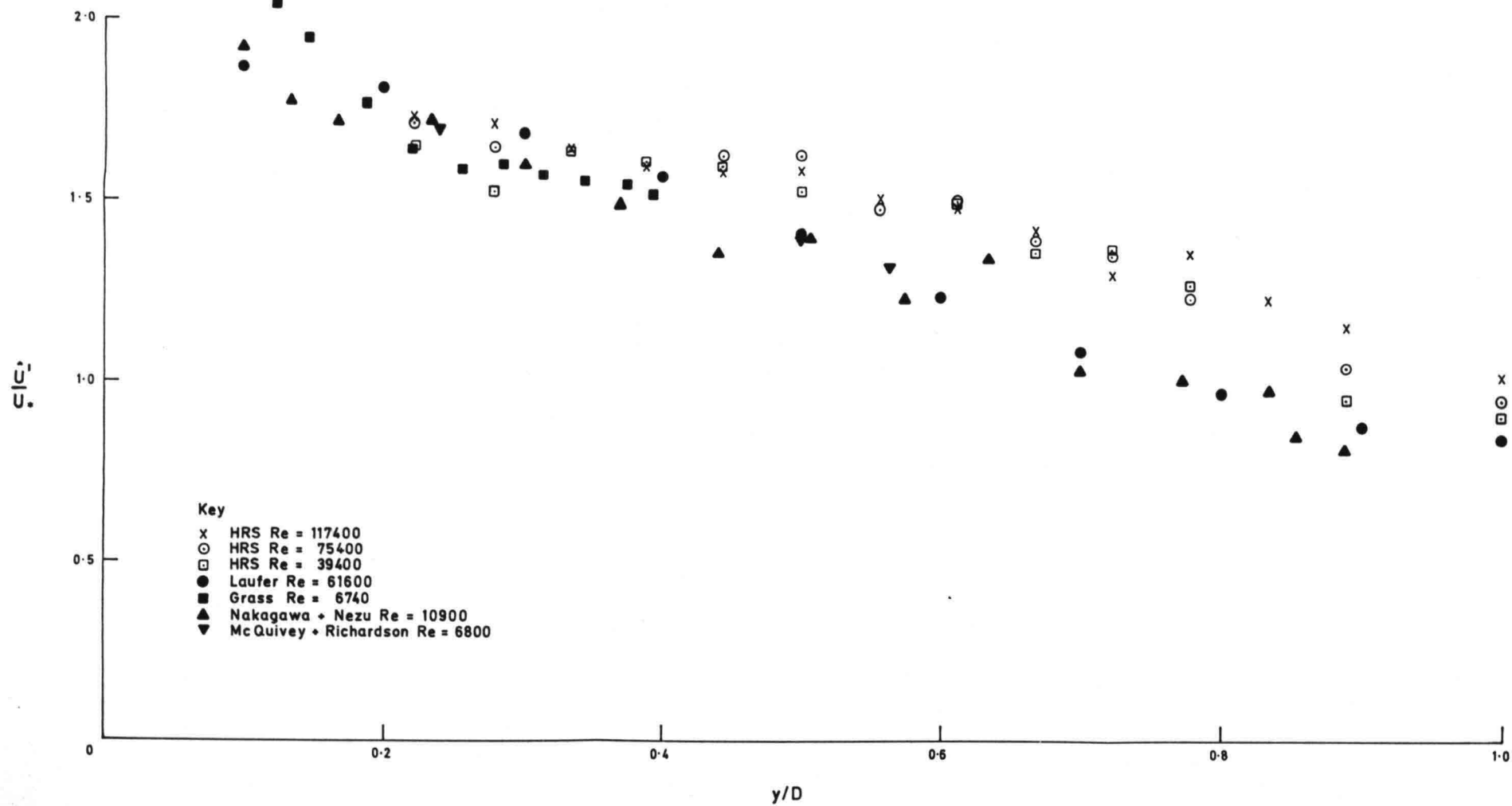
**TURBULENCE MEASUREMENTS USING A SMALL ELECTRO-
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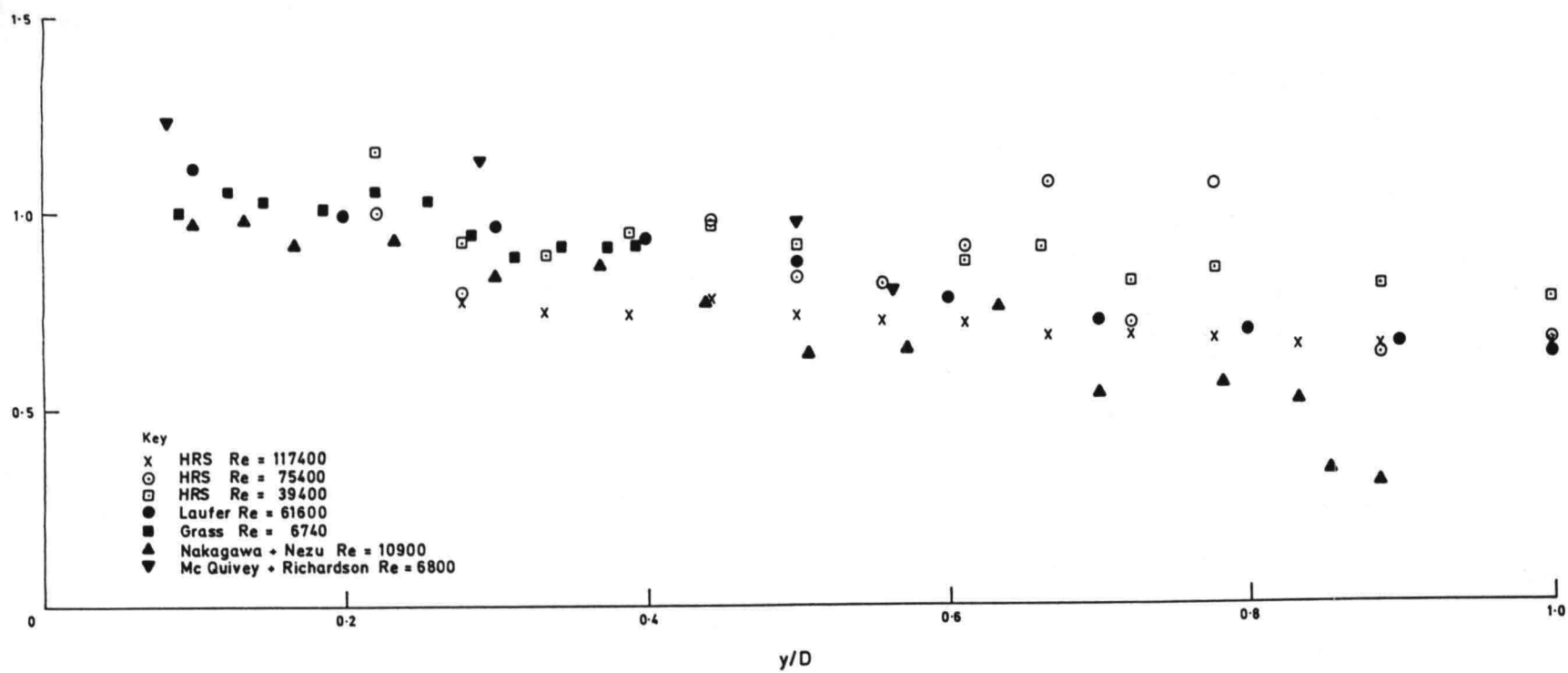
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Longitudinal turbulence intensity distributions



Vertical turbulence intensity distributions

Fig 2

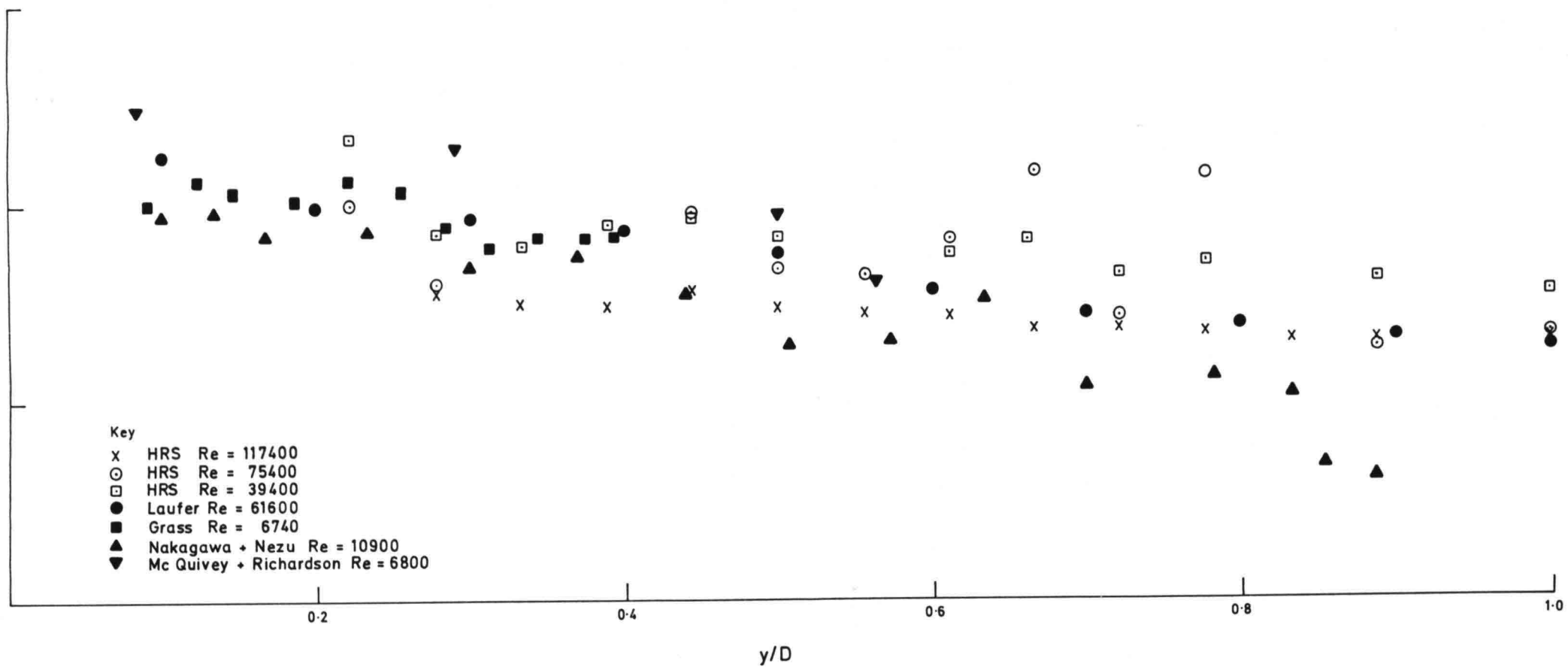


Fig 2

CONTENTS

PAGE

ABSTRACT

INTRODUCTION

1

EXPERIMENTAL FACILITY

1

ELECTROMAGNETIC CURRENT METER

2

EXPERIMENTAL PROCEDURE

3

ANALYSIS OF DATA

4

DISCUSSION OF RESULTS

4

CONCLUSIONS

5

ACKNOWLEDGEMENTS

5

REFERENCES

5

FIGURES

- 1 Longitudinal turbulence intensity distributions
- 2 Vertical turbulence intensity distributions
- 3 Reynolds shear stress distributions

PLATES

- 1 Experimental flume
- 2 Electromagnetic current meter in flume

ABSTRACT The use of a small two-component electromagnetic current meter to record turbulent velocities in a laboratory flume is described. The results from these experiments are compared with results obtained previously using different measuring techniques.

INTRODUCTION

A better understanding of the mechanisms of turbulence is necessary for the improvement of mathematical models of the dispersion of scalar quantities; heat and salt for example. The usefulness of any experimental work depends basically upon the accuracy and reliance that can be placed upon the instrument which is being employed.

Over the last thirty or so years the study of turbulent characteristics in air flows has improved to a stage where they are quite common place. This rapid improvement is due to the advent of reliable hot-wire anemometry systems and latterly with the introduction of the Laser-doppler anemometer. One of the earliest investigations was reported by Laufer (Ref 1) in which measurements were made of all three components of velocity and Reynolds shearing stress in two-dimensional air-flows using cross-wired sensors.

The progress of the equivalent studies of turbulence in water flows has not been so rapid. With the introduction of special film probes for use in water hot-film anemometers have been used to improve knowledge to turbulent water flows. Richardson and McQuivey (Ref 2) used a single yawed film sensor to investigate water flows in the last 1960's. In the middle 1970's Nakagawa, Nezu and Ueda (Ref 3) reported their results using a crossed-film probe in water. The use of hot-film anemometers in water, however, is usually accompanied with difficulties arising from impurities in the water causing contamination of the probe, but in carefully controlled environments good results have been achieved.

In water a further technique can be used. This involves the electrolysis of water to produce hydrogen bubbles as tracers which are then photographed using a high speed camera. A complete description of this method is given by Grass (Ref 4).

As part of a basic research project undertaken at the Hydraulics Research Station (HRS) experiments were conducted to investigate accelerating and decelerating flows. The aims of these experiments were to establish, in a laboratory flume, the following parameters: mean velocity profiles, water surface slopes, bed friction velocities and turbulence intensity profiles. It is intended that the results of this investigation should be of use to the experimentalist as well as the engineer. It was originally intended to use a single sensor hot-film anemometer to investigate the turbulence levels, however, a small (25mm diameter) electromagnetic current meter was used as an alternative because so much trouble was experienced with the hot-wire anemometer.

A description of the electromagnetic current water will be reported and the results obtained in the present study will be compared with those obtained previously using different methods of measurement.

EXPERIMENTAL FACILITY

The flume used for this research project was an existing facility and consisted of a closed circuit system with the measuring flume having a straight working length of 27m, Anwar and Atkins (Ref 5) fully describes the experimental flume. The flume was rectangular in section with dimensions 0.6m wide by 0.4m deep, the water depth was 0.3m, and was constructed from plywood having a smooth painted finish, it was supported and strengthened by a steel frame work, the flume was covered using hardboard to try to keep the water as clean as possible. Guide vanes were positioned in the flume entrance to ensure uniform flow at the measuring section, the uniformity of the flow was confirmed by preliminary measurements. The measuring section was 19.5m from the flume entrance in a region where the turbulence was well developed but the flow unaffected by the flume exit. Plate 1 shows the general layout of the facility, flow in the flume is from top left to bottom right in this photograph.

ELECTROMAGNETIC CURRENT METER

Electromagnetic current meters (ECM) have been used for a number of years in field studies to measure turbulent velocities. One of the earliest successful studies was reported by Bowden and Fairburn (Ref 6) in which a discus type electromagnetic current meter, having a diameter of 100mm was used to measure horizontal and vertical velocities in water depths of up to 22m off Red Wharf Bay, Anglesey. The Institute of Oceanographical Sciences (Taunton) have successfully been using large ECMs for many years and have been leaders of the development of the instrument in this country. However, it is not until fairly recently that a reasonably small, reliable, ECM has been manufactured for laboratory use.

The major advantages of the ECM is that there are no moving parts which can be fouled and that its calibrations are linear.

The principles of operation of the ECM are fully described by Tucker et al (Ref 7) therefore only a brief summary will be given here. Basically the ECM works on electromagnetic induction, a field coil within the ECM head is energised with a given frequency square wave signal. A magnetic field, reversing in direction on every half cycle of the square wave, is generated parallel to the axis to the coil. Water flowing through the magnetic field induces a square wave voltage at right angles to both the magnetic field and the flow velocity. The induced voltage, which is very small, is picked up by a pair of electrodes on the face of the ECM, the induced voltage is proportional to the flow velocity. The use of square wave energisation makes it possible to discriminate between the flow induced voltage and other signals, for instance, electro-chemical emf's and emf's caused by varying stray magnetic fields.

The frequency at which the coil is switched is a fundamental limitation on the frequency response of the instrument, as each cycle of the energising signal results effectively in a single sample of flow velocity. After rectification; the samples are passed through low-pass filters which control the actual frequency response of the output (described later).

The ECM head used in these experiments had two pairs of electrodes, at right angles to each other, therefore it was able to record velocities for two components of the flow, in this report the head was aligned to record the longitudinal and vertical components, the head was obtained commercially from Colnbrook Instrument Development Ltd. The electronics unit used to power the head and to produce the output voltages was built at HRS to a Institute of Oceanographical Sciences design.

The coil in the head of the ECM was encapsulated in an epoxy moulding with the electrodes just protruding from the front face, a supporting spar was moulded into the back of the head. The head was circular in elevation and ellloptical in cross-section, this shape resulting from a compromise between physical and hydrodynamic requirements.

A framework was built over the flume at the measuring section to support the ECM head. The ECM head was clamped rigidly to a duralamin bar which in turn was held vertically by the framework. Plate 2 shows the ECM in position in the flume. The ECM and its supporting rod were checked on an engineers surface table to ensure that they were correctly aligned to each other thus the ECM would be correctly positioned when in the flume. Cleaning the ECM head was carried out daily using a fine carbide paper followed by washing in neat liquid soap and rinsing in clean water. Further washing and rinsing was carried out during the day as required.

Each of the two components of the ECM had its frequency response controlled by a critically damped three pole active filter. The cut-off frequency of which was 17Hz, thus resulted in negligible attenuation of the signal in the range 0 – 10Hz was thought to be the maximum attainable frequency of the instrument. The output signals from the ECM were further filtered by three pole Bessel filters, these filters provided the dominant restrictions on the frequency response of the whole system, resulting in a response which was 0.15dB down from unity at 10Hz, ie 2% low.

The output voltages from the ECM, after filtering, were amplified and the final signals were sampled at a continuous rate of 50Hz using a data-logger. The data-logger also recorded the digitised voltages on magnetic tape. It was not possible to sample the two velocity signals simultaneously, therefore, the data signals were sampled consecutively, at 50Hz this gave an effective 25Hz sampling rate for each component with a 0.02s displacement between records.

As well as the digital records of the ECM voltages continuous records of the voltages from the ECM head were made on an ultra-violet oscillograph. Ultra-violet recordings were made of the voltages output from the ECM, further recordings were made of the analogue voltages sampled by the data-logger, ie after the final filtering and amplification. These ultra-violet recordings were made not only for permanent record but, more importantly, to enable the rejection of data which was affected by the random interference which was occasionally picked up by the complete data collection system. The cause of this random interference was mainly due to stray 50Hz fields "beating" with the 40Hz square wave energisation thus causing apparent velocity fluctuations at 10Hz; within the measurement band width. Initially problems were experienced with 'earth loops', these low potential loops were remedied but were potentially very damaging to the investigation because of the small voltage changes that were being measured. The overall noise level on the instrument was found to be equivalent to $\pm 5\text{mm/s}$ in static water.

Direct calibration of the ECM was carried out in the flume by comparing the output voltage recorded on the data-logger against the velocity of the water in the flume. The ECM head was mounted in the flume in the free-stream flow with the head orientated so that the current meter component under calibration was aligned with the mean flow direction. The flow in the flume was steady. After each velocity change the flow was allowed to settle down for several minutes then simultaneously the head output voltages were recorded, using the data-logger, and the water velocity was measured using a 10mm miniature propeller current meter mounted at the same height as, and 2.5m upstream of, the ECM head. The resulting mean velocities and voltages were used to plot the calibrations for the two components, both of the components yielded calibrations of approximately 800mV/m/s before amplification.

During preliminary work it was found that the gradients of the voltage/velocity calibrations remained constant but that the voltages at zero flow (system offset) drifted in a random fashion. It was not known what caused these drifts, however, they were overcome by frequently monitoring the system offsets and applying them to the calibrations during analysis.

EXPERIMENTAL PROCEDURE

As part of the present experimental programme, outlined earlier, as well as unsteady flows, all tests were carried out in steady flows before progressing to the unsteady situations. The reason for doing this was to allow the comparison of results with previous work and to provide a bench-mark for the unsteady flow cases.

The tests were carried out at nominal free-stream velocities, U , of 0.25m/s, 0.5m/s and 0.75m/s, however, variation from these nominal velocities occurred because it was not possible to set velocities with a great deal of precision.

Records of the turbulent velocity components were taken at intervals throughout of the depth from heights above the bed, y , of 0.04m to 0.18m, the effective depth of flow. The length of each record was 200s, simultaneously the free-stream velocity was being measured using a 10mm miniature propeller current meter positioned at 0.18m above the bed and 2.5m upstream of the measuring section. The free-stream velocity was recorded as a check to ensure that it did not vary appreciably between records.

The ECM head was orientated vertically and horizontally by virtue of the way in which it was supported, however, care was exercised to ensure that the head

was correctly positioned with the front of the head parallel to the mean flow direction. The great care with which the instrument was positioned was to minimise errors caused through misalignment. Heathershaw (Ref 8) demonstrates that, for large ECM's it is necessary to position the sensor to within $\pm 0.5^\circ$ from the horizontal/vertical in order to achieve $\pm 6\%$ accuracy in the Reynolds stress measurements.

ANALYSIS OF DATA

The data from the ECM system was recorded digitally on magnetic tape. Analysis of these data was carried out using a purpose written computer program. This program read the recorded voltages from the magnetic tape and converted them into velocities using the established voltage/velocity calibrations. The time averaged mean velocity for the longitudinal, x, component was calculated using an equation of the form

$$U = \frac{1}{N} \sum_{i=1}^N U_i \quad (1)$$

where U_i is the i term in a time series of U , length N , u' is a fluctuation from the mean value, U , ie

$$u'_i = U_i - U \quad (2)$$

The root mean square value of the longitudinal velocity fluctuations was calculated using

$$\hat{u} = \left[\frac{1}{N} \sum_{i=1}^N u_i'^2 \right]^{1/2} \quad (3)$$

Similar expressions were used to calculate these parameters for the vertical (y) component yielding the time averaged vertical velocity, V , vertical velocity fluctuations, v'_i , and the vertical rms value, $\hat{v}$.

The time averaged value of the product of each u'_i and v'_i value, $\overline{u'v'}$ was calculated using the equation

$$\overline{u'v'} = \frac{1}{N} \sum_{i=1}^N u'_i v'_i \quad (4)$$

This is a measure of the Reynolds shear stress, Reynold shear stresses, or "apparent stresses" are caused by turbulent velocities (see Hinze (Ref 9)). Reynold shear stresses are defined for the longitudinal/vertical (xy) plane as

$$\tau_{xy} = -\rho \overline{u'v'} \quad (5)$$

By plotting Reynolds shear stress against height the value of the shear stress on the bed τ_0 , can be extrapolated, the bed friction velocity, u_* can be calculated from

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \quad (6)$$

DISCUSSION OF RESULTS

In order to express the violence or intensity of a turbulent flow the root mean square value of the turbulent velocity fluctuations is used, the relative intensity, (turbulence intensity) of the turbulent flow is taken as the root mean square normalized by a scale velocity. For comparison between different work it is usual to use the bed friction velocity, u_* , as a scale velocity.

The ECM results have been compared with the results of Laufer (Ref 1), Richardson and McQuivey (Ref 2), Nakagawa et al (Ref 3) and Grass (Ref 4), all of which represent similar established work conducted mainly in water, with the exception of Laufer's work, carried out in air, but using different techniques.

It was found during the analysis of the data that spurious results were being obtained from the ECM when the head was at heights less than 40mm ($y/D = 0.22$),

this was thought to have been caused by the ECM head creating disturbances to the flow when close to the bed, hence no ECM results are shown for heights less than $y/D = 0.22$.

The ECM results are compared with the four sets of results using different techniques and fluid mediums in Figs 1, 2 and 3. Fig 1 shows the longitudinal turbulence intensities and Fig 2 the vertical intensities. Fig 3 shows the Reynolds shear stress comparisons, the line shown on this figure is the trend line that all results should show.

In general the ECM results are in broad agreement with the other results, they demonstrate the same trends and have similar numerical values. When looking at the results the size and frequency range of the instrument should be remembered, it should also be borne in mind that the ECM results were obtained in flows having a depth-to-width ratio of 0.3 and these results have been compared with results obtained in truly two-dimensional flows, that is flows having depth-to-width ratios less than 0.2.

CONCLUSIONS

Allowing for the limitations of the ECM, namely size and limited frequency range; the results show that the instrument can be used for turbulence studies in water in the laboratory. However, in making this statement qualifications must be added. Apart from the size and frequency range it appears that the instrument should not be used less than 40mm from a boundary. As stated earlier initially problems were encountered with earth loops in the system, these were spotted because a visual record of the output voltages were being made, hence, it is recommended that records are made of the output voltages to enable problems such as this to be spotted immediately.

Overall the ECM is a comparatively simple piece of equipment to use and is very well suited to carrying out this type of investigation in a situation such as that at HRS where it is difficult to keep water really clean enough to use a hot-film anemometer for instance.

ACKNOWLEDGEMENTS

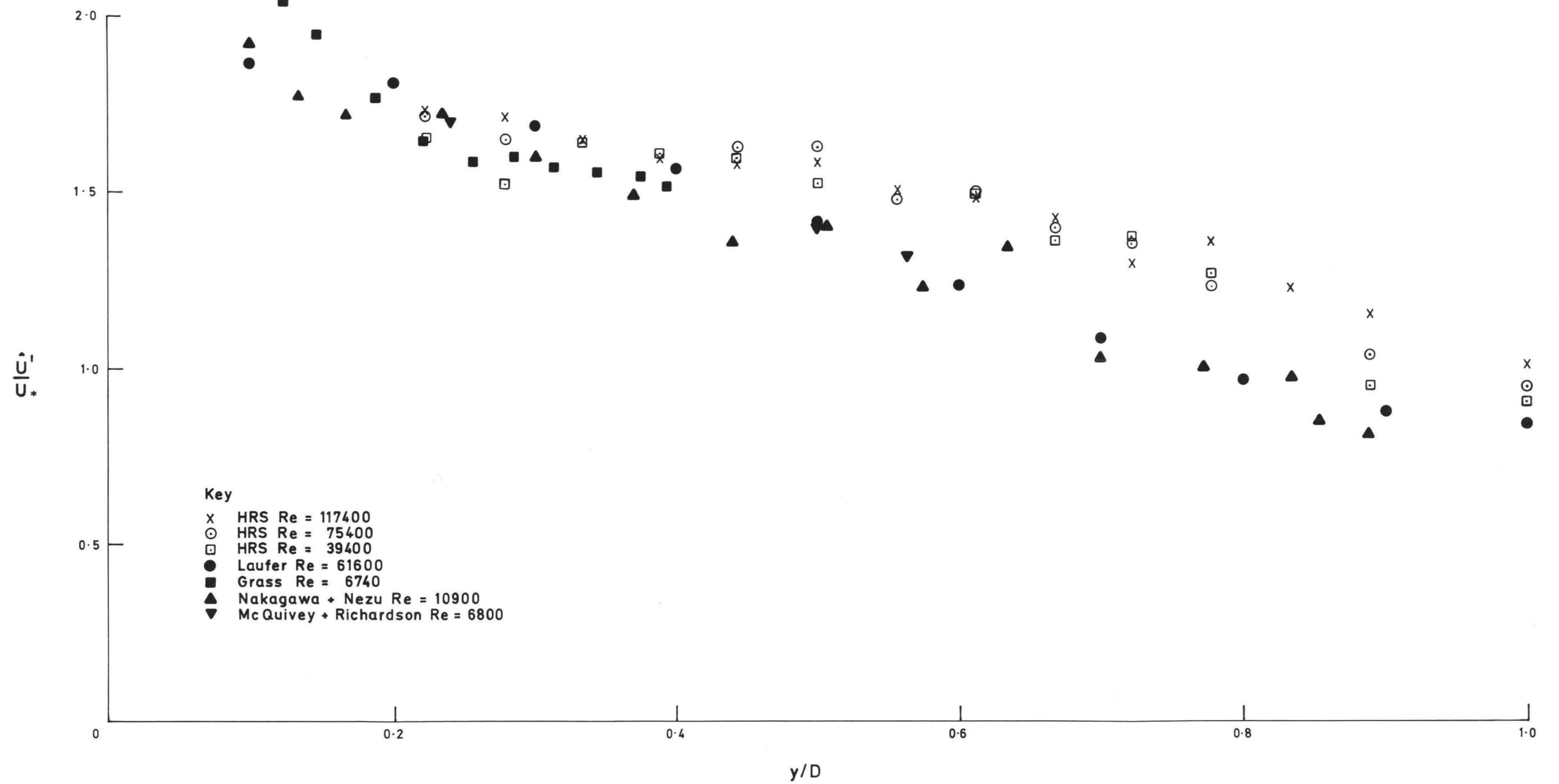
This report describes some of the experiments which have been conducted as part of an investigation into simulated tidal flows carried out in Dr Anwar's section of the Hydraulics Research Station. The valuable advice and assistance given by all members of the groups headed by C B Waters, D K Fryer and P H Simmonds of the EDFs section of the Hydraulics Research Station was greatly appreciated.

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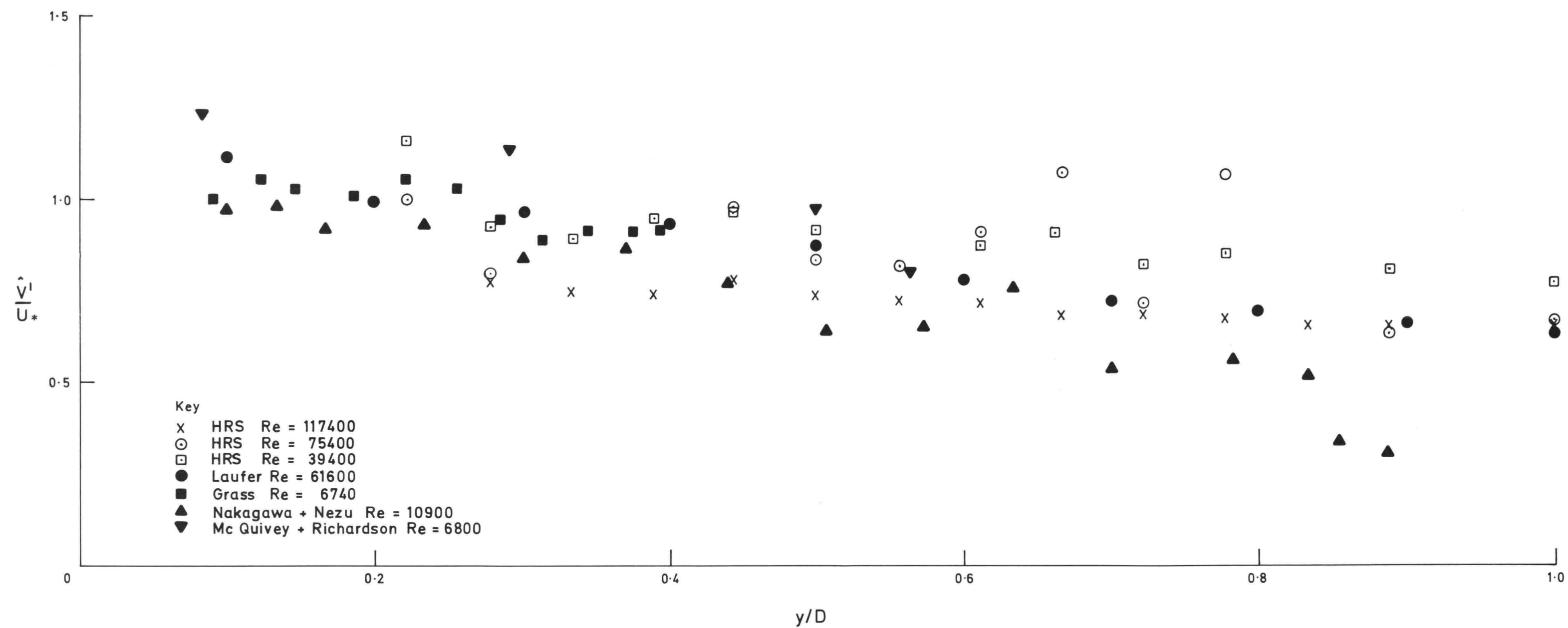
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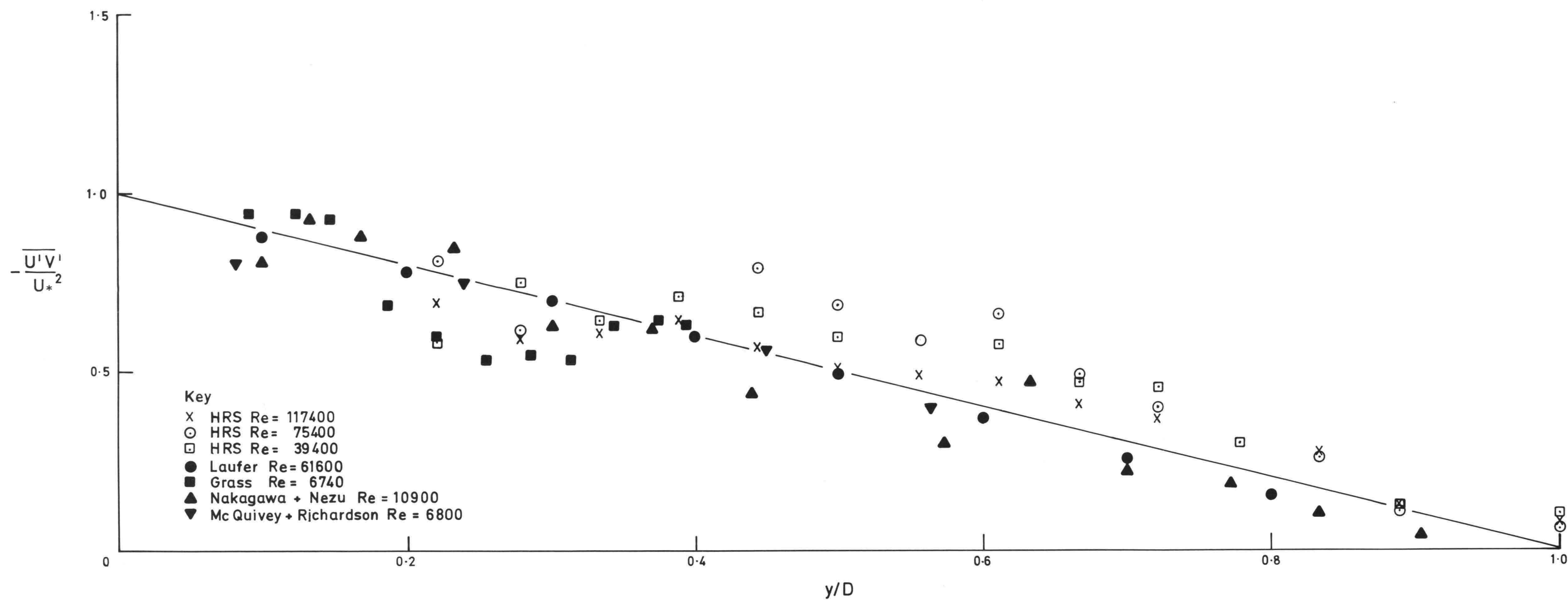
FIGURES



Longitudinal turbulence intensity distributions



Vertical turbulence intensity distributions



Reynolds shear stress distributions

PLATES



PLATE 1 Experimental flume

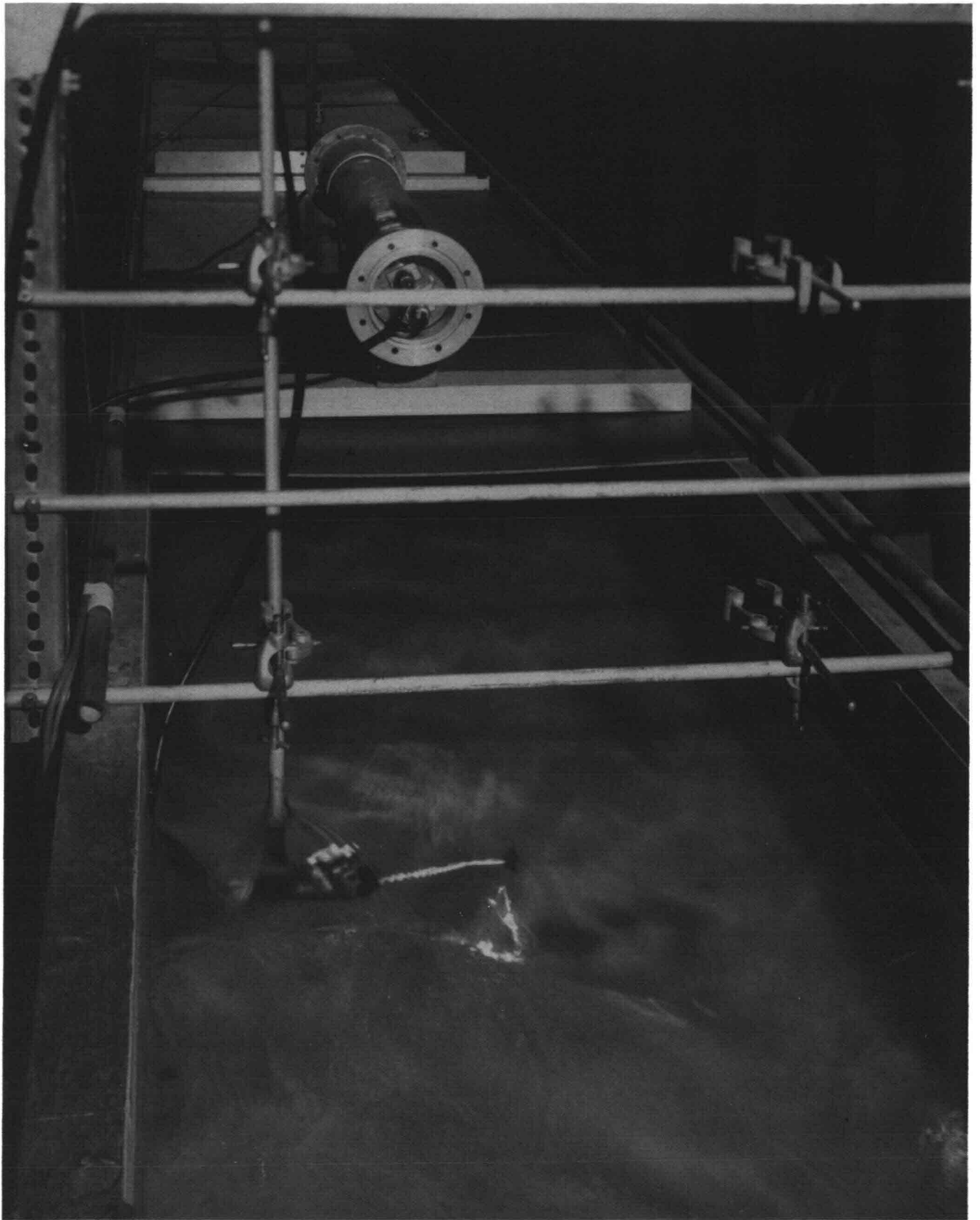


PLATE 2 Electromagnetic current meter in flume

