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THE EFFECT OF HIGH TURBULENCE ON WALL SHEAR IN A TWO DIMENSIONAL WALL JET

M. A. Badri Narayanan
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Turbine Components
Aero Propulsion and Power Directorate

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The effect of turbulence on skin friction was examined in the developing stage of a high Reynolds number wall jet. Skin friction was computed from the law of the wall measurements of mean velocity profiles in the sublayer. It was observed that constant "A" in the law of the wall relation $U/U^* = A \log YU^*/\nu + B$ was a universal one equal to 5.6 while "B" was linearly dependent on the turbulence intensity near the wall. The wall shear was not significantly altered from that of an ordinary flat plate turbulent boundary layer even at high turbulence levels. The decay of the mean velocity in the longitudinal direction was found to be independent of the momentum flux of the jet at the nozzle exit.

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NOMENCLATURE

X	Distance along the plate in the longitudinal direction from the exit of the nozzle
Y	Distance in the vertical direction from the surface of the plate
$Y_{(1/2)}$	The distance Y where $U = 1/2\ U_{max}$
Y_{max}	Y at U_{max}
H	Width of the nozzle = 6.5 cm in the present set up
U	Mean velocity in the X direction
U_{max}	Maximum in the mean velocity distribution at a given X
U'	RMS value of the velocity in the in the X direction
Tu	u'/U_{max}
U^*	Friction velocity = $(\text{Wall shear stress/density})^{.5}$
C_f	Skin friction coefficient
υ	Kinematic viscosity
R_x	$U_{max}\ X / \upsilon$
R_m	$U_{max}\ Y_{max} / \upsilon$
R_{em}	$Ue\ Y_{max} / \upsilon$

SECTION 1

INTRODUCTION

A knowledge of skin friction is of considerable importance in fluid mechanics since it is a major contribution to the drag of bodies such as aircraft wings and turbine blades. Although the relations between the flow parameters and the skin friction coefficient were established several years ago (Ref 1 and 2), they are confined to flows with low free stream turbulence. In the gas turbine engine flows occur in which the fluctuating component of velocity is 20 to 30 percent of the mean velocity. The present knowledge on the effect of large fluctuating disturbances on wall shear is in its infancy and requires further investigation.

The origin of large scale turbulence or unsteadiness in flows over turbine blades results from the periodic wake generated by the upstream vanes, from the film cooling flows on the blades and vanes, from vortices generated at the hub and tip of the blades as well as from the turbulence generated in the combustion chamber. These flows are very complex and involve many factors which make it difficult to separate and analyze only the effect of high turbulence. It is preferable to restrict the investigation to a simple case, such as the flow over a flat plate, to understand the fundamentals.

Generation of controlled turbulence of high intensity and variable scale in the laboratory is a formidable task. The most common method employed to generate turbulence is to introduce biplanar grids into the flow. The major drawback with this technique is the rapid decay of turbulence due to the breakdown of the large eddies into smaller ones in the initial period of decay. This initial period of decay takes place within a very short distance. The grid generated turbulent fluctuations often are reduced to less than 10 percent of the freestream velocity in a length comparable to that of the experiment or at a length scale so large that the flow is not of interest for simulation of turbine flows (Ref 3 and 4). An improved version of the grid system; the jet grid has been developed to futher enhance the turbulence intensity (Ref 5 and 6). The less than 10% disadvantage is improved but not significantly alleviated.

The wall jet employed in this investigation generates suitable flow conditions for the above study, because this flow inherently contains high turbulence not only over considerable distance along the flow but also across shear layer. In addition, the domination of large scale structures makes this flow suitable for research on gas turbine blades which encounter the upstream wakes and corner vortices containing large eddies during their operation. A sketch of the two-dimensional wall jet used in the present investigation is shown in Figure 1. Even though several references already exist on the skin friction of wall jets they do not explicitly provide information on the effect of turbulence intensity on the wall shear. Previous investigators have determined wall shear using the following techniques; (a) the direct measurement of wall shear using the well known floating element technique (Ref 7), (b) the Preston tube method (Ref 8) and (c) the heat transfer gauge (Ref 9). Apart from these methods some have employed the law of the wall concept to determine the coefficient of skin friction (Fig 2). In the law of the wall:

$$U/U^* = A \log YU^*/\upsilon + B \tag{1}$$

both "A" and "B" in the logarithmic region were considered to be universal constants equal to 5.6 and 5.45 respectively. Others have considered both "A" and "B" to be variables. A detailed review by Launder and Rodi (Ref 10) on law of the wall measurements has clearly distinguished the discrepancies between various results. It is not surprising that all of results are not in agreement since each technique has its own deficiencies. The Preston tube technique is valid and will yield reliable results only if the same similarity law holds both in the wall jet and in the flow where the tube is originally calibrated. This implies that the constants "A" and "B" in the law of the wall should be the same in both the flows. While "A" maybe a universal constant, "B" is known to be variable in the case of a rough wall. The functional relationship of "B" will be discussed in the latter part of this report. The use of heat transfer gauge which relies on the well known "Reynolds analogy" (Ref 2) equating the heat transfer and the skin friction coefficients is also questionable in high turbulence flows. The relationship between C_f and the Stanton number undergoes significant variation when the disturbances are large (Ref 11 and 12). Measurement of wall shear directly using the floating element system by Alcaraz (Ref 7) is restricted to low Reynolds number flows. Launder and Rodi's (Ref 10) evaluation of the slope of the mean velocity at the wall is found to be 20 to 35 percent below the data from the Preston tube. These remarks are merely meant to indicate some of the uncertainties involved in the measurement of wall shear.

The present study is on the effect of turbulence intensity on wall shear. The existing information on wall jets was inadequate for the calculation of wall shear, being deficient in turbulence measurements, in range of turbulence intensity, in range of Reynolds numbers, and in resolution of the velocity profiles near the wall. The majority of experimental data available pertain to large distances from the nozzle (X/H>60) where the flow has reached a near equilibrium condition and the outer shear layer has eroded deeply into the wall boundary layer. The shear layer formed at the free end of the nozzle generates strong eddies in the flow and these large structures transfer momentum from the outer part of the jet to the fluid near the wall. This action results in a high level of turbulence of near constant intensity across the wall jet region. This trend persists for some distance from the nozzle, up to X/H of 60, as seen in the present measurements. The input energy of the overall flow beyond this region of X/H is limited by the strength of the large eddies. The strength of the large eddies is reduced as is their penetration toward the wall for large values of X/H. This effect coupled with the large viscous forces at the wall reduces the turbulence intensity in the vicinity of the wall. The u′ profiles get modified as a result of the reduction in turbulent kinetic energy. This trend can be noticed in the measurements by Wygnanski et al. (ref 13) in the range of X/H = 60 to 120. Their propfiles exhibit a smaller constant u′ region near the wall indicating that the decay has begun. Several other measurements at large X/H (Fig 9 in Ref 10) also indicate the same trend. Figure 3 illustrates the shape of the u′ profiles as inferred from various measurements of others for the three X/H regions of the planar wall jet. In the range of X/H > 60 the influence of the turbulence intensity on the wall would be much less than the influence of the outer part of the shear layer. All earlier investigations belong to this regime of large X/H. The measurements of wall shear by Bradshaw and Gee with a Preston Tube (X/H > 300) were shown to agree with the experiments of Alcaraz who measured shear directly. Some investigators have taken this to mean there is no change in either "A" or "B" in the law of the wall. Later it will be shown that when the free-stream turbulence is less than the near wall (shear layer) turbulence the value of "B" in the log law approaches that of an ordinary flat plate boundary layer. Under such conditions the agreement between the wall shear measurements made by Preston tube and the floating element technique is understandable, but this does not necessarily mean that both A and B are constant.

The aim of the present investigation is to understand the effect of high turbulence on skin friction and wall shear. The range of the parameter X/H was 0 to 60. This range of X/H provided nearly constant u' levels in the Y direction for subsequent heat transfer investigations.

SECTION 2

EXPERIMENTAL SET UP

The experiments were conducted in a two dimensional wall jet with a standard nozzle (ASME long radius). The slot height was 6.5 cm and the span of the jet was 48.25 cm. Three high pressure compressors provided dry air to the system. A 81.3 cm dia by 152.4 cm settling chamber containing a honeycomb and a set of graded screens was installed between the control valve and the nozzle contraction. The wall jet was formed on a smooth flat surface 350 cm long and 48.25 cm wide positioned tangent to the lower surface of the nozzle as shown in Figure 1. This arrangement forms a part of the general facility of the laboratory which has been used extensively by several workers to investigate heat transfer problems as well as the characteristics at high turbulence levels. Hot wire anemometer, fine pitot tubes, and a three component laser Doppler velocimeter was used to obtain the mean velocity and turbulence profiles. It was possible to position the hot wires and the pitot tubes to an accuracy of 50 microns using a precision traverse which was driven by a stepper motor. The laser velocity measurements were made with a TSI three component off axis system in the back scatter mode. The laser measurement crossection was 25 microns in diameter. The exit velocity at the nozzle could be varied from 10 to 100 m/s.

SECTION 3

DESCRIPTION OF THE FLOW

These experiments were restricted to X\H locations from 0 to 60. Sidewalls were employed in the measurements by Badri Narayanan and also Dino Ishikura. These sidewalls were 15.24 cm high and tangent to the jet nozzle outlet. Sidewalls were also employed in an earlier experiment by MacMullin et al. with a three dimensional wall jet. MacMullin's walls were 15.24 cm high with a 2.3 cm gap from the tangent to the jet nozzle outlet. These walls were used to enhance 2D flow for film cooling experiments. However, LV profile measurements by Rivir & Eckerle were also made without walls with no appreciable mean velocity profile differences from those measured by Ishikura on the wall jet center line with walls. Measurement of the of the mean velocity was made at forty locations in the vertical direction across the span at an X=212 cm from the jet exit, using a fine pitot tube. This measurement indicated the flow to be two dimensional, except for a 2 cm zone next to the walls (Figure 4). The two dimensional nature of the flow has also been confirmed by heat transfer measurements.

A significant aspect of the flow in this large facility is the high exit Reynolds number ($R_j = U_e H/\upsilon$). An exit velocity (U_e) of 100 m/s corresponds to R_j of about 400,000 and the local Reynolds number ($Y_m U_m/\upsilon$) can be as high as 200,000. Similarly the Reynolds number ($U_m X/\upsilon$) can be increased to ten million. Comparison of results of experiments conducted in this facility at high Reynolds numbers with those of others, indicates some differences. Wygnanski et al. (Ref 13) based on their experimental results as well as on the arguments by Narasimha et al. (Ref 14) have indicated that the rate of decay of the maximum velocity is dependent on the momentum of the flow at the exit of the nozzle. In the present investigation which was conducted at three higher Reynolds numbers (R_j=381,646, 177,800 and 85,800) the rate of decay was found to be independent of R_j and the decay characteristics coincide with R_j=19,000 in Wygnanski's experiments, the highest Reynolds number in their investigation (Figure 5). There is also good agreement of the present data with the rate of decay suggested by Launder and Rodi (Figure 4 in Ref 10), which covers a wide range of jet Reynolds numbers (R_{ej}).

The level of velocity fluctuations at the exit of the jet was uniform across the nozzle and equal to 2% of the local mean velocity. The transition from the uniform jet flow to a wall jet along X was very rapid occurring in less than five nozzle heights. The mean velocity profiles exhibited similarity even at X/H=20, when plotted with $Y_{(1/2)}$ and U_{max} as the appropriate length and velocity scales (Fig 6). The profile also coincides with that reported by Wygnanski et al (Ref 13) and other investigators (Figure 5 in ref 10). The mean velocity and the turbulence intensities measured by both the hot wire as well as by the laser doppler velocimeter are shown in Figures 7 and 8. Rivir and Dino Ishikura (R&D) conducted the experiments with a single exit velocity whereas Rivir and Eckerle (R&E) maintained the same value for U_m at all longitudinal stations (X) by adjusting the settling chamber pressure for each set of measurements. It is observed that the turbulence intensity (u') is nearly constant for considerable distance from the wall in the (Y) direction.

The turbulence intensity at an X/H of 50 still remains almost invariant across the flow. Tu increases initially in the axial direction from 2% at the jet exit to 21% (Figure 9) and then remains constant at 21% up to X/H = 50 in the present wall jet study. The mean velocity and turbulence profiles gathered in this two dimensional wall jet facility by previous investigators (Ref 15, 16) have also been used to reach these conclusions. Other investigators whose data has been used in this report will for berivity be referred to as R&D (R.B. Rivir & Dino Ishikura), R&B for (R. B. Rivir & M.A. Badri Narayanan), B&D for (M.A. Badri Narayanan & Dino Ishikura), R&E for R.B. Rivir & W.C. Eckerle, SCH for John Schauer, W for I. Wygnanski et al. and PA for (Paul Maciejewski and Robert Moffat).

SECTION 4

DETERMINATION OF WALL SHEAR

The wall shear in this investigation has been determined by two different methods (a) direct determination of the slope of the mean velocity at the wall by probing the linear region of the sublayer and (b) utilizing the law of the wall concept assuming a single constant "A". Both the techniques yielded results which were in good agreement supporting the view that "A" has a universal value equal to 5.6. The mean velocity near the wall was measured by a single element hot wire. A five micron diameter Wollaston wire was used for the sensor. The wire with its outer silver coating was initially soldered to a two prong probe to form a loop (Figure 10) and the middle of the wire loop was etched and stretched straight for a length of 0.5 mm. The probe was attached to a micrometer traverse which could be positioned to an accuracy of $\pm$ 0.01 mm. A TSI-IFA-100 hot wire anemometer was used for the measurement of the mean velocity. The voltage output from the anemometer was integrated over a period of 3 minutes to obtain steady and consistent readings. Initially the wire was positioned at a distance of 2.5 cm from the wall and then moved towards the surface of the flat plate. As the wire approaches the wall a reversal in the wire voltage is observed indicating that the conduction between the wire and the surface of the wall has become significant. The wire was further lowered until it touched the wall. At this point the wire either broke or changed its heat transfer characteristics abruptly due to contamination by the wall. This enabled identification of the location of the wall to an accuracy of about 15 microns. The slope of the mean velocity was then determined from the hot wire data discarding any of the contaminated points very close to the surface. The hot wire was discarded after each profile measurement and a new wire was prepared for the next traverse. These experiments were performed to verify the universality of constant "A" and only a few traverses were take this way. Considering the uncertainties involved in the other techniques, this method provides the best measurement of wall shear, provided the thickness of the linear region is large enough to allow measurements near the wall before conduction effects dominate. Three velocity profiles measured with this technique are shown in Figures 11, 12, and 13. When the profiles were plotted in the law of the wall form the constant "A" was found to be 5.6 in all of these cases.

It was also noted that the experimental results of Moffat and Maciejewski (Ref 12) indicate the same conclusion (Figures 14 and 15). Their experiments were carried out over a flat plate placed in a free jet with the leading edge of the plate located downstream of the nozzle so that high levels of turbulence were incident at the leading edge of the flat plate. The rest of the data available on the mean velocity profiles R&B, R&D, R&E, B&D, PA and SCH were analyzed for wall shear using the logarithmic law with "A" = 5.6. U* was varied in small increments until the slope of the logarithmic region was equal to 5.6. "B" was evaluated from the intercept using an iteration process. The value of "A" for the laser Doppler measurements could only be adjusted to an accuracy of ±0.1 due to the scatter in the experimental data. The mean velocity profiles in the logarithmic form are shown in Figures 16 to 31. Wygnanski et al. (Ref 13) have also suggested that "A" should have a universal value even though their mean velocity profiles plotted in the logarithmic form do not exhibit this factor explicitly. The wall shear in their analysis was obtained from the slope of the mean velocity profile in the linear region, one of the two procedures employed by the authors. Considerable length of the straight segment in the logarithmic plot is observed in the present investigation which is not present in wall jet studies at large values of X/H making possible an accurate evaluation of "A" & "B".

SECTION 5

DISCUSSION

The skin friction determined in the above manner from various experiments indicated that high turbulence has only a marginal effect on wall shear over that of a flat plate boundary layer (Figure 32). It was observed that in the experiments of R&B, B&D, & R&E the transition region was not distinctly noticeable as the flow became turbulent across the entire wall jet within a very short distance from the nozzle exit. The entire longitudinal distance from the exit was used in the evaluation of the Reynolds number (R_x) in this investigation. The above result suggests, that the mechanism that is responsible for the generation of wall shear is not significantly modified from that of an equilibrium turbulent boundary layer inspite of the variation in the level of turbulence from 2 to 20%.

Significant variation of "B" could be observed with the turbulence level. Its value lies between 2.0 to 10.0 in the present investigation as shown in Figure 33. "B" and "Tu" are found to follow a linear relation:

$$B = 1 + 42 \times Tu \qquad (2)$$

independent of Reynolds number. This relation which covers a large range of turbulence intensity seems to be valid even for an equilibrium flat plate turbulent boundary layer which has maximum turbulence level of 10 to 12%. In the present analysis the data of Schauer has also been included even though he did not directly measure the intensity of turbulence. It was assumed that the turbulence level in Schauer's experiments was around 20% by comparing the X/H locations of his measurement with others. Schauer made measurements at X/H locations greater than 57.

The variation in "B" can be considered as a measure of the increase in the width of the buffer zone between the linear region and the straight or log region (Figure 2). Since the linear region always seems to extend up to YU^*/υ of about 10 to 15 from the wall the increase in the length of the buffer zone would be towards the straight segment of the log zone. Such an effect is possibly due to enhanced mixing by penetration of the strong and large eddies towards the wall. Below the sublayer ($YU^*/\upsilon = 10$) the viscous force is so powerful that the effect of outer disturbances in this region are negligible. The original wall shear therefore remains almost unaffected. The new law of the wall becomes

$$U/U^* = 5.6 \log YU^*/\upsilon + 1 + 42 \times Tu \qquad (3)$$

Wygnanski et al. (Ref 13) have suggested that the appropriate Reynolds number for the wall jet is the one based on local Reynolds number ($R_{em} = U_m \; Y_m/\upsilon$) where U_m is the local maximum of the mean velocity and Ym is distance from the wall at U_m. The present data when plotted in this form (Figure 34) were appreciably different suggesting that R_{em} might not be the relevant parameter which governs the wall shear. The departure of the relation suggested Bradshaw and Gee (Ref 8):

$$C_f = 0.0315 \; R_{em}^{\;-0.182} \qquad (4)$$

from the present data further confirm that R_{em} is not the governing Reynolds number (Figure 34).

SECTION 6

CONCLUSIONS

The experiments conducted in a high Reynolds number two dimensional wall jet indicated that the rate of decay of the maximum velocity is independent of the momentum of the flow issuing from the nozzle exit. Similarity in the mean velocity profiles was observed even at distances very close to the nozzle. The longitudinal velocity fluctuations (Tu) remained nearly constant across the shear layer for a considerable distance from the wall. There was variation in Tu with X from 2.0 to 21% of the mean velocity. This enabled investigations of "A" and "B" over a wide range of turbulence intensities. When the mean velocity profiles were plotted in the law of the wall form "A" was found to be a true universal constant equal to 5.6 (log base 10) whereas "B" was dependent on the intensity of turbulence following the linear relation. 1 + 42 Tu Skin friction determined from the law of the wall was in good agreement with the values obtained from direct measurement of the velocity gradient at the wall. C_f thus obtained was the same as that of a flat plate turbulent boundary layer when the maximum velocity and the distance from the exit were considered as the velocity and the length scales, respectively.

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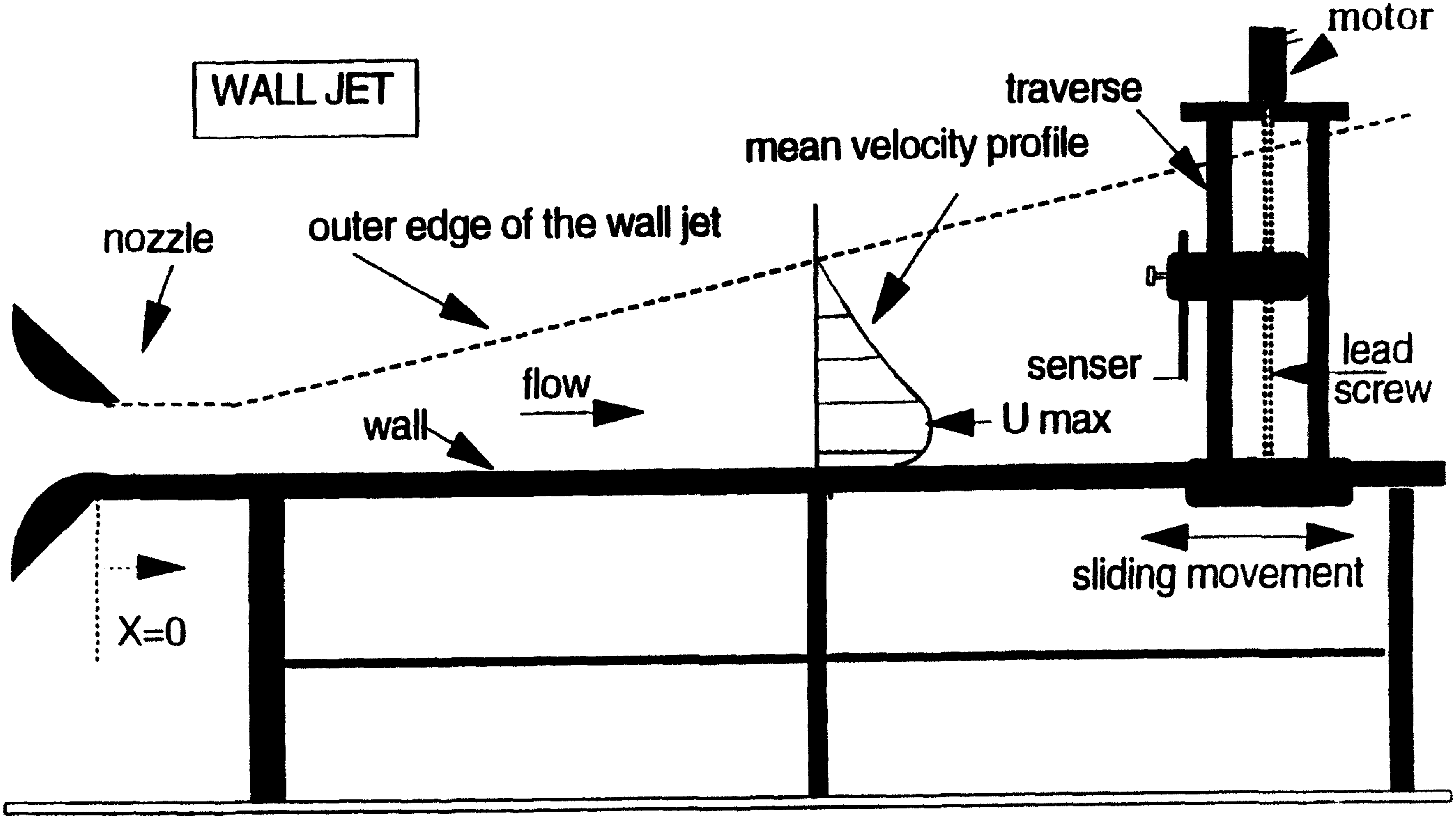
Table 1. Characteristics of High Turbulence wall Shear Layers

FIG.No	Umax(m/s)	X cm	U* (m/s)	Rx mill	Cf	Tu%	"B"
11	36.2	90	1.44	2.09	0.003165	15	7.5
12	32.93	114.3	1.28	2.413	0.003022	16.5	7.8
13	24.04	183	0.902	2.82	0.002816	19	9.6
14	6.71	40	0.333	0.172	0.004896	13.6	6.5
15	4.57	220	0.2	0.664	0.003831	15.8	7.2
16	40.85	25	1.89	0.655	0.004281	5	3.5
17	45	38	1.95	1.096	0.003756	7.5	4.2
18	39.02	50.8	1.646	1.27	0.003559	10	5.4
19	37.5	63.5	1.564	1.526	0.003479	12	5.5
20	45.5	96.8	1.7	2.823	0.002792	15.5	7.8
21	36	89	1.433	2.054	0.003169	15	7.5
22	40.33	52.1	1.737	1.347	0.003701	10	5.8
23	38.41	101.6	1.433	2.501	0.002784	16	8.5
24	36.9	162.6	1.363	3.846	0.002729	18	8.5
25	35.67	175.5	1.305	4.013	0.002677	18	9
26	35.37	200.6	1.256	4.548	0.002498	19.2	9.5
27	37	302	1.28	7.162	0.002394	22	9.6
28	37	353	1.239	8.372	0.002243	20	9.5
29	20.21	72.6	0.89	0.94	0.003879	20	9
30	16	122	0.64	1.251	0.003201	20	10.3
31	11.46	240	0.472	1.763	0.003393	20	9.5



length of flat plate --- 3.5 m
width of nozzle---48.29 cm
height of nozzle--6.5 cm

Fig. 1 Experimental set up of the wall jet

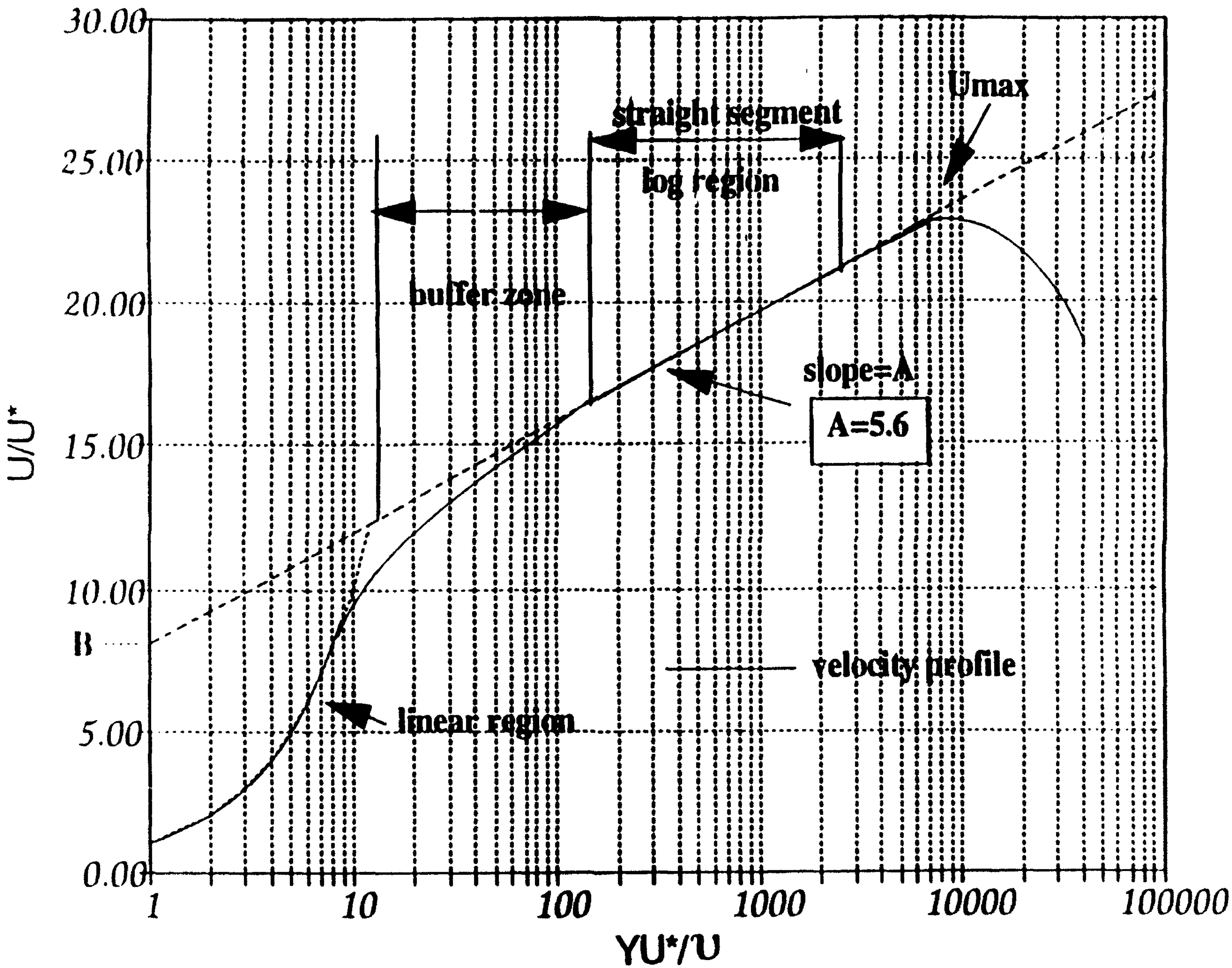


Fig. 2 Law of the wall for a wall jet--illustration

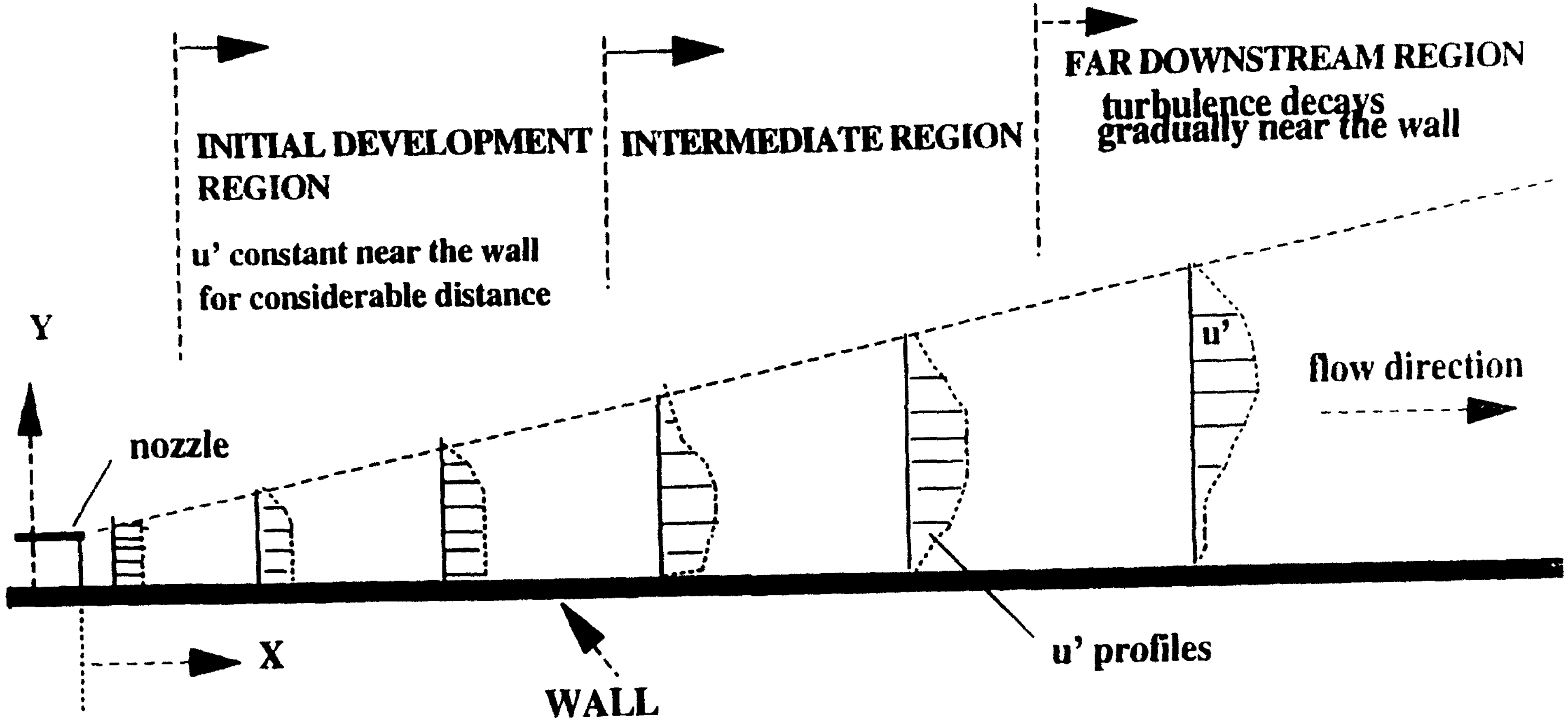


Fig. 3 Development of the u' velocity profiles at different regimes of the flow

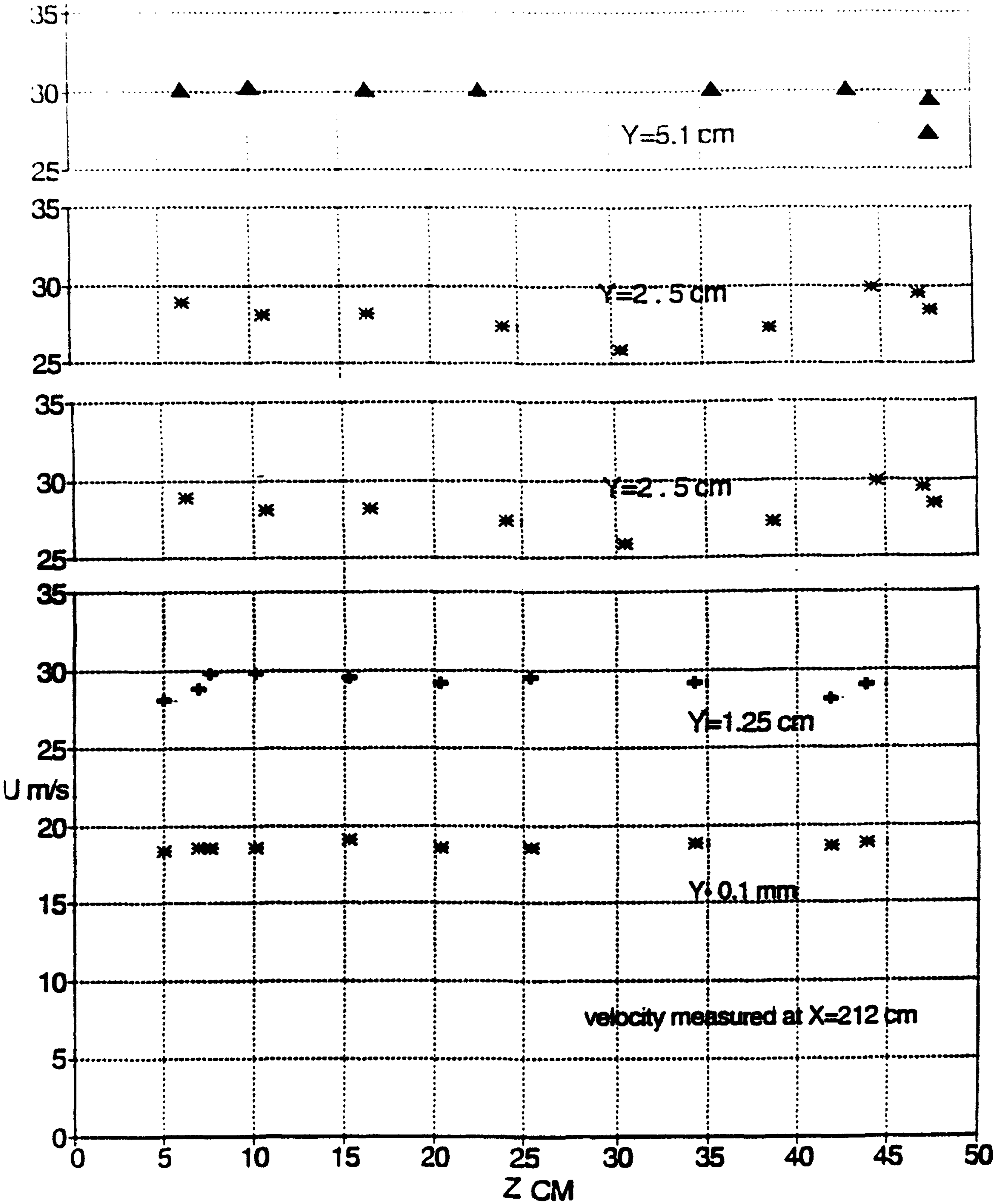


Fig. 4 Mean velocioty distribution across the span

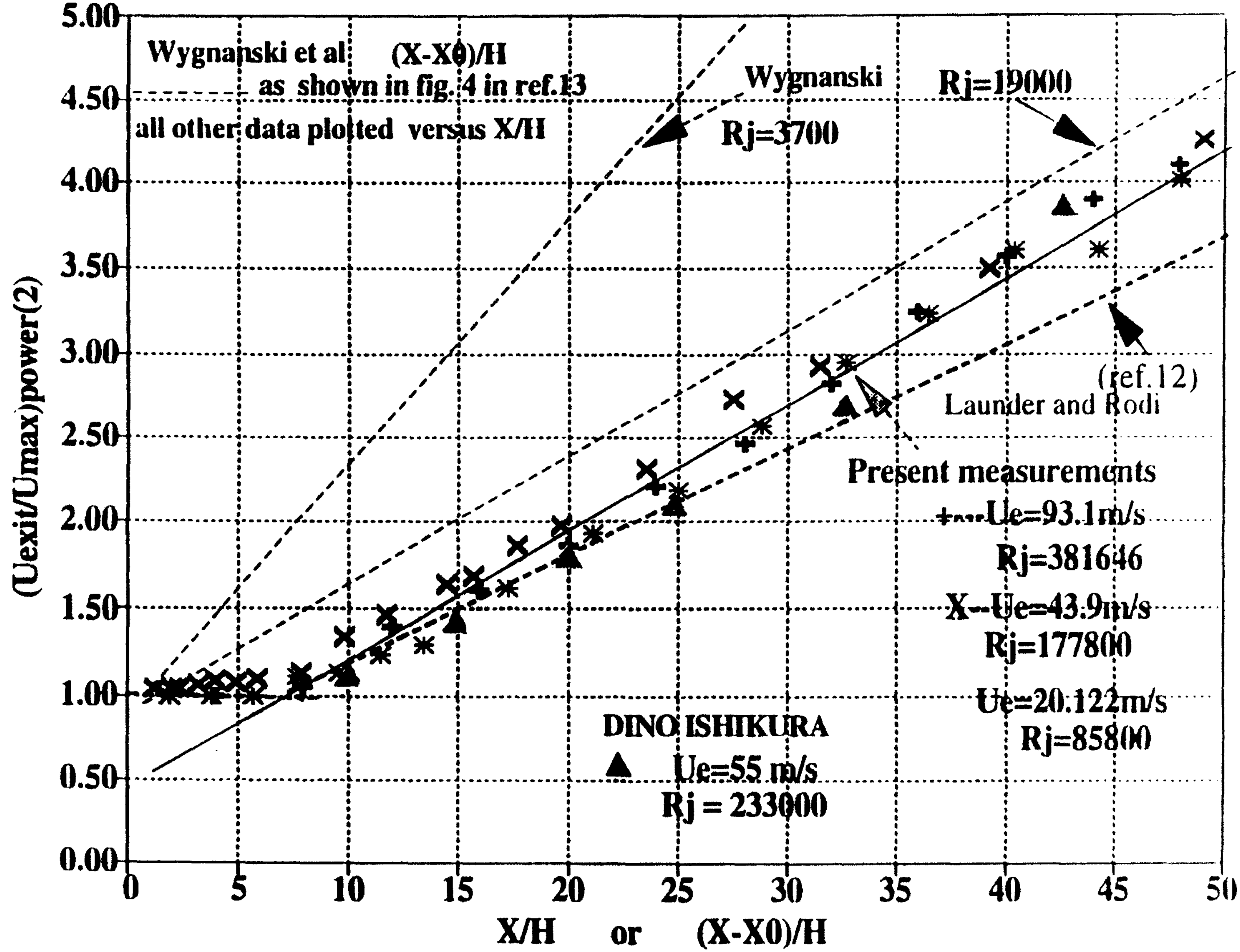


Fig. 5 Variation of maximum velocity with X distance

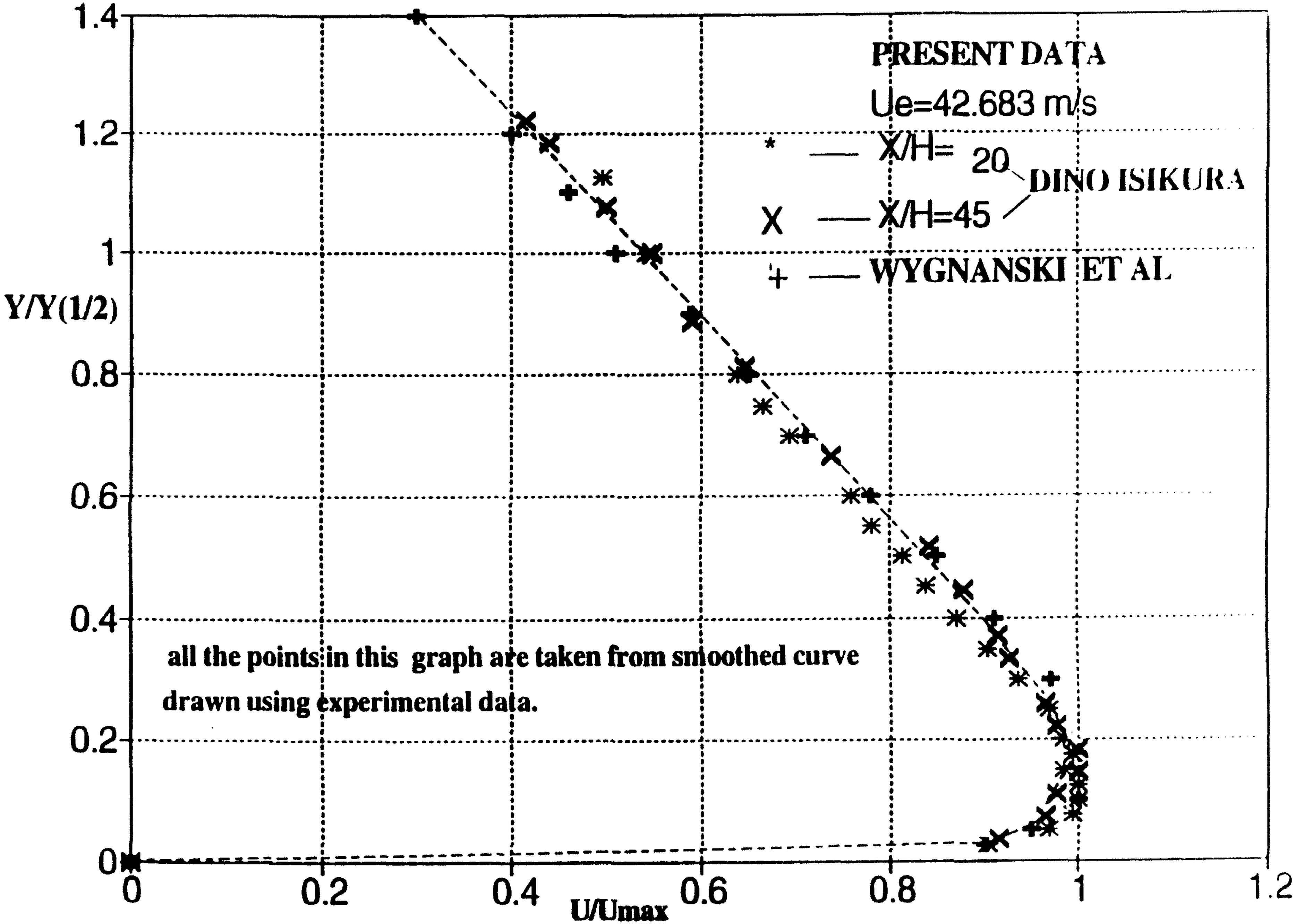


Fig. 6 Similarity in the mean velocity profiles

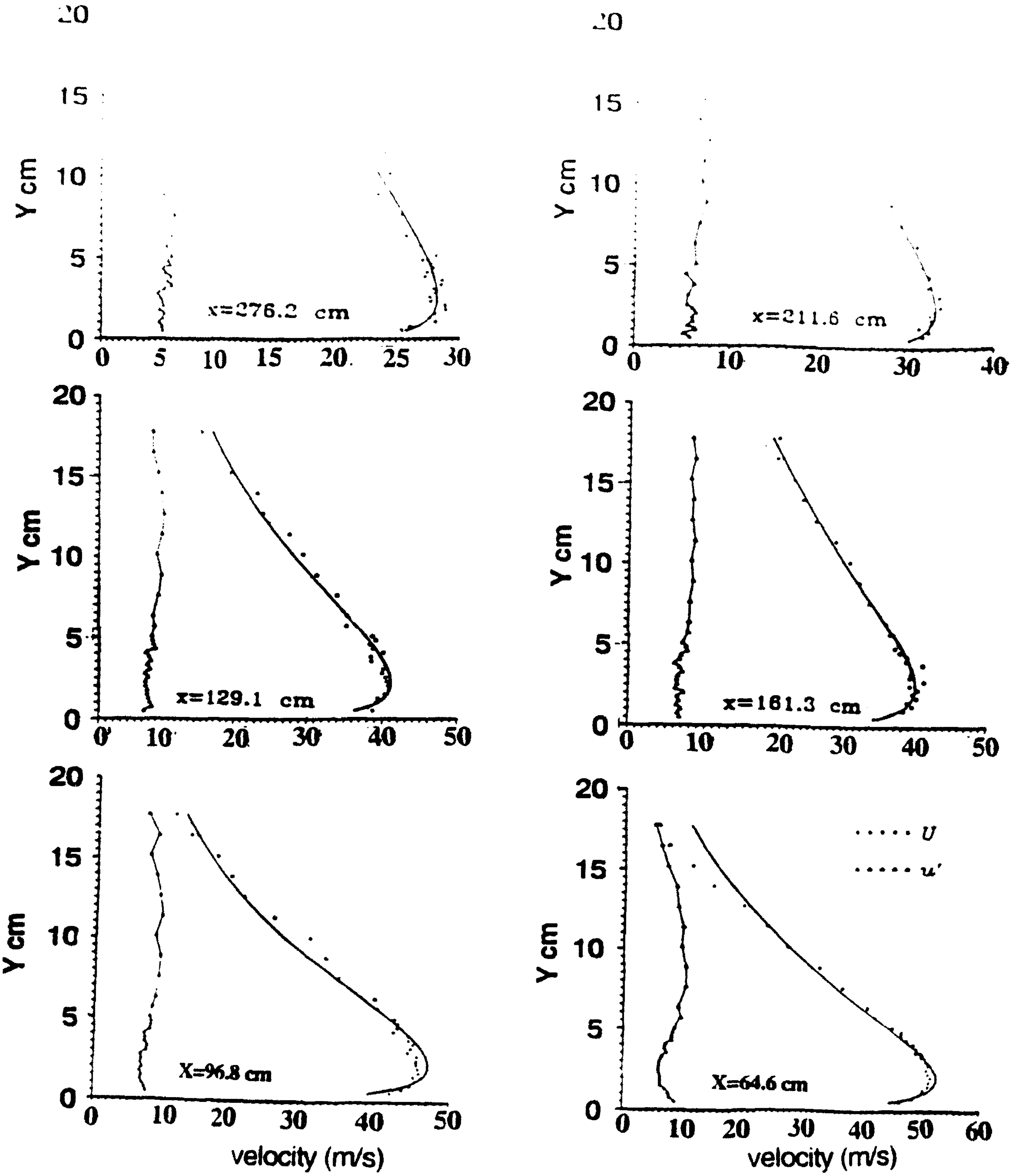


Fig. 7 Mean velocity profiles and turbulence intensity distribution in a two dimensional wall jet Rivir and Ishikura (Hot wire)

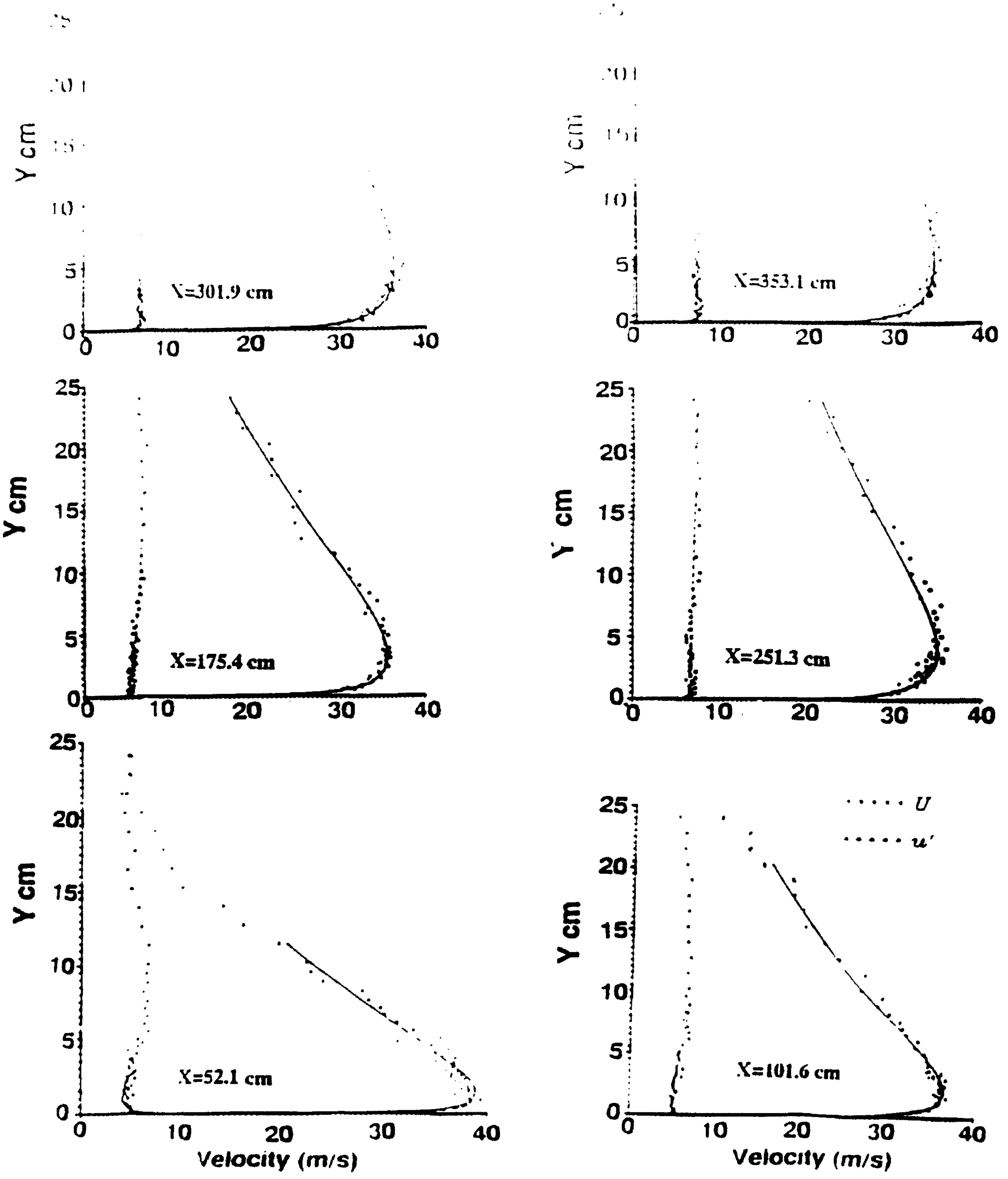


Fig. 8 Mean velocity profiles and turbulence intensity distribution in a two dimensional wall jet Rivir and Eckerle (LDA)

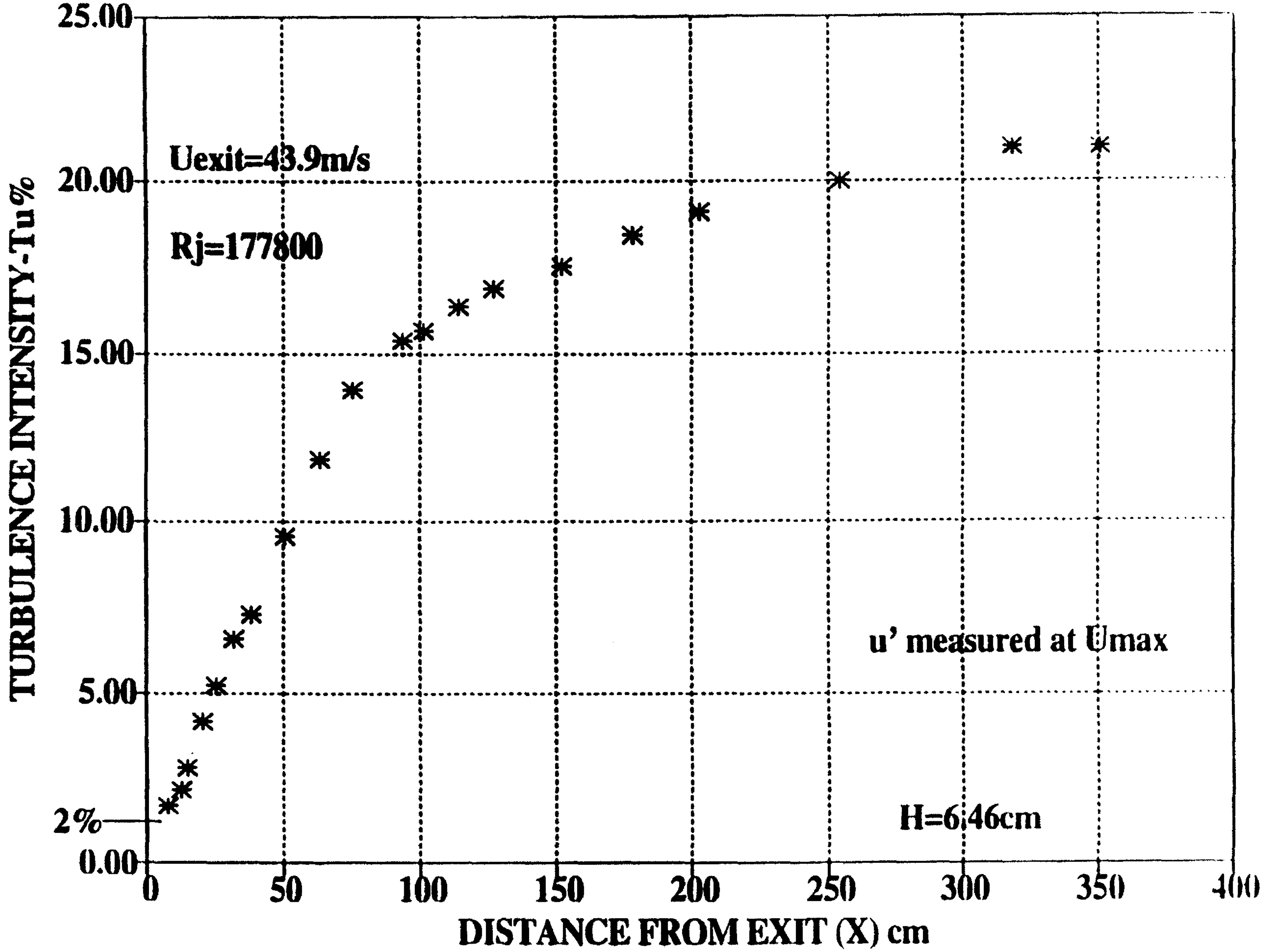


Fig.9 Variation of turbulence intensity

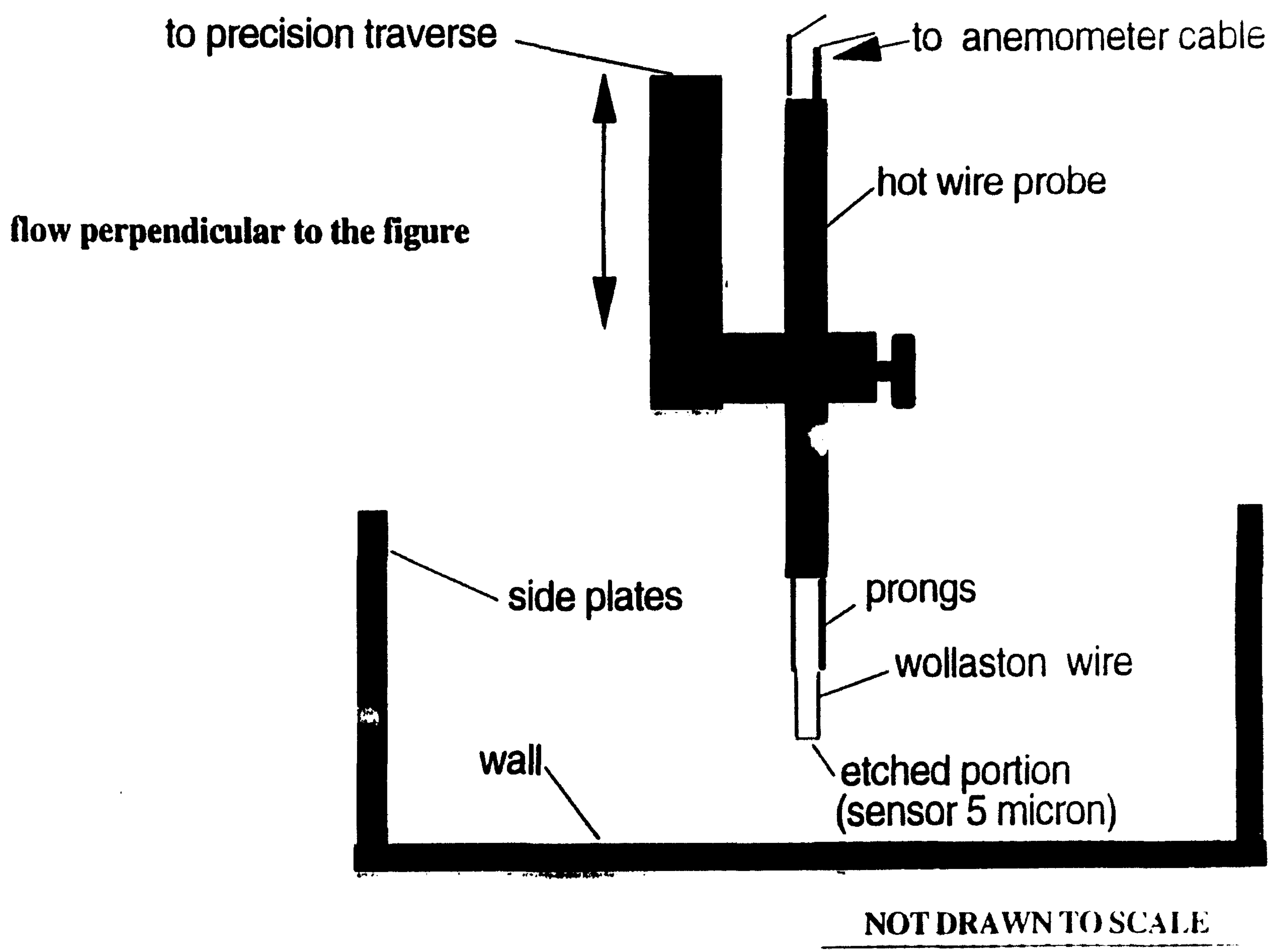
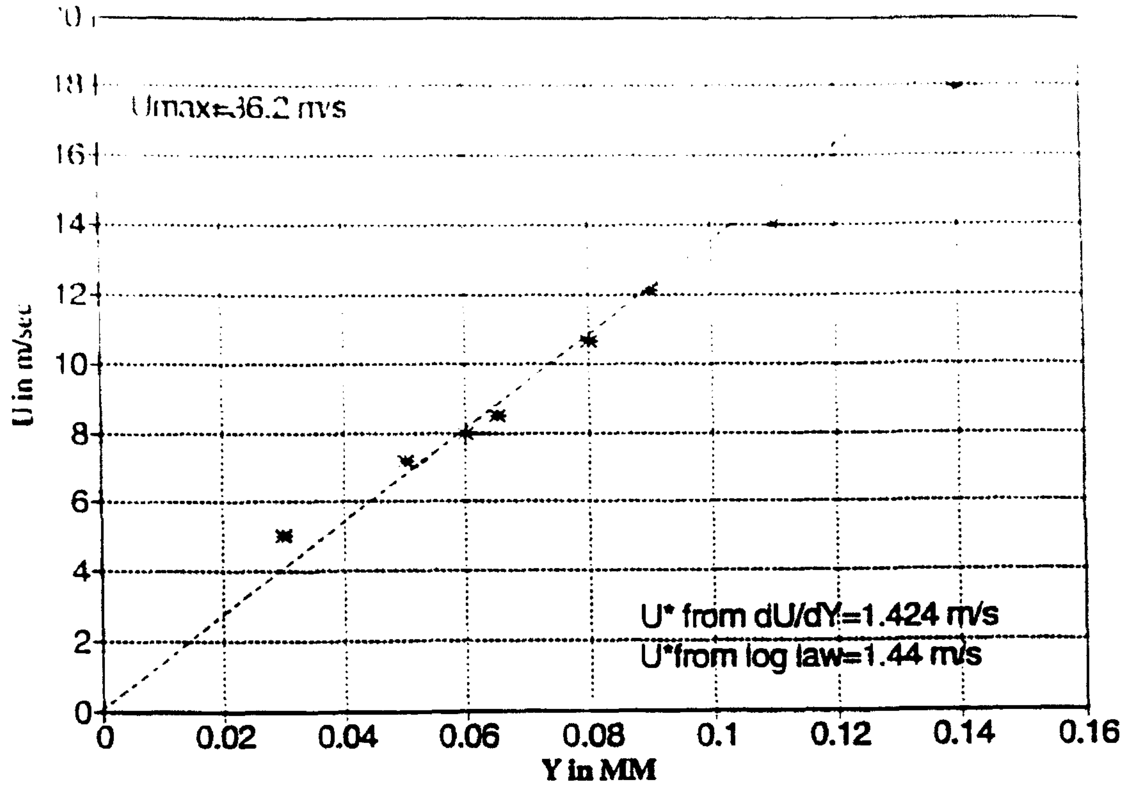


Fig. 10 Hot wire arrangement for near wall measurement



NEAR WALL

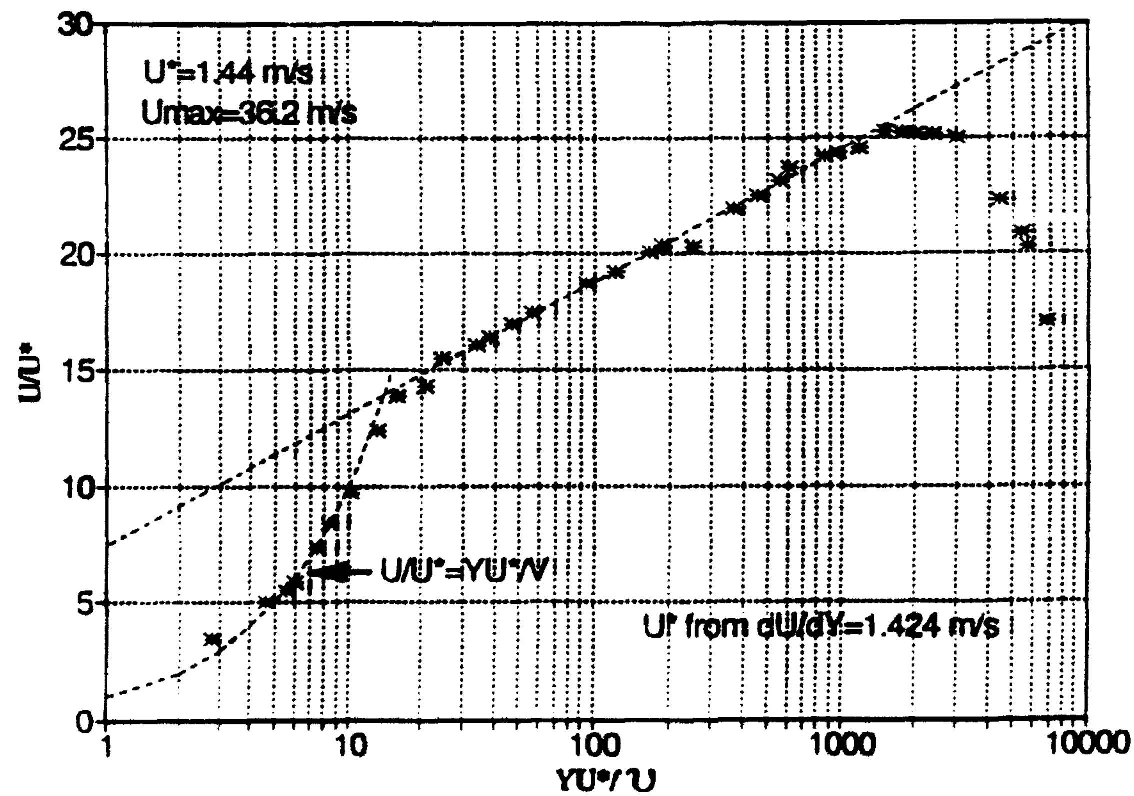
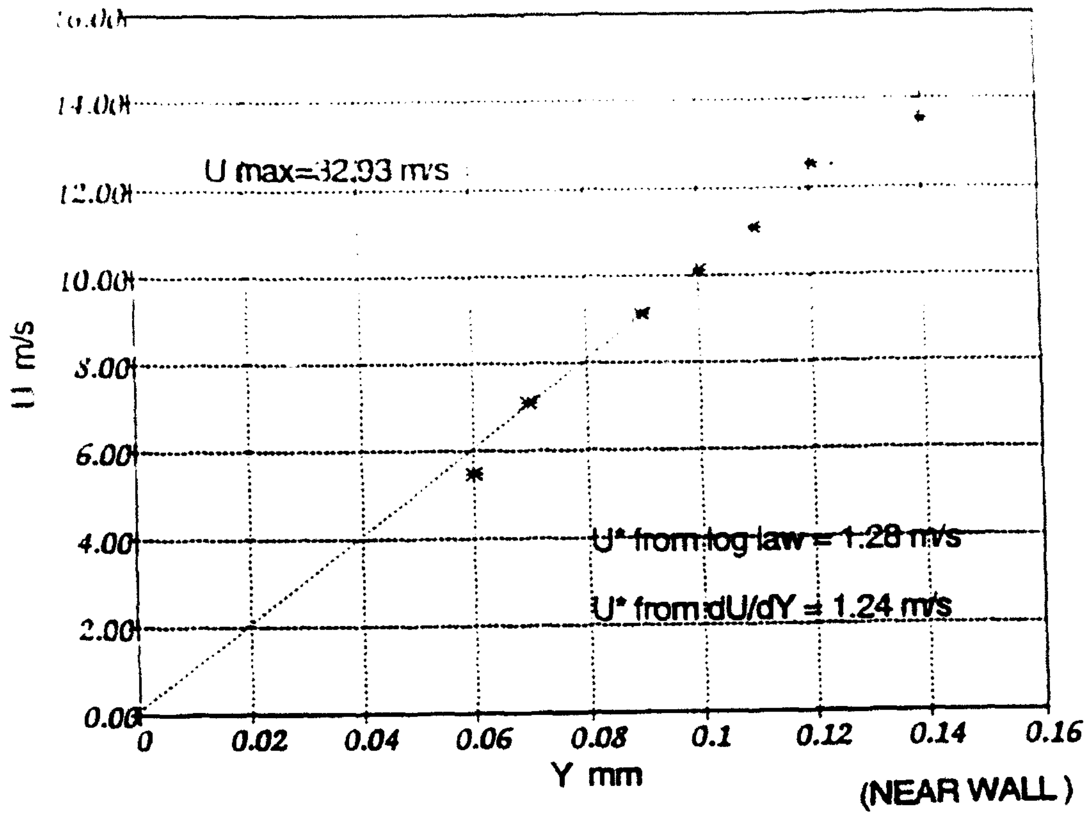


Fig. 11 Mean velocity profile Tu=15%
X=90 cm, H.W., (R&B)



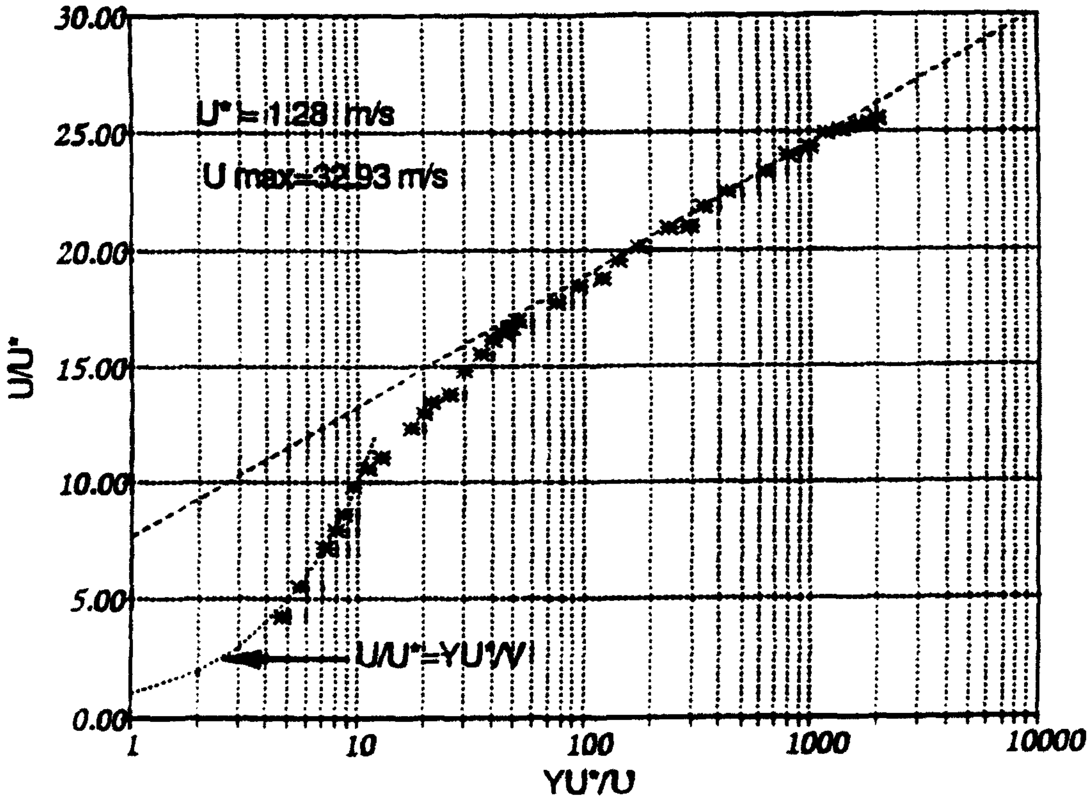
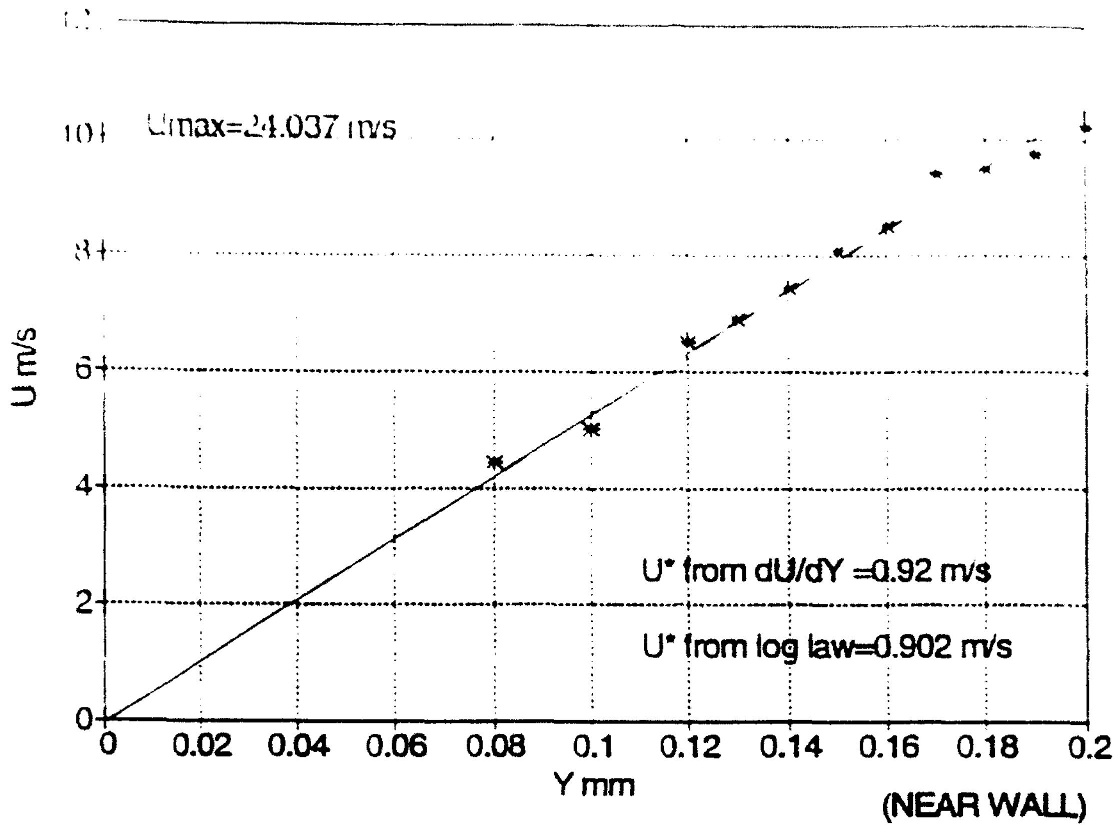


Fig. 12 Mean velocity profile, Tu=17.5%
X=114.3 cm, H.W., (R&B)



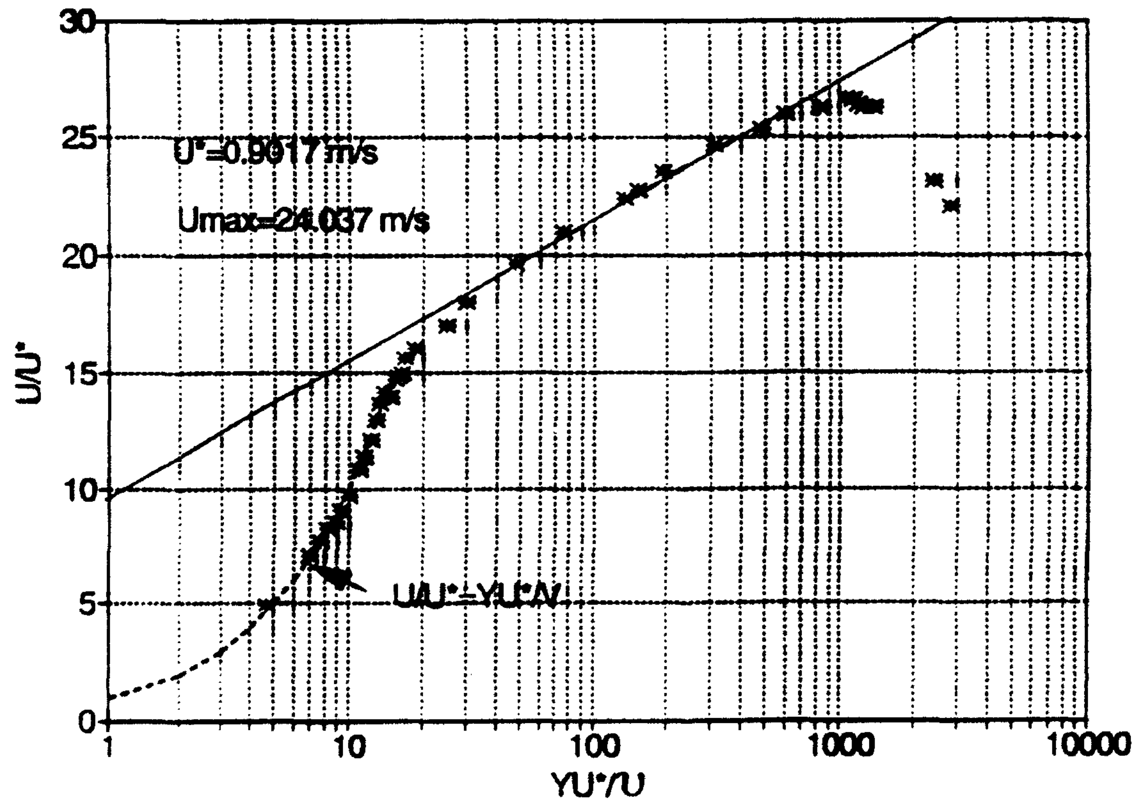


Fig. 13 Mean velocity profile, Tu=19%
X= 183 cm, H.W., (R&B)

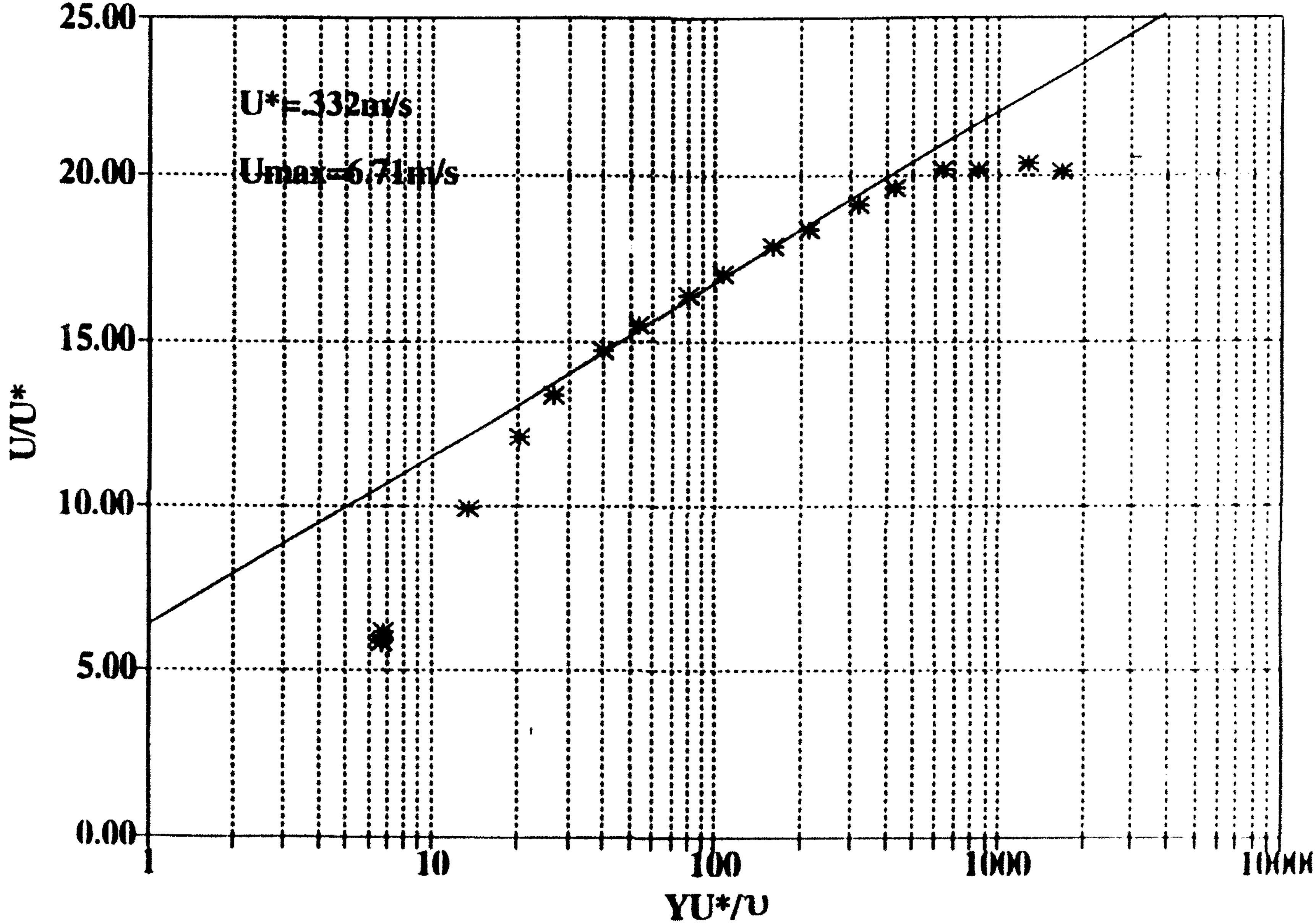


Fig. 14 Mean velocity profile, Tu=13.6%
X=40cm, H.W.,(PA)

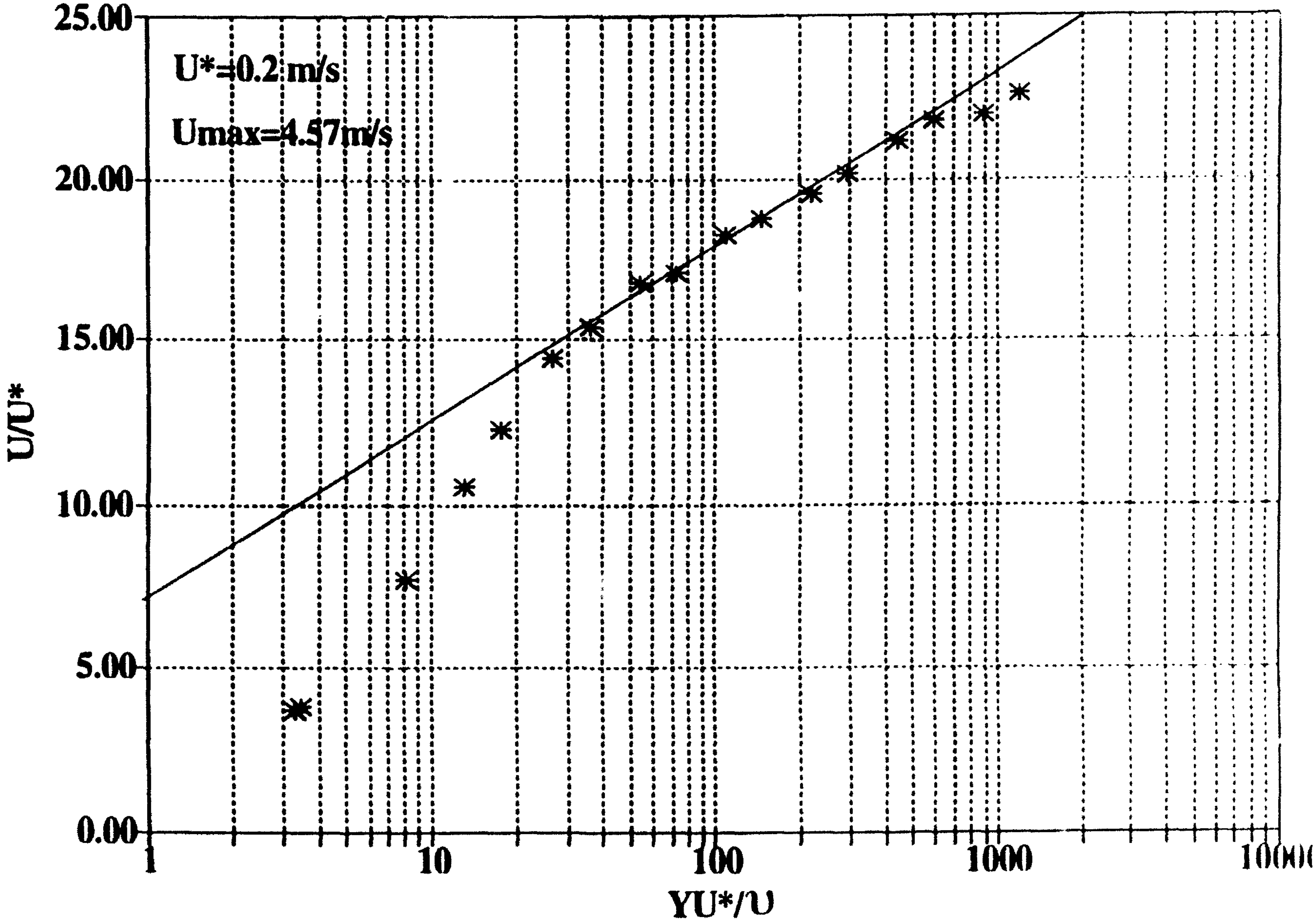


Fig.15 Mean velocity profile, Tu=15.8%
X=220cm, H.W., (PA)

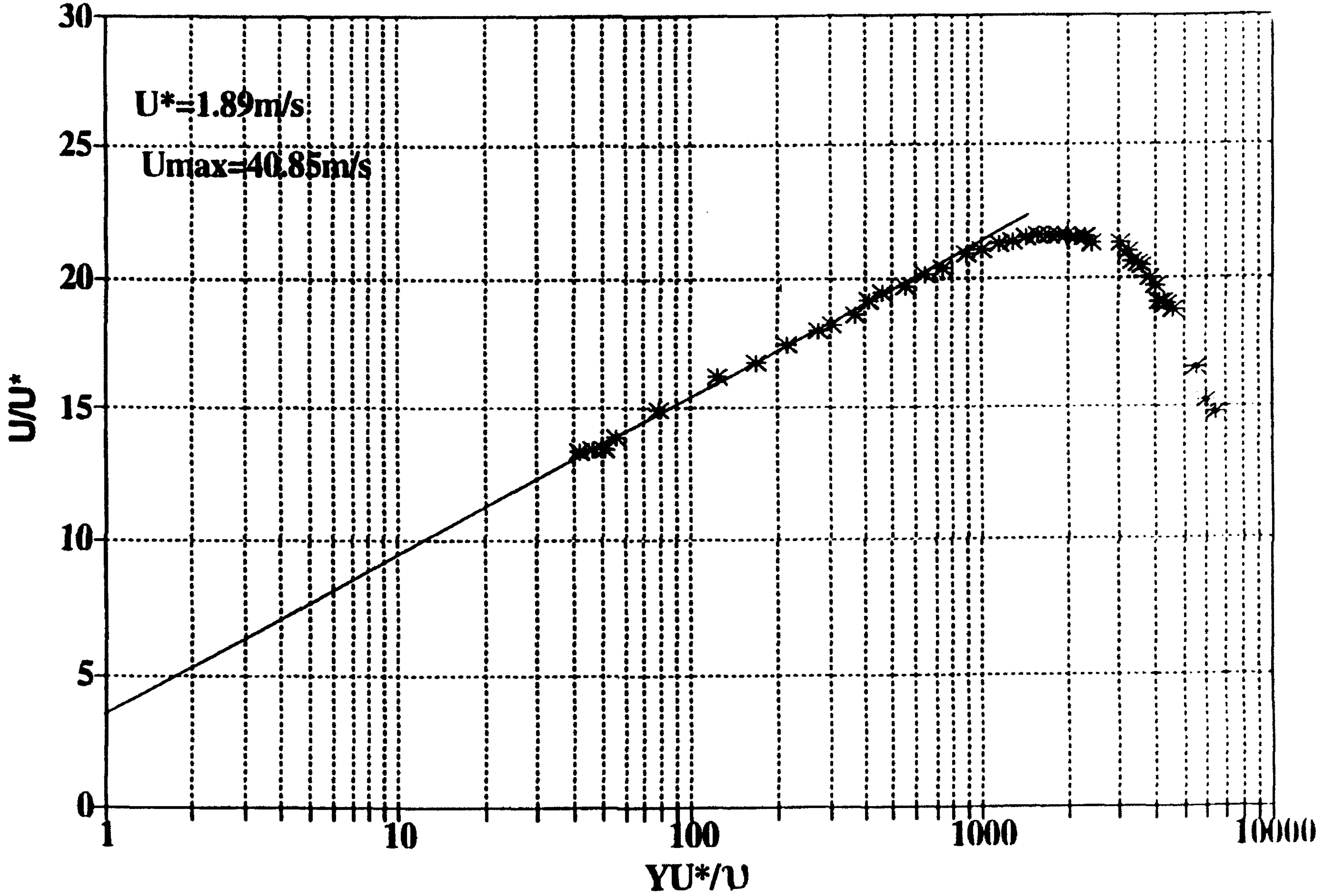


Fig. 16 Mean velocity profile Tu=5%
X=25cm, pitot tube, (R&B)

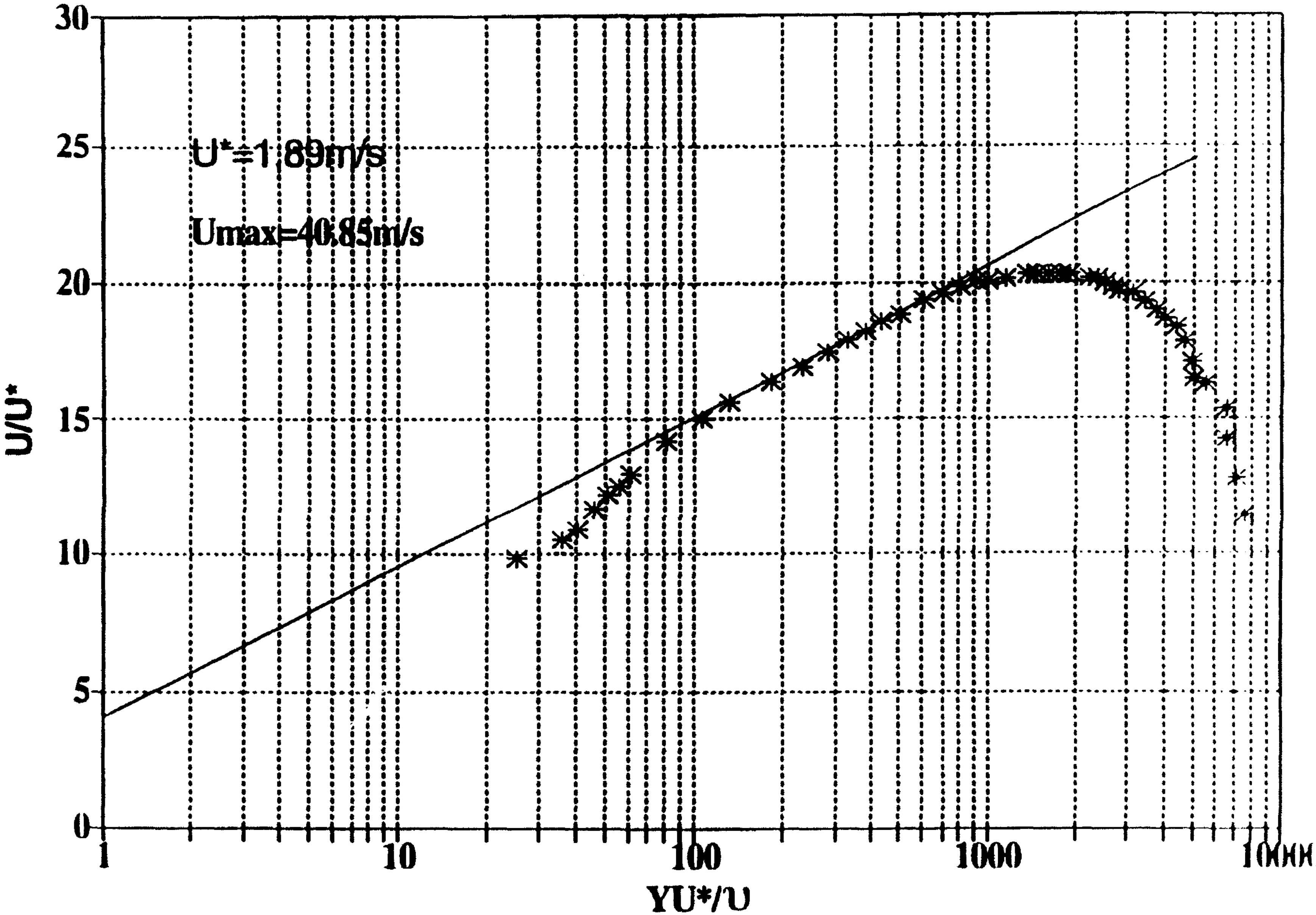


Fig. 17 Mean velocity profile Tu=7.5%
X=38cm, pitot tube, (R&B)

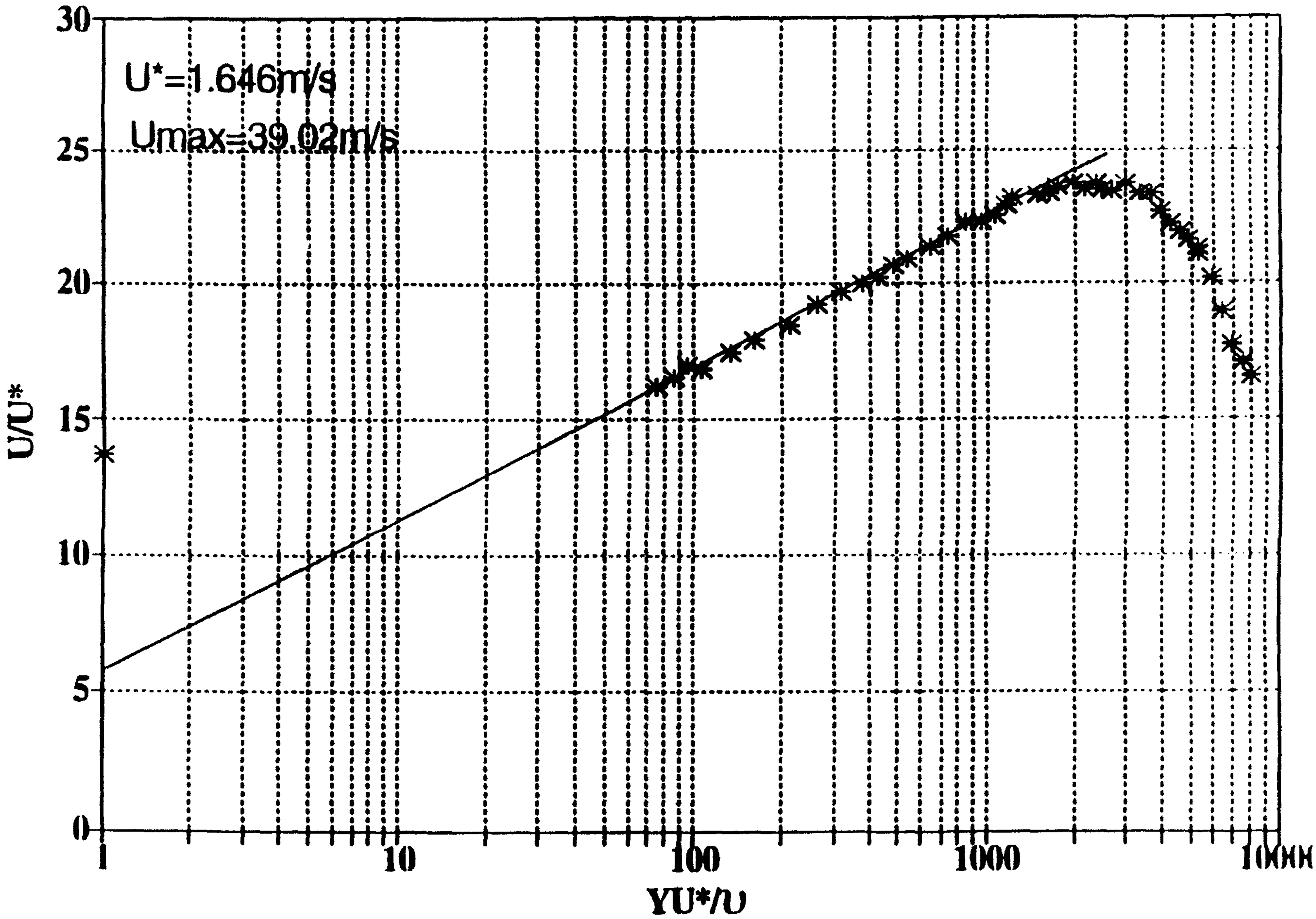


Fig. 18 Mean velocity profile Tu=10%
X=50.8cm, pitot tube, (R&B)

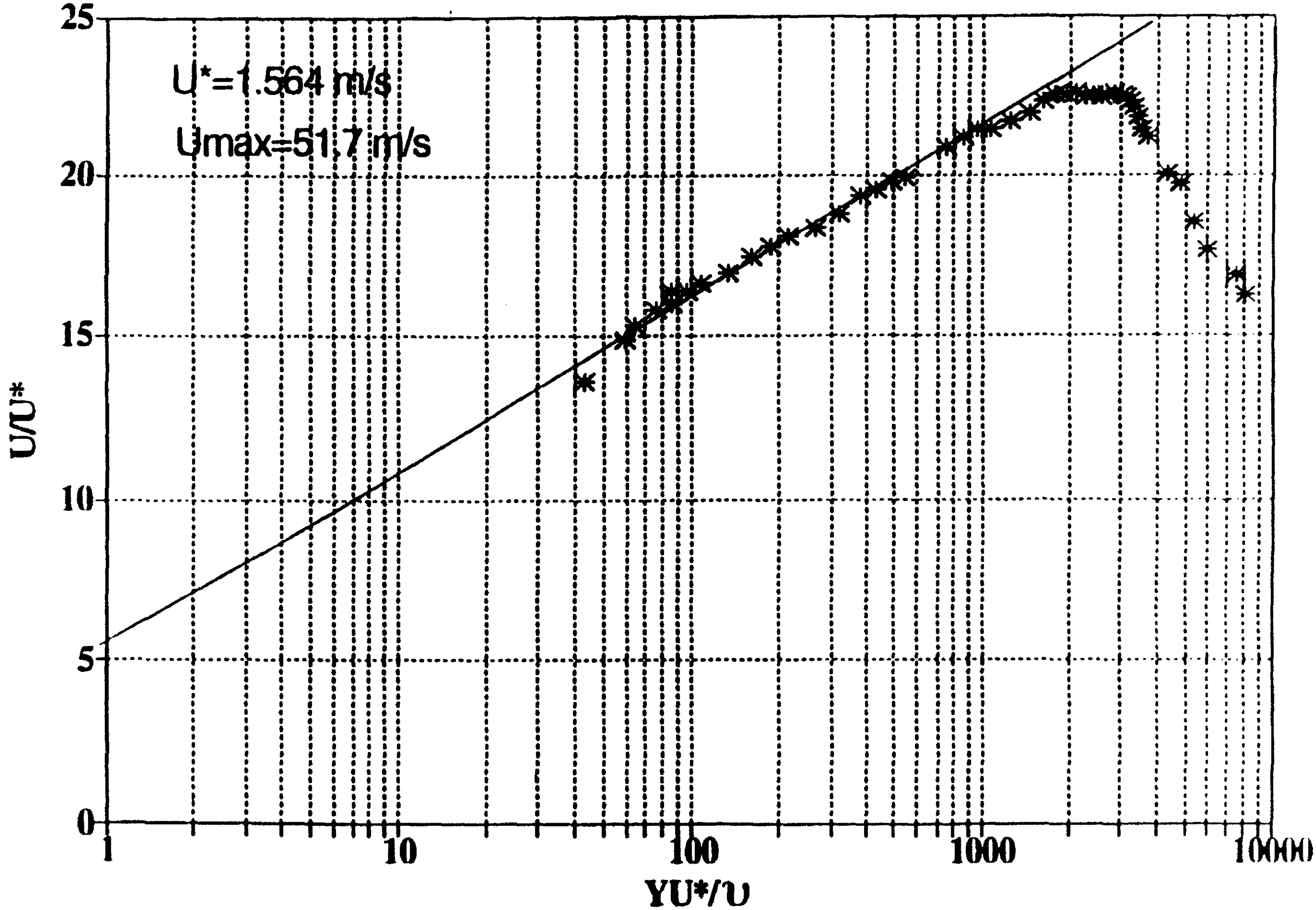


**Fig. 19 Mean velocity profile,Tu=12%
X=63.5cm, pitot tube,(R&B)**

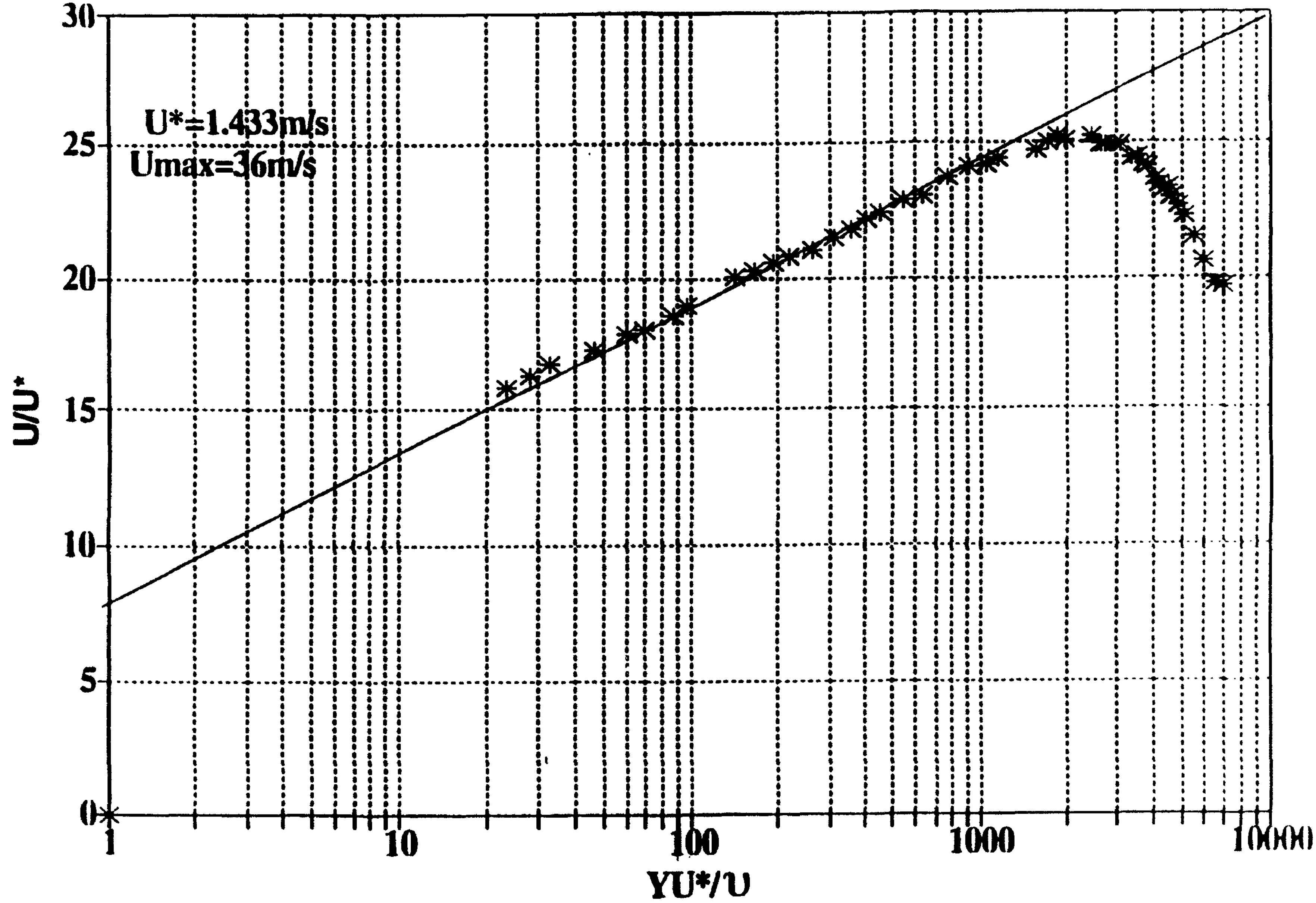


Fig. 20 Mean velocity profile Tu=15%
X=89cm, pitot tube, (R&D)

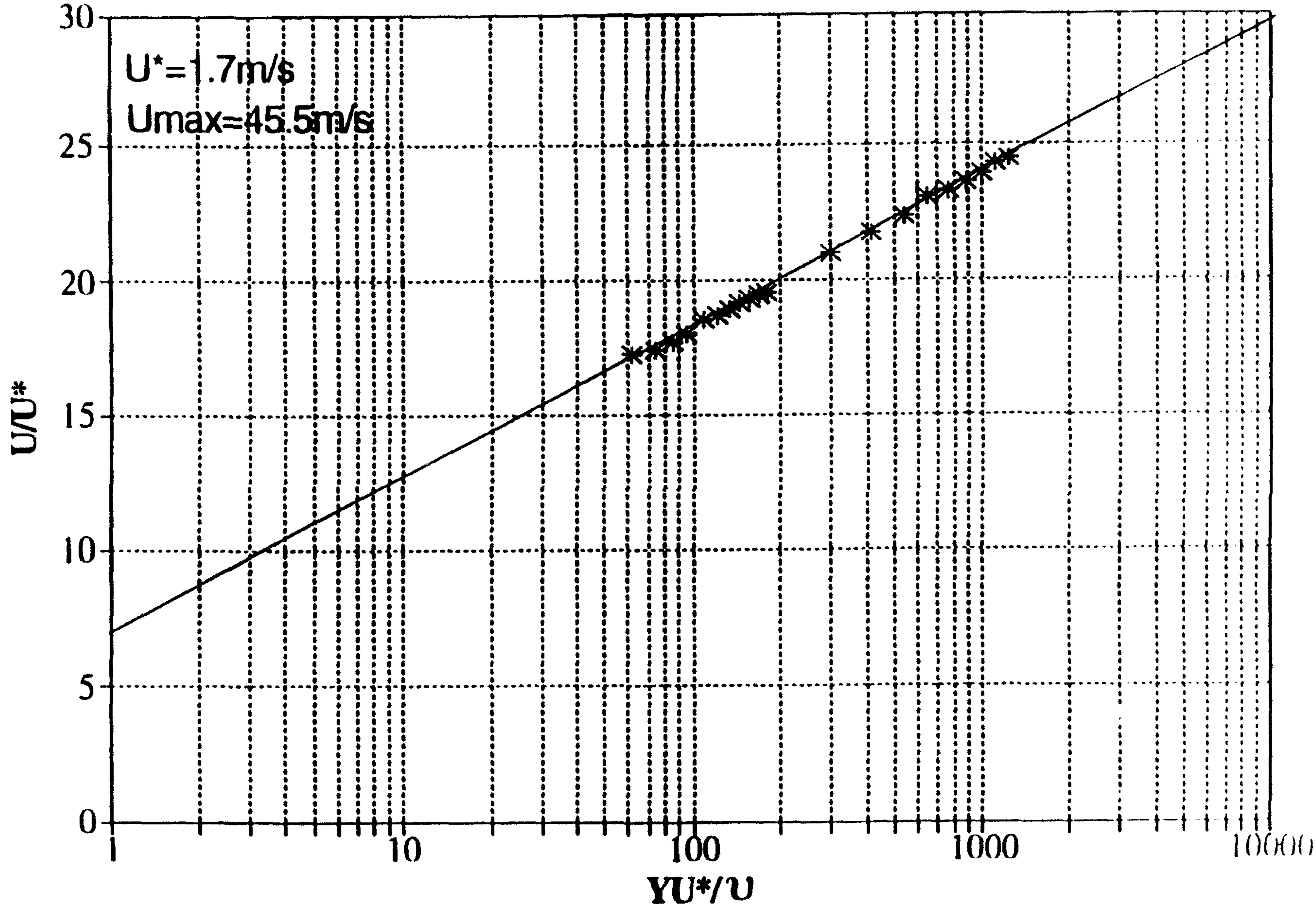


FIG. 21 Mean velocity profile Tu=15.5%
X=96.8cm, pitot tube, (R&D)

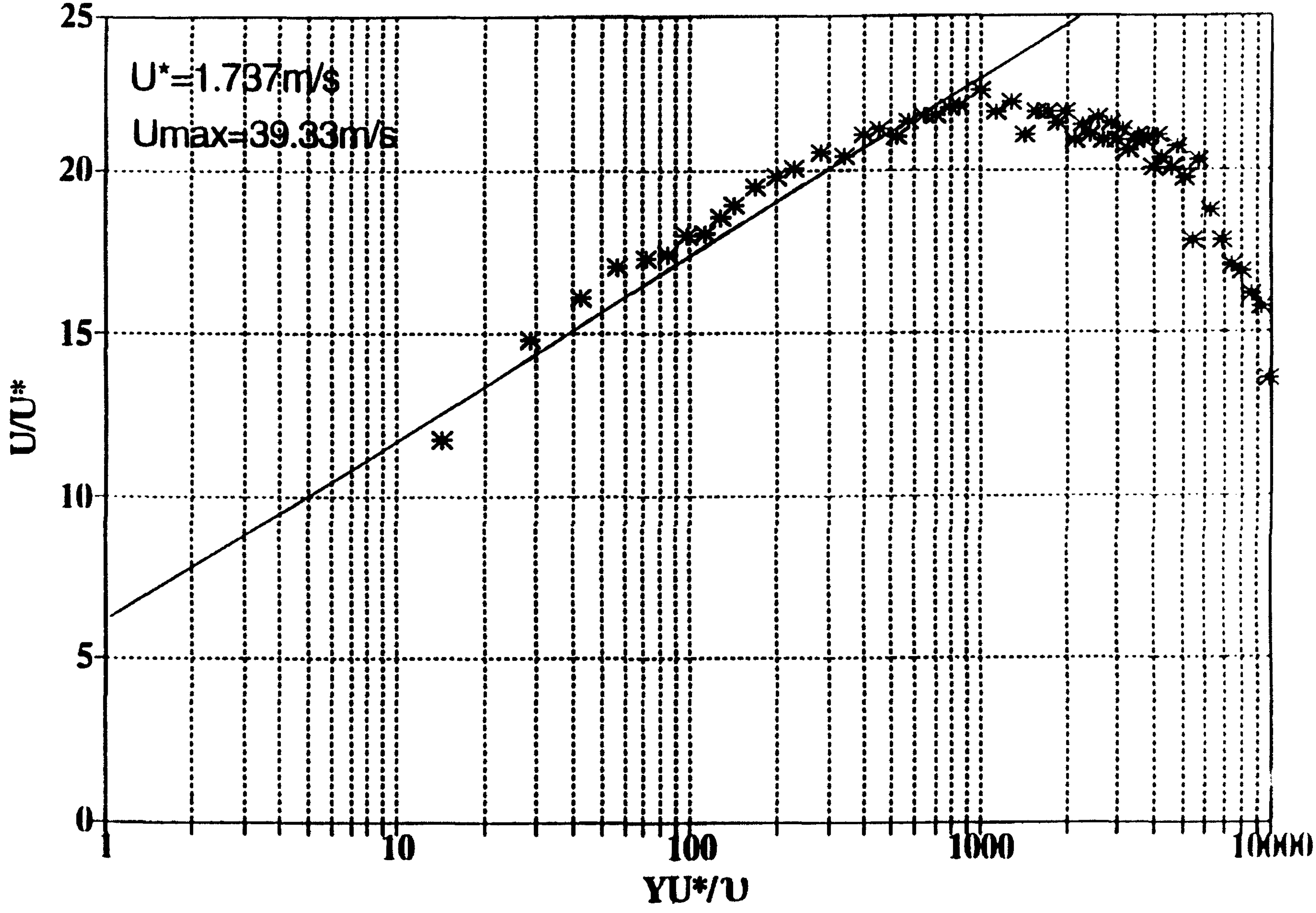


FIG. 22 Mean velocity profile Tu=10%
X=52.1cm, LDA, (R&D)

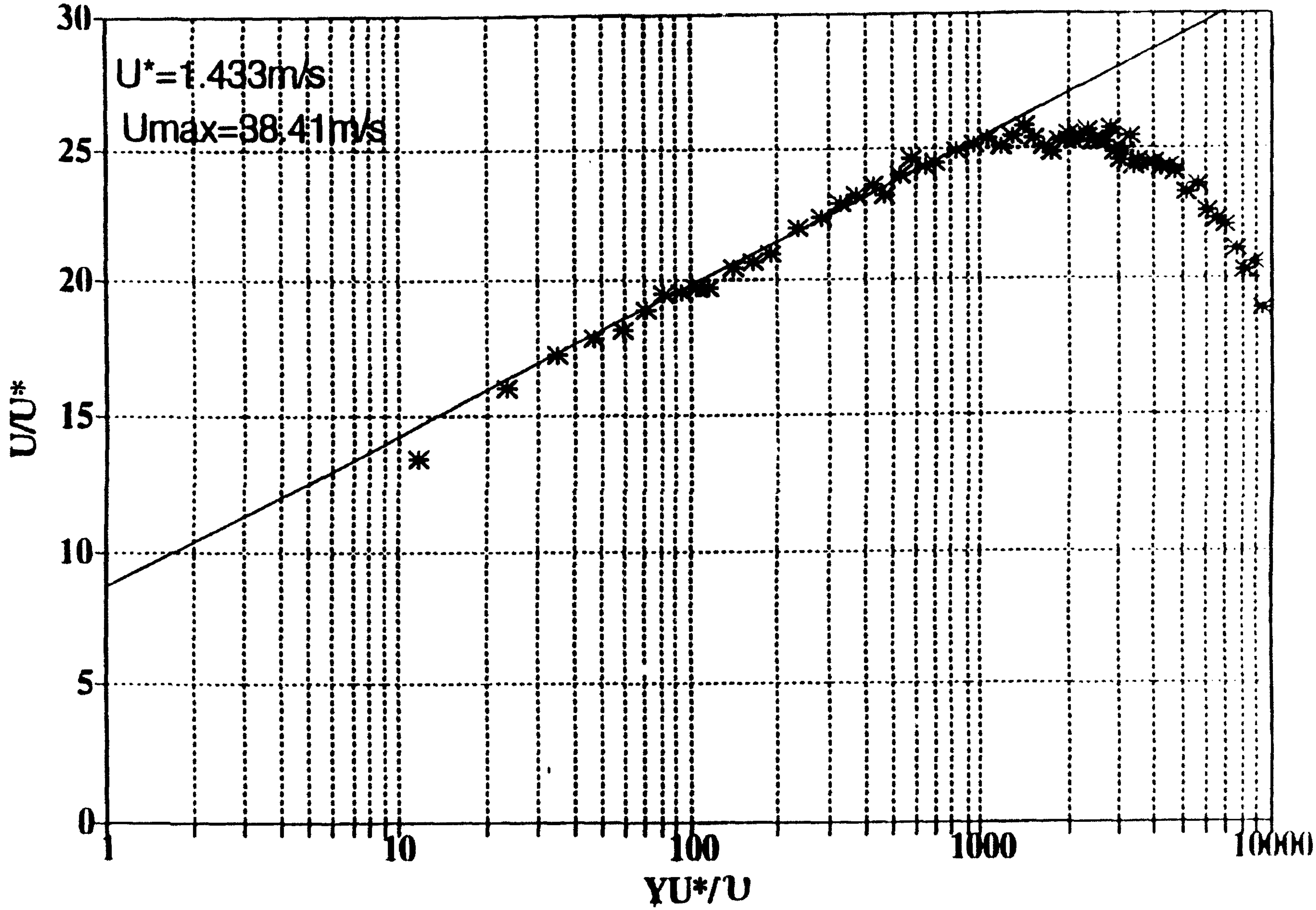


Fig. 23 Mean velocity profile Tu=16%
X=101.6cm, LDA, (R&E)

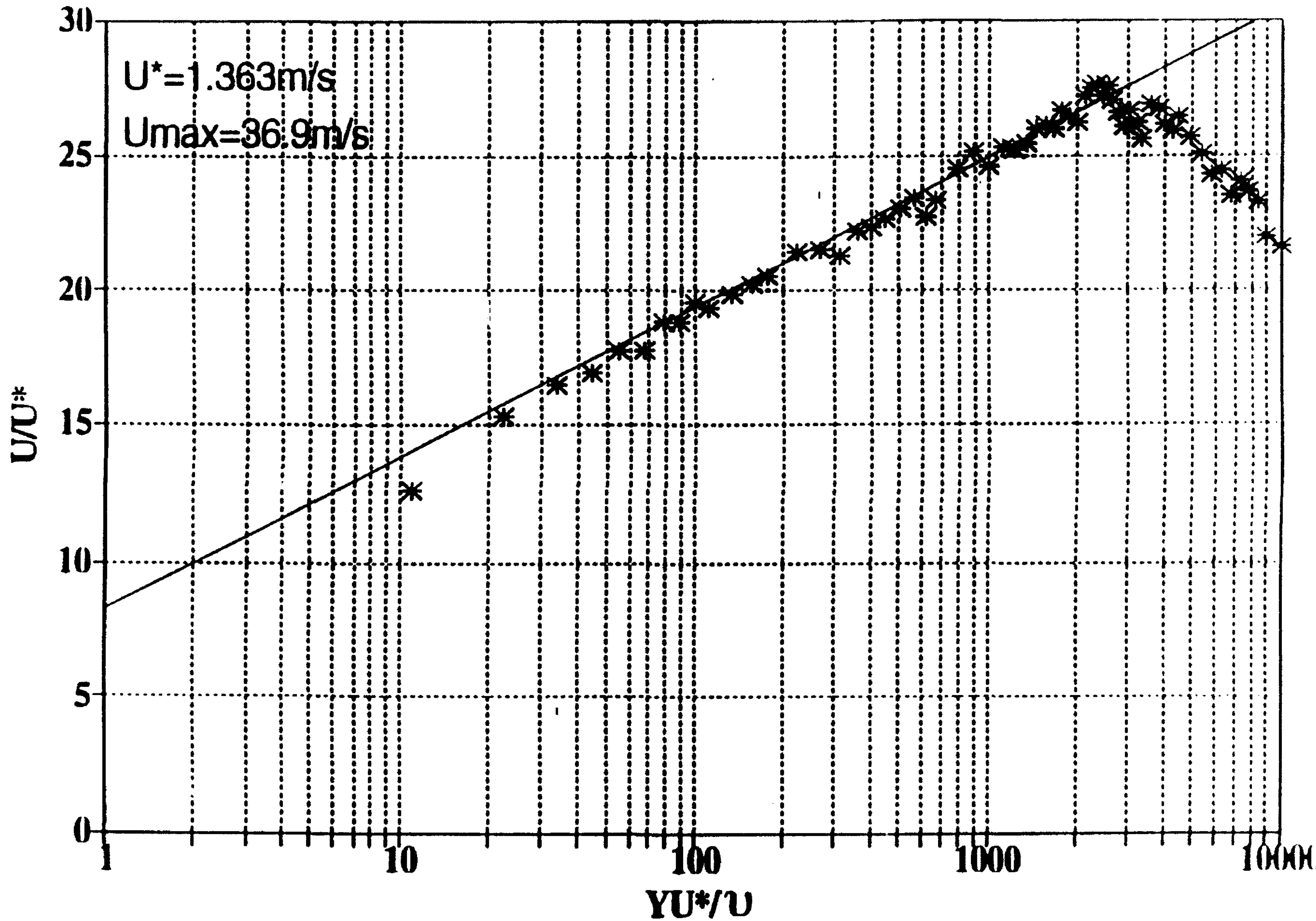


FIG. 24 Mean velocity profile Tu=18%
X=162.6cm, LDA, (R&D)

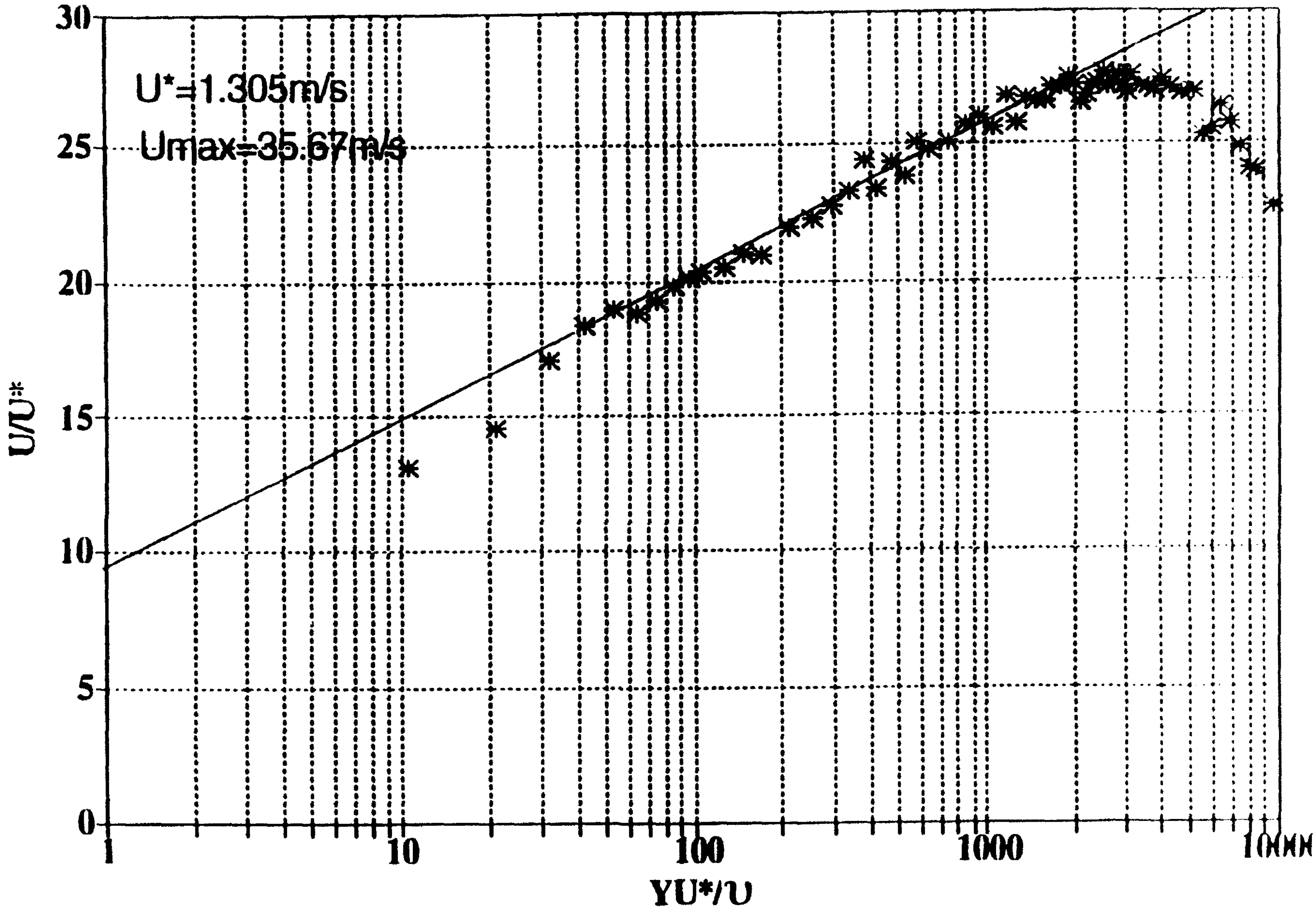


FIG. 25 MEAN VELOCITY PROFILE Tu=18%
X=175.5cm---(R&E)--LDA

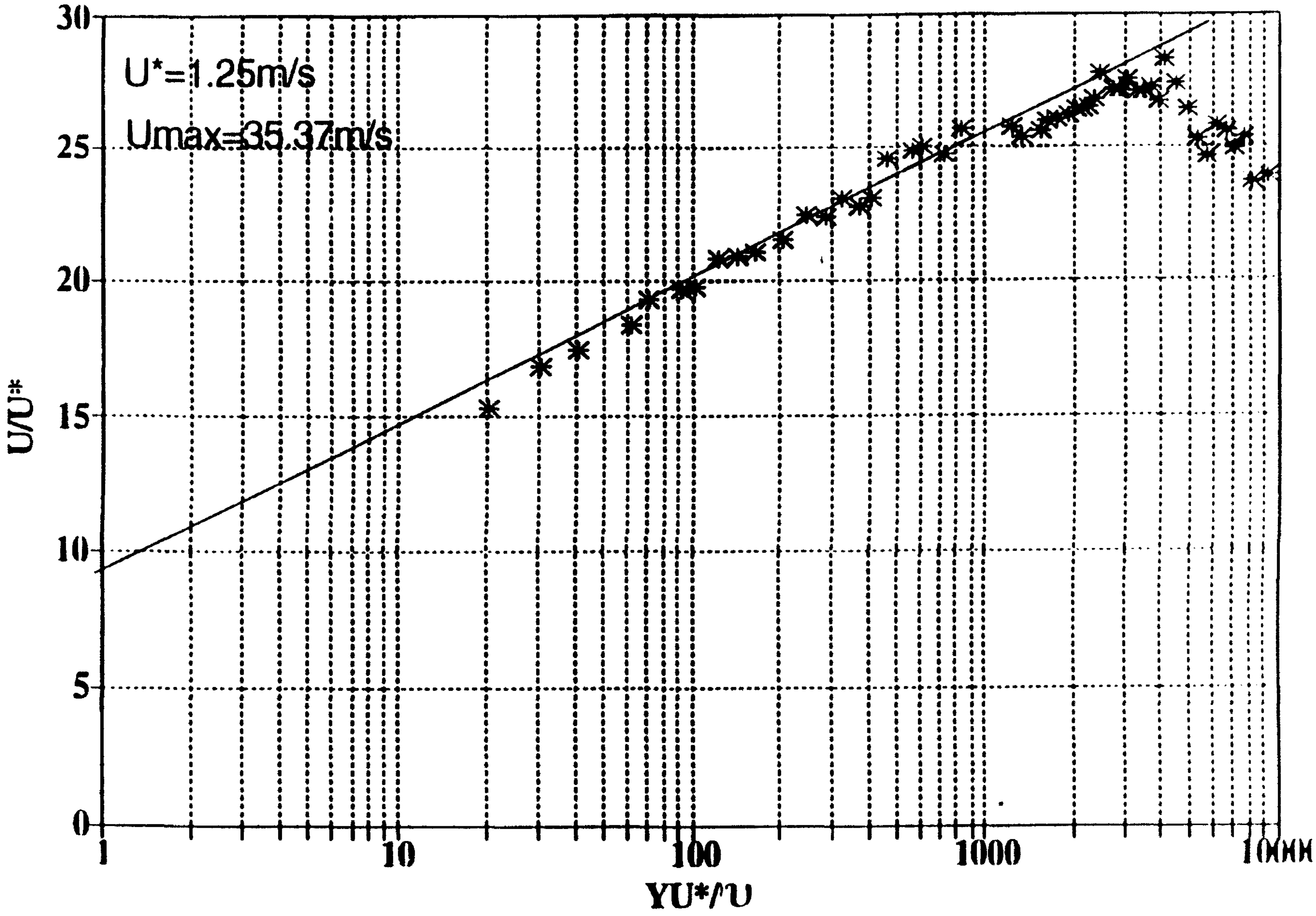


FIG. 26 Mean velocity profile Tu=19.2%
X=200.6cm, LDA, (R&E)

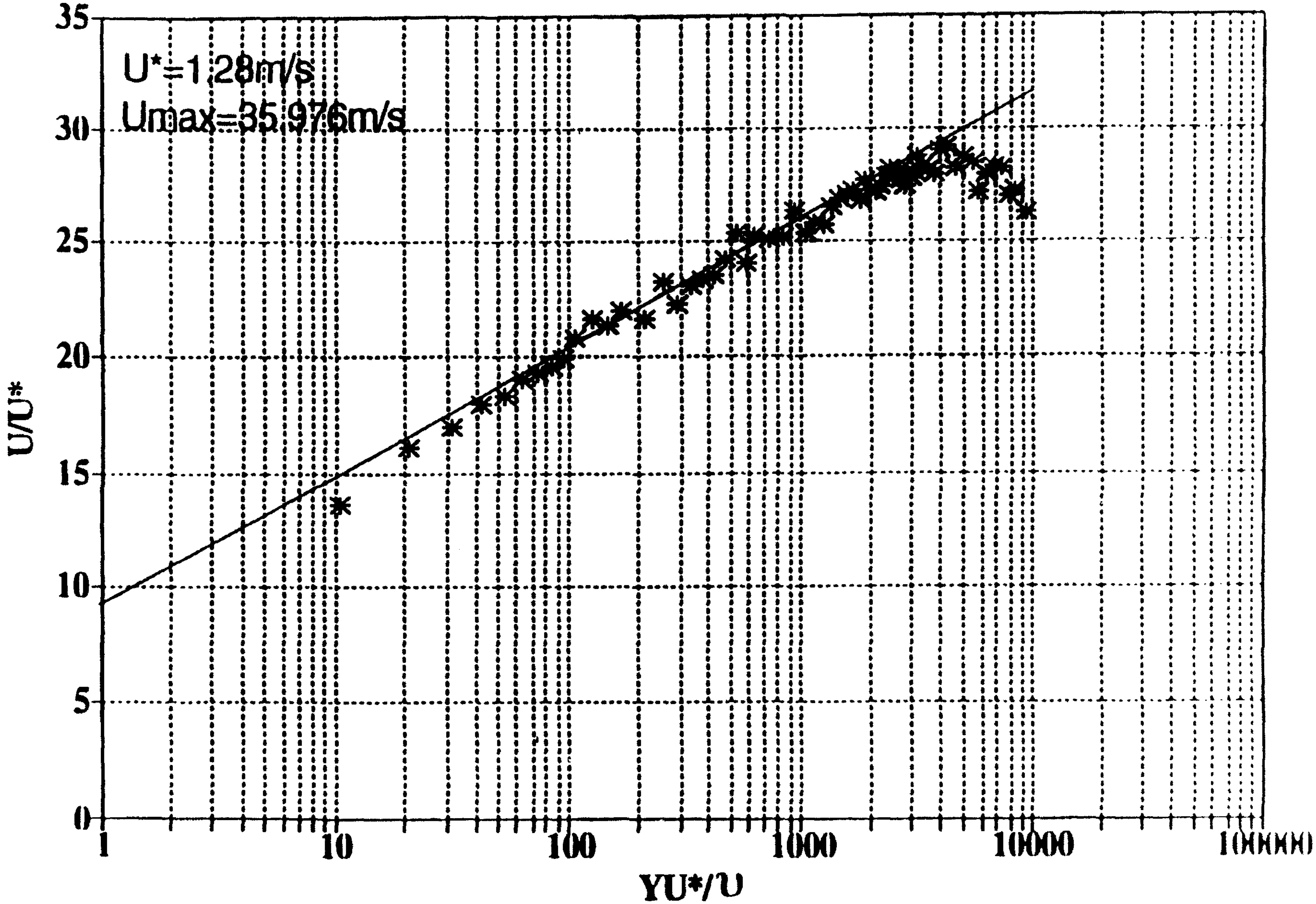


FIG. 27 Mean velocity profile Tu=22%
X=302cm, LDA, (R&E)

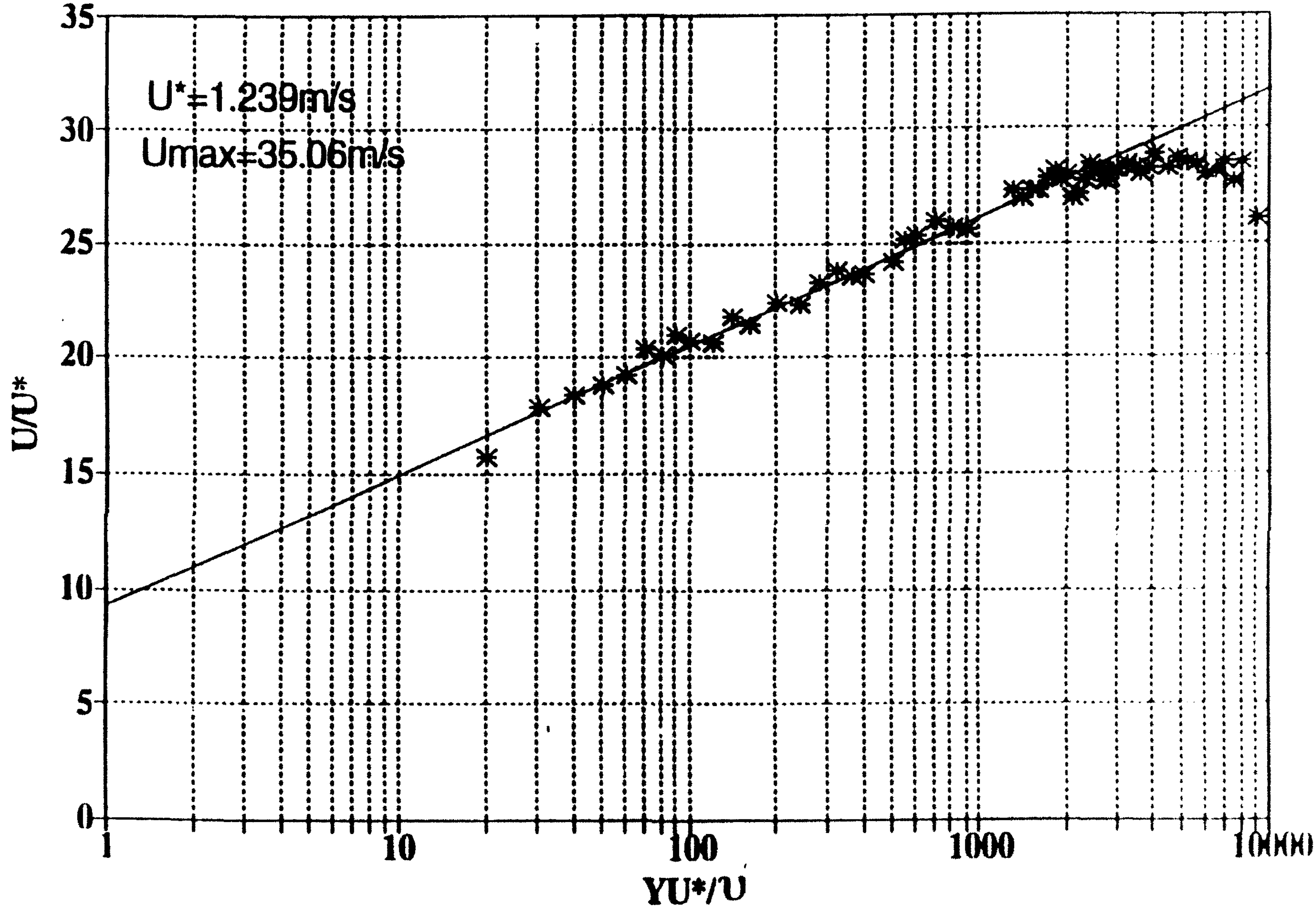


FIG. 28 Mean velocity profile Tu=20%
X=353cm, LDA, (R&D)

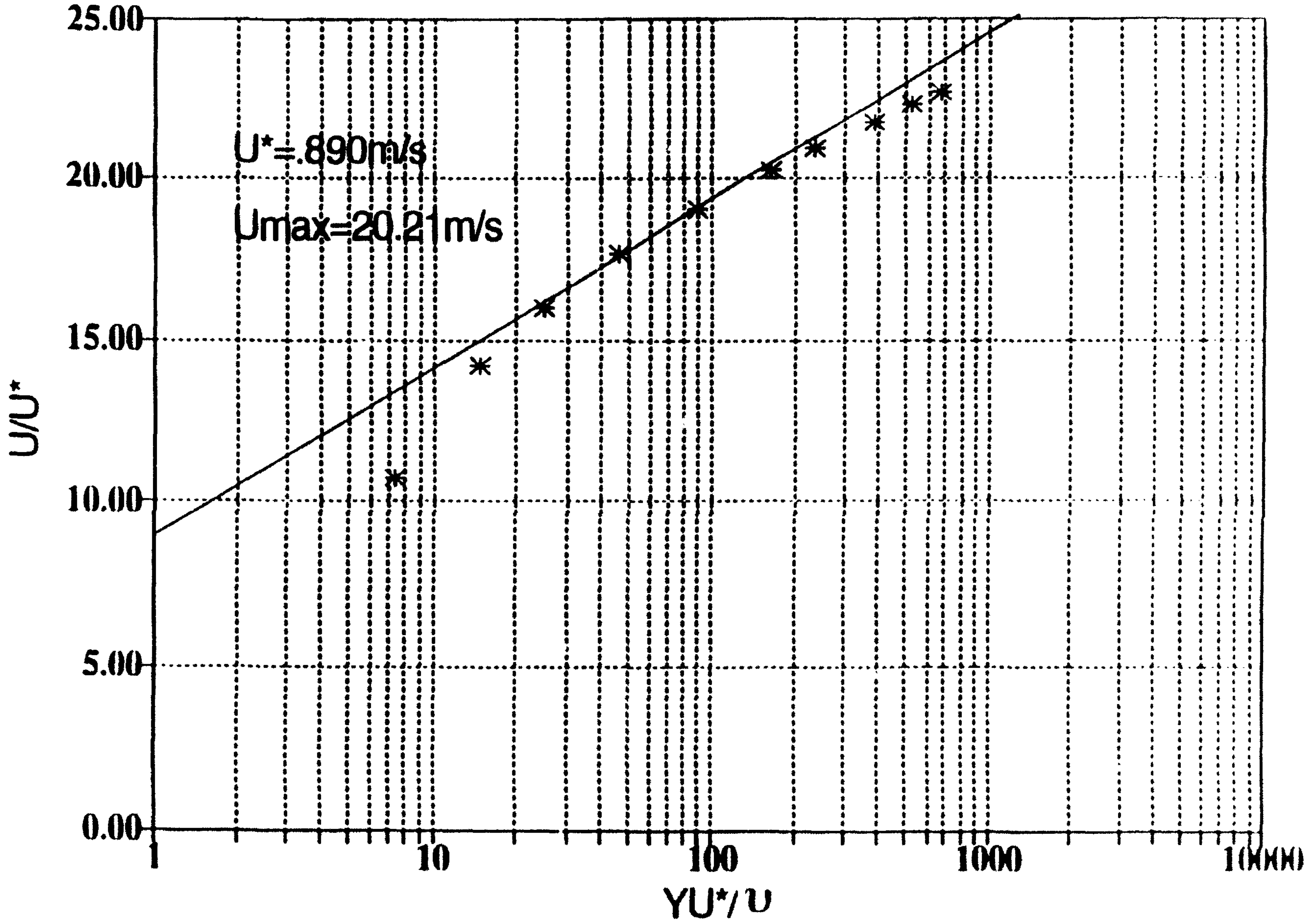
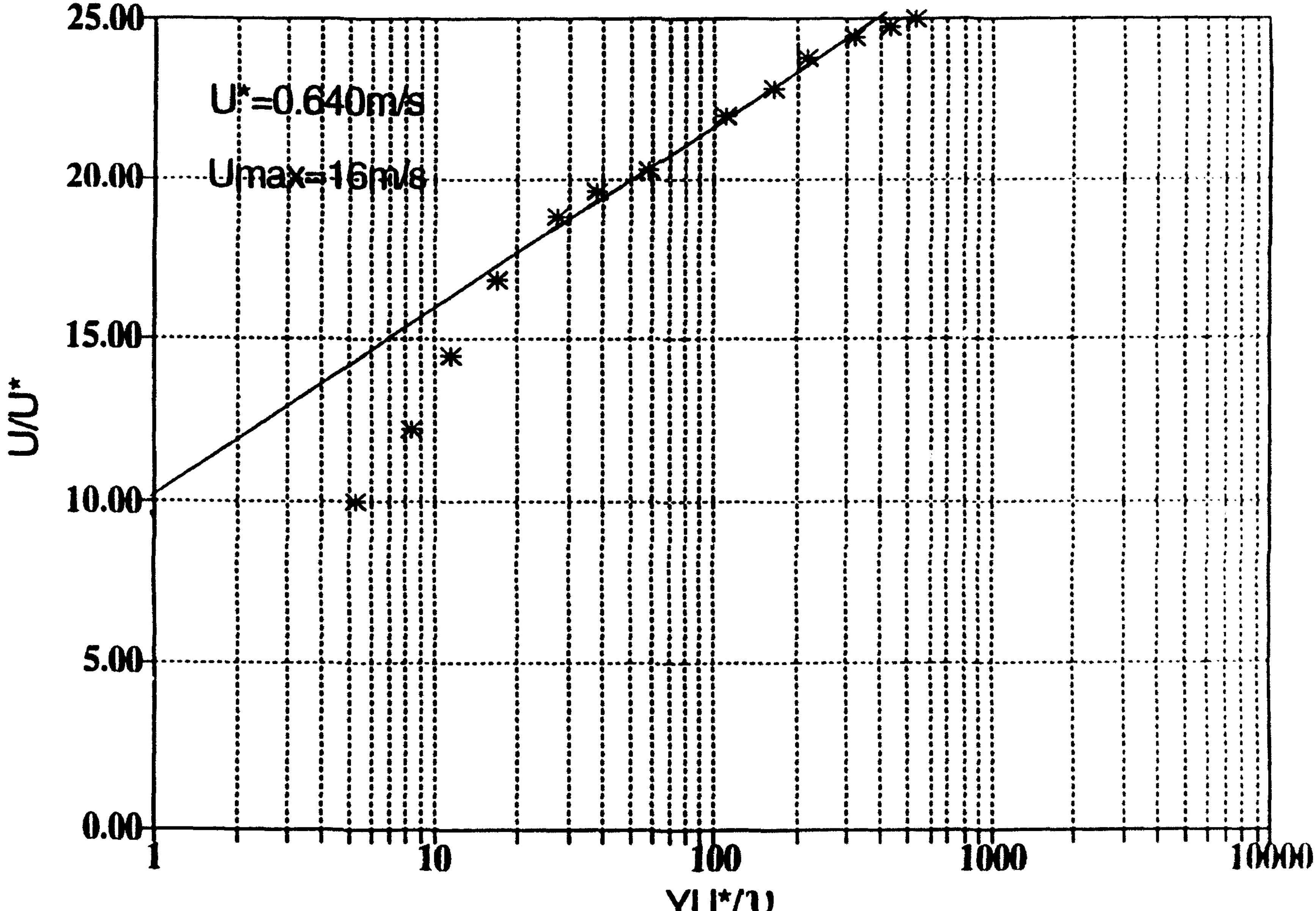


Fig. 29 Mean velocity profile, Tu~20%
X=72.6cm, pitot tube, (SCH)



Tu approximately 20 % not measured

Fig. 30 Mean velocity profile, Tu=20%
X=122cm, pitot tube, (SCH)

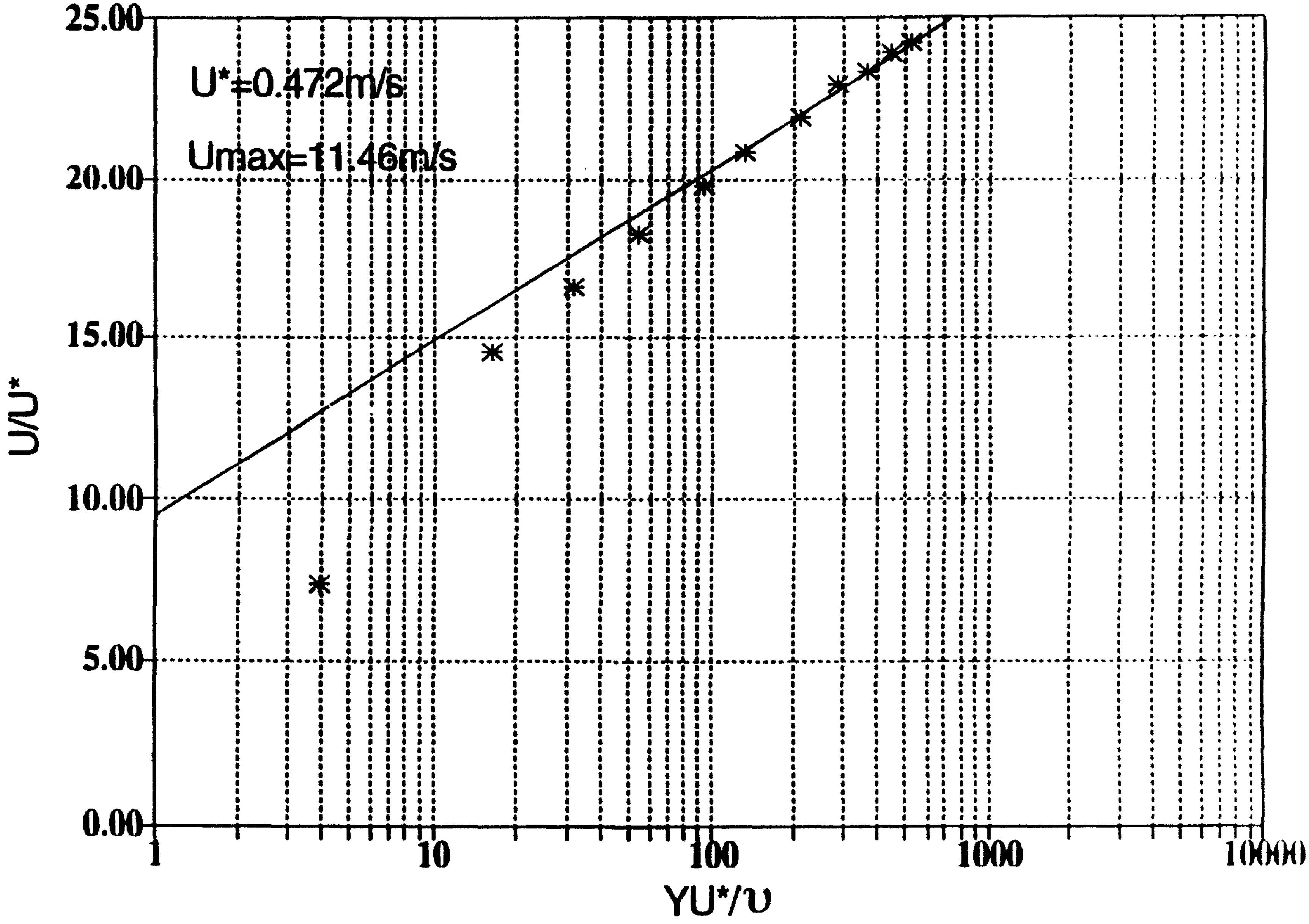


Fig. 31 Mean velocity profile, Tu~20%
X=240cm, pitot tube, (SCH)

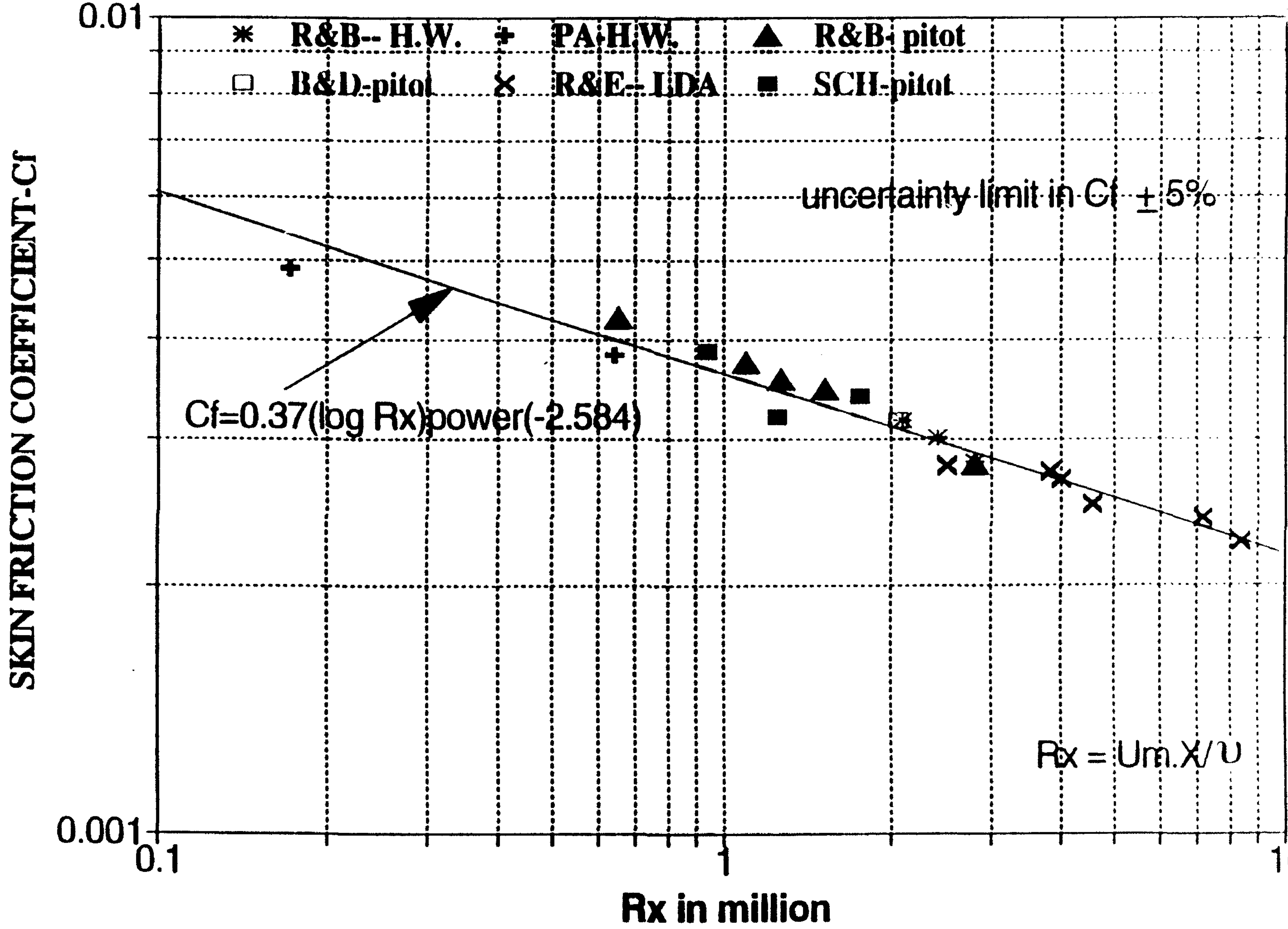


Fig. 32 Wall shear in highly turbulent flow

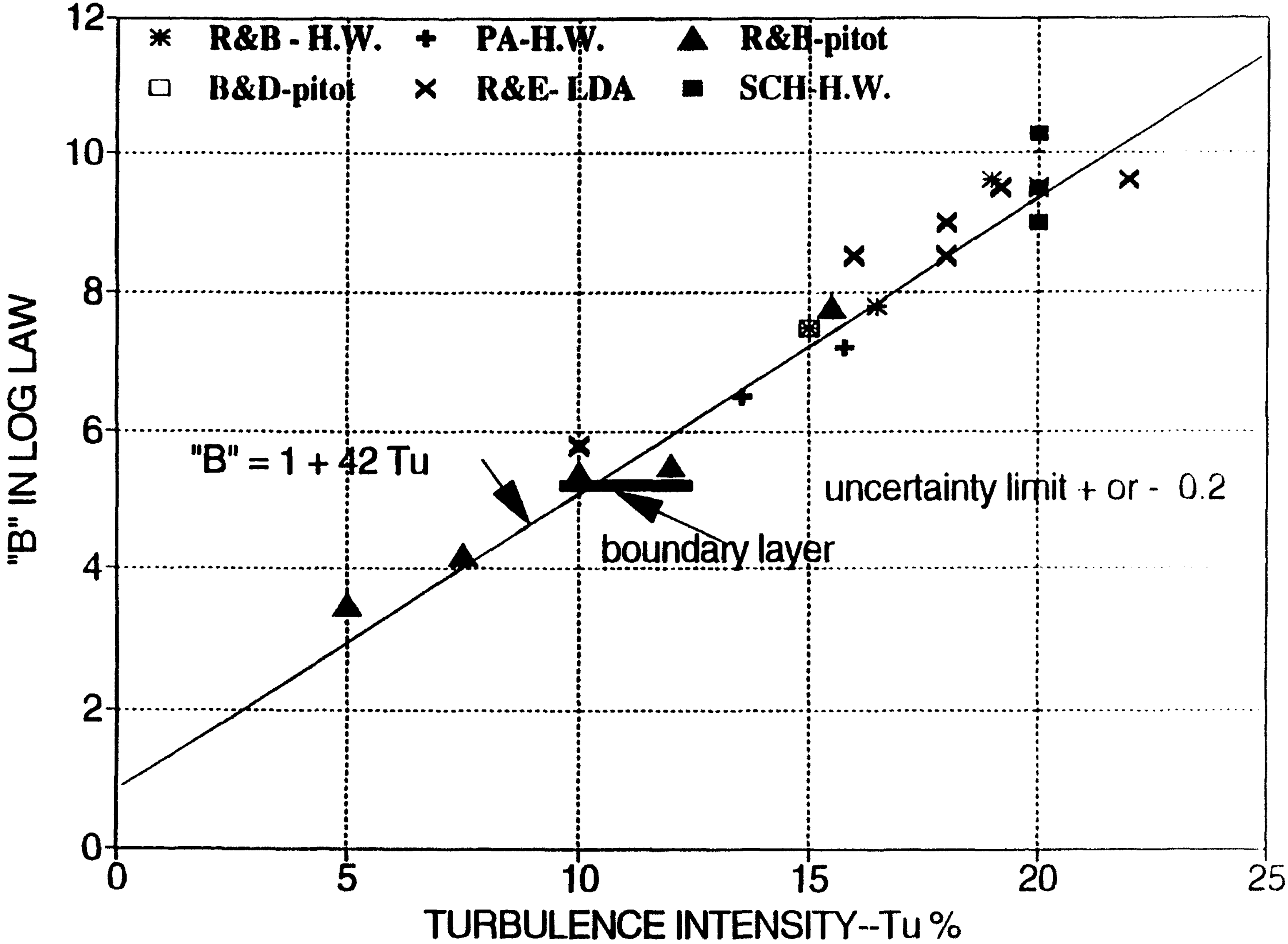


Fig. 33 Variation of "B" with turbulence intensity

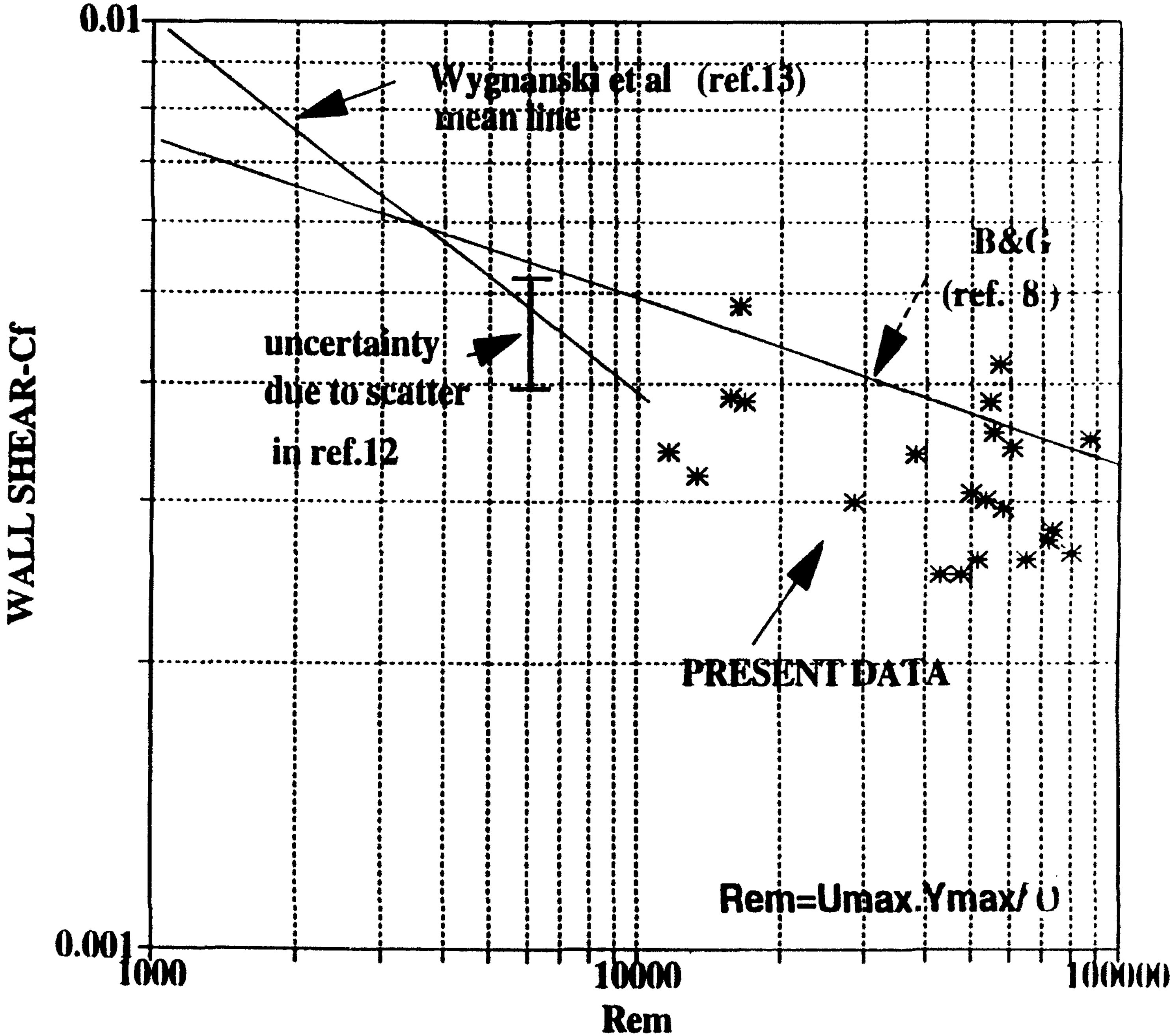


Fig. 34 Variation of skin friction with local Reynolds number