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Laser Doppler anemometer flow measurements in a channel with a wall cut-out(*)

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MEASUREMENT of horizontal velocity and turbulent intensity in a water channel with a wall cut-out are presented for two Reynolds nujmbers. The design features of the present system gives neither a fully-developed turbulent flow nor a purely two-dimensional one. In order to investigate how the flow is affected by this experimental apparatus, comparisons have been made with the previous results for turbulent flows between two parallel plates. In the wall cut-out there is the possibility of obtaining a stationary vortex which wholly emphasizes the complex nature of separated flows. A laser Doppler anemometer with frequency shift was employed because of the negative velocities in the recirculating region.

Przedstawiono pomiary prędkości poziomej i intensywności turbulencji w kanale cieczowym z wycięciem w ściance dla dwóch liczb Reynoldsa. Charakter zaprojektowanego urządzenia nie daje ani w pełni rozwiniętego przepływu turbulentnego, ani przepływu czysto dwuwymiarowego. Aby zbadać jaki wpływ wywiera ten przyrząd doświadczalny na przepływ, porównano go z wynikami wcześniejszymi dla przepływów turbulentnych między dwoma równoległymi płytami. W wycięciu ścianki istnieje możliwość otrzymania stacjonarnego wiru, który całkowicie uwzględnia złożoną naturę odrywanych strug. Dopplerowski manometr laserowy z przesunięciem częstotliwości zastosowano z uwagi na ujemne prędkości w obszarze recyrkulacji.

Представлены измерения горизонтальной скорости и интенсивности турбулентности в жидком канале, с вырезом в стенке, для двух чисел Рейнольдса. Характер проектированного устройства не дает ни вполне развернутого турбулентного течения, ни чисто двумерного течения. Чтобы исследовать какое влияние оказывает этот экспериментальный прибор на течение, оно сравнено с более ранними результатами для турбулентных течений между двумя параллельными пластинками. В вырезе стенки существует возможность получения стационарного вихря, который полностью учитывает сложную природу оторванных струй. Допплеровский лазерный манометр со сдвигом частоты применен из-за отрицательных скоростей в области рециркуляции.

Nomenclature

λ	wavelength of laser light,
ν	kinematic viscosity,
θ	beams' angle,
d	cavity dimension,
D	channel dimension,
f_d	Doppler frequency,
Re_C	cavity Reynolds number, $(U_0 d)/\nu$,
Re_{CH}	channel Reynolds number, $(U_0 D)/2\nu$,
U	time average streamwise velocity,
U'	turbulent streamwise velocity fluctuation,
X_d	streamwise distance.

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1. Introduction

THE STUDY of flows involving separated regions has been the subject of many investigations in recent times. The phenomenon of separation is associated with the formation of unsteady vortices. The study has a complex nature both from the numerical and experimental point of view. The flow over a cut-out allows one to describe a first approximation of the flow in the presence of boundary irregularities, namely the interaction between the boundary layer and the recirculating region. In this case the vortex generated is stationary and thus investigation into it is easier. Nonetheless, the complex nature of the separated flow is emphasized.

Many numerical [1, 2] and experimental [3, 4] studies have been carried out. Roshko carried out velocity and pressure measurements in a rectangular cavity on the floor of a wind tunnel, varying depth-breadth ratio. His work pointed out that the drag due to the cavity issues mainly from the high pressure on the downstream edge, and that there is a momentum transport into the cavity.

Haugen's study is an analytical and experimental work aimed at delineating the turbulent momentum transfer mechanism in the mixing zone of the cavity. The prominent aspect of his results are: both the turbulence and the local shear stress are maximum at a point coinciding with the dividing stream line, and they are quite sensitive to change in the relative thickness of the approaching boundary layer.

The present study is a purely experimental work aimed at measuring the velocity and the turbulent intensity in the mixing zone of the cavity and inside this cavity. The measurements were performed at different cavity Reynolds numbers $\mathrm{Re}_C = 3340$ and $\mathrm{Re}_C = 5080$.

2. Experimental apparatus

The experimental apparatus consists of a water channel illustrated in Fig. 1. Two resevoirs at constant level feed the channel, the water goes through a divergent into a plenum chamber where a honeycomb suppresses the large scale vortices generated in the feed pipe; the water goes into the channel through a convergent. The underlined design gives a significant reduction in the length necessary for the full developement of the mean flow and of the turbulence structure, as well as the removal of any upstream originated large scale structure.

The channel has a square cross-section with the inside dimension of the edge equal to 10 cm, the developing flow length is 30 times the width of the channel cross-section. Two questions arise in relation to this configuration: a) on front of the cavity is the turbulent flow fully developed? b) is the flow two-dimensional? Depending on which kinds of measurements are needed, different answers can be given to the first question. A duct flow is said to be fully developed for $\mathrm{Re} > 3000$ and for $X_d/D = 20$ to 40 if the objective is only to know the friction factor. For two-dimensional ducts a state of fully developed turbulent structure may not be achieved until X_d/D exceeds a value of 80 for a high Reynolds number. The best rule in order to know if the fully developed turbulent flow is reached, is to see if the turbulent intensity at a given X_d/D station does not change with X_d/D. In

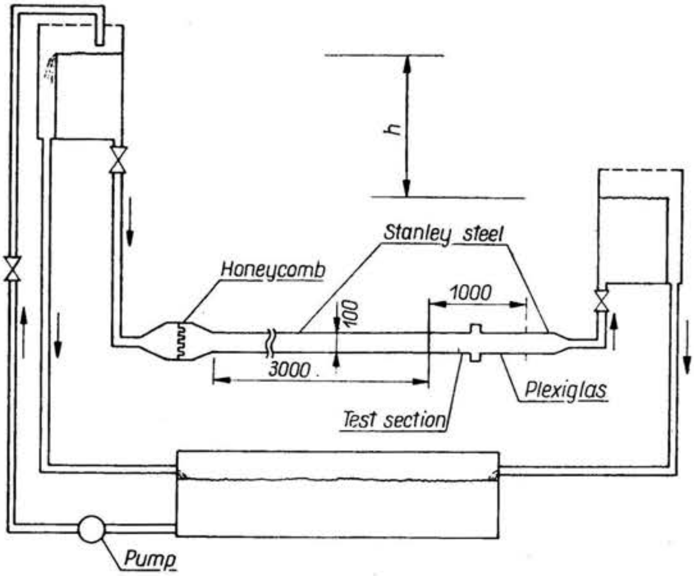

FIG. 1. Experimental apparatus.

the channel used here not even one of the three rules is completely respected. The turbulent intensity profiles measured at a section $X_d/D = 30$ have been compared to those at a section $X_d/D = 29$; there is only a week difference near the wall but this is not so important because of the research being aimed at delineating the effect of the cavity on the boundary layer thickness and measuring the quantities inside the cavity.

The answer to the second question is that the flow is not two-dimensional in a square channel. A secondary flow of Prandtl's second kind is generated, that is a flow driven by gradients of $U_i' U_j'$. This secondary flow moves inward along the corner bisector and tends to sweep the isovels (lines of constant U) towards the corner. This effect is emphasized at a short distance from the inlet and is attenuated at high values of X_d/D, at a value of $X_d/D = 30$ the symmetry of the flow is satisfactory [5].

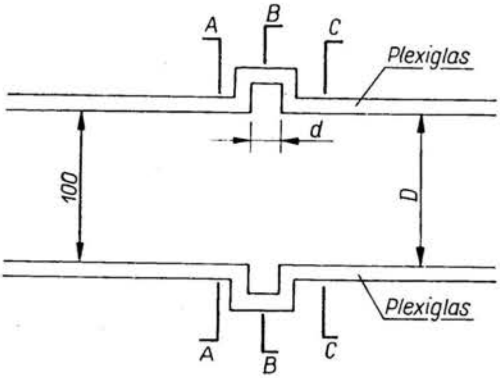

FIG. 2. Test section.

It can be concluded that the turbulent flow in front of the cavity is neither completely developed nor purely two-dimensional with this apparatus, but it reaches a condition satisfactory enough to investigate the interrelation between the boundary layer and the recirculating flow inside the cavity and its effects on the thickness of the boundary layer.

Figure 2 shows the test section made of plexiglas, where cut-outs are made on the upper and bottom floor, thus any source of asymmetry being eliminated. The cavity has a height and width of 2 cm, thus it has an aspect ratio equal to 5, giving inside it a flow near to a two-dimensional condition with respect to the external one.

3. Laser anemometer instrumentation

The advantages of the laser anemometry consists in the fact that it has a linear response to one component of the velocity. The relation between the velocity and the Doppler frequency is

$$U = f_d \lambda/2 \sin\theta/2.$$

The LDA does not disturb the flow and it is particulary relevant when measurements in water flows are requested, where the transported particles are needed to scatter the incident beams. On the contrary the hot-film anemometer requires clean water. The hot-film has a nonlinear response, it must be calibrated. It could disturb the flow if the measurements were performed in small regions like the cavity considered here. If measurements in recirculating regions are carried out, the hot-film will need special arrangements, while the laser anemometer with a frequency shifting will make it possible to carry out measurements in a simple manner.

The equipment used here is a DISA instrument consisting of a helium-neon 5m W laser and a 55L88 LDA transducer, a modular optical unit which can be mounted rigidly with respect to the laser. In the optical unit there is a beam splitter section, one beam is frequency shifted (40 MHz) with respect to the other one through a Bragg cell; it permits to measure negative values of the velocity component. The electronics system consists of the 55L20 doppler signal processor, the 55L70 LDA control unit, and the r.m.s.

The LDA system can be arranged for different operation modes, differential doppler mode-forward scatter, Fig. 3a, and differential doppler mode-backscatter, Fig. 3b. In the second operation mode the flow is attacked from one side only, thus the intensity of the scattered light is usually much lower than that of forward scattered light: a higher concentration of particles is then required. In this operation mode the photomultiplier is solidal to the optical unit, it is useful when vertical profiles of the quantities are needed. In the present study the backscatter mode has been employed, the water was inseminated by TiO_2; thus a good noise to signal ratio was found.

In investigating a boundary layer flowing over a cavity, two important aspects of velocity and turbulent intensity measurements arise: measurements in regions of low mean velocity with high turbulence level (vortex eye), and where high gradients of the quantities are present (walls). The first one, if the frequency shifting is used, does not involve any difficulty, in fact, no Doppler signal releasing was found inside the cavity. Two distinct difficulties arise in the measurements near the walls, namely, swamping of the scattered

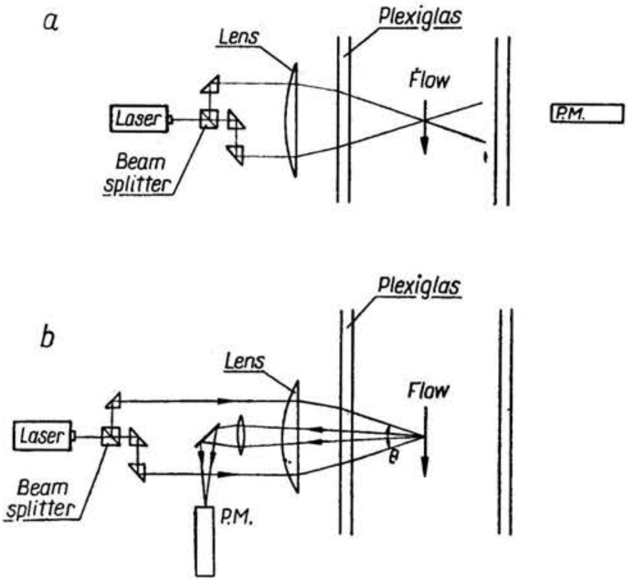

FIG. 3. Laser Doppler anemometer operation modes.

light of the measure volume with the light scattered from the interface between the fluid and the walls, enhanced by the backscattered operation mode, and the presence of high turbulence and mean velocity gradients. To avoid the first difficulty the optical unit and the laser were inclined; in this way a good signal was found to the noise ratio at a distance of 1.5 mm from the wall. The second difficulty, related to the physical phenomenon, consists in having more fluctuating signals; thus, to have meaningful results the signals must be integrated for a longer period of time.

4. Results and discussion

The experimental measurements serve mainly to investigate the velocity and the turbulent intensity profiles in the cavity and the effect of the cavity on the boundary layer flowing over it.

The velocity and the turbulence profiles in front of the cavity have been compared to the profiles available in the literature [6, 7]. Figure 4 shows the vertical profile of $\sqrt{\overline{U'^2}}/U$ at $\mathrm{Re}_{CH} = 8300$ and $\mathrm{Re}_{CH} = 12720$ and these obtained by Reynolds and Laufer, respectively, at $\mathrm{Re}_{CH} = 12300$. The profiles in the central zone of the channel are in a good qualitative and quantitative agreement, at a non-dimensional distance from the wall equal to 1. Near the wall a discrepancy between the results obtained with the apparatus described above and those given in the literature were found. The profiles measured here assumed lower values; this depends mostly on the fact that the flow is not completely fully developed

Figure 5 shows the profiles, measured at the section A—A, of $\sqrt{\overline{U'^2}}/U_0$ at $\mathrm{Re}_{CH} = 8350$ and 12 720, at a lower Reynolds number, $\sqrt{\overline{U'^2}}/U_0$ assumed higher value, the distance from the wall where the maximum is established is smaller as the Reynolds number in-

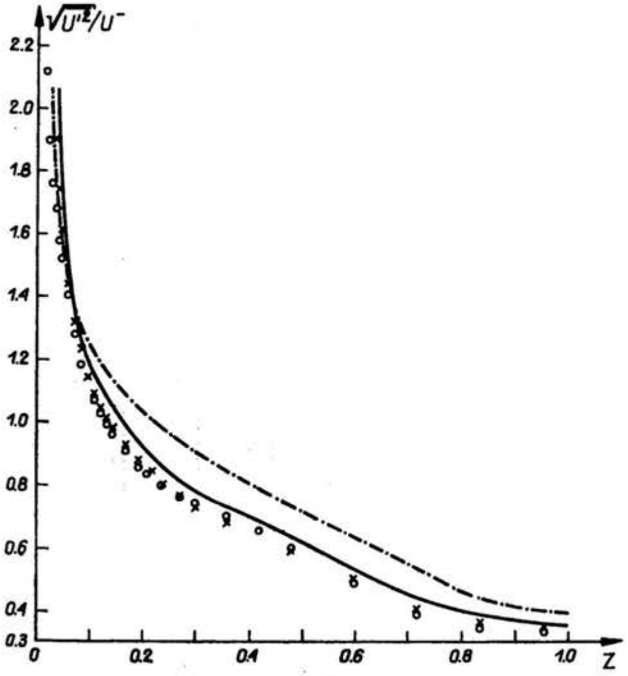

FIG. 4. Vertical profile of $\sqrt{U'^2}/U$ at the section A-A;
o $Re_{CH} = 12720$, × $Re_{CH} = 8300$, ——— Laufer measurements,
—·— Reynolds measurements.

creases. The turbulent intensity maximum values are of the same order as these obtained by Laufer and Reynolds.

Figures 6 and 7 show the velocity and the turbulent intensity measured at the sections A—A, B—B, C—C, at $Re_C = 3340$. The velocity profile downstream the cavity assumes lower values near the wall: the cavity gives a drag and higher pressures are established on the downstream edge, as pointed out by ROSHKO [1]. In the central section B—B, high gradients of the velocity are found on the interface between the boundary layer and the cavity region. Just below the interface the velocity profile is vertical in a small zone, and its value is of the same order as the maximum negative value. The inversion point of the horizontal velocity is established at the center of the cavity and around it the profile is linear. The velocity measurements inside the cavity are in qualitative agreement with the theoretical results [8] obtained at $Re = 1.63 \cdot 10^5$.

Figure 7 shows the profiles of the turbulent intensity at the sections A—A, B—B, C—C, the turbulent intensity at the downstream section assumes the same value as the upstream one, but it is established at a higher distance from the wall. At the section B—B a higher value of the turbulent intensity is found above the interface, with respect to the value on front of the cavity. High gradients of $\sqrt{U'^2/U_0}$ at the interface are found. Inside the cavity (Fig. 10a) the turbulent intensity is smaller than in the external part, and the profile shows higher values in harmony with the higher gradients of the horizontal velocity; the higher value is found near the wall on the bottom.

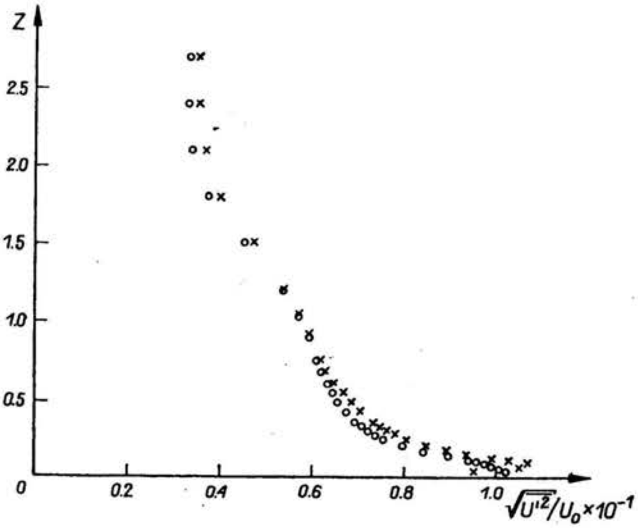

FIG. 5. Vertical profile of $\sqrt{\overline{U'^2}}/U_0$ at the section A-A; o $Re_{CH} = 12720$, × $Re_{CH} = 8300$.

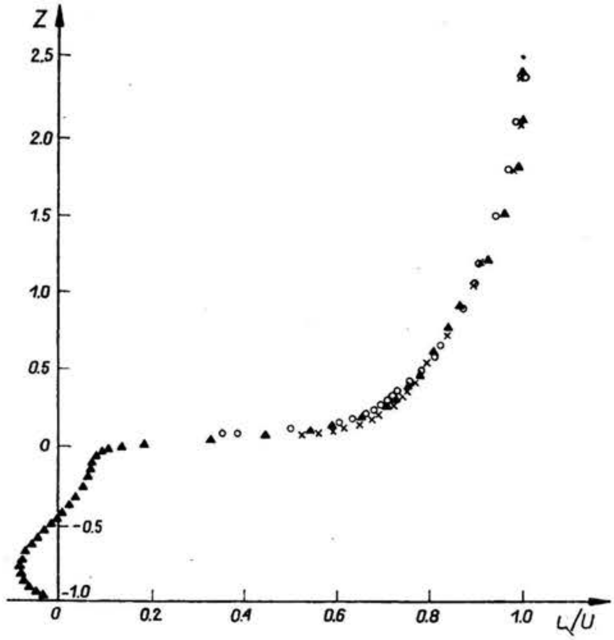

FIG. 6. Vertical profile of U at $Re_C = 3340$, × section A-A, ▲ section B-B, ○ section C-C.

Figures 8 and 9 show the horizontal velocity and the turbulent intensity profiles at $Re_C = 5080$. They are similar to these at $Re_C = 3340$; near the walls upstream and downstream the cavity has higher values and the turbulent intensity has smaller ones. The cavity

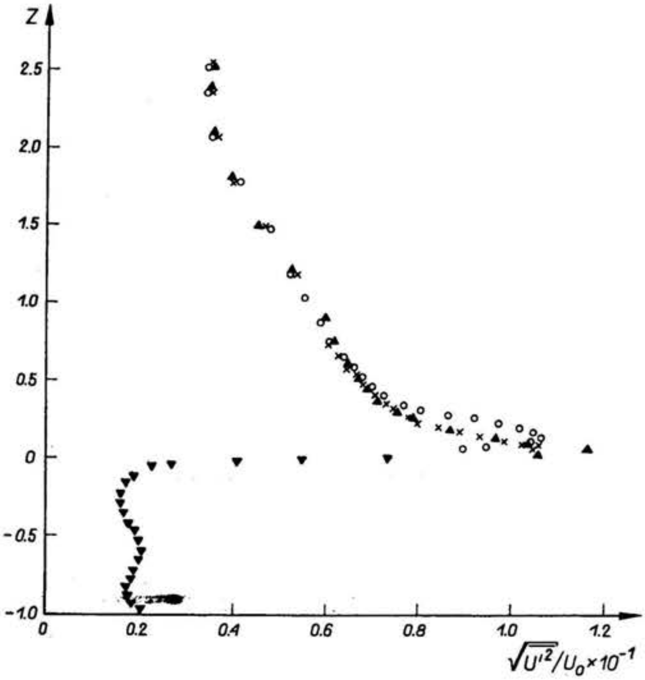

FIG. 7. Vertical profile of $\sqrt{\overline{U'^2}}/U_0$ at $\mathrm{Re}_C = 3340$, × section A-A, ▲ section B-B, ○ section C-C.

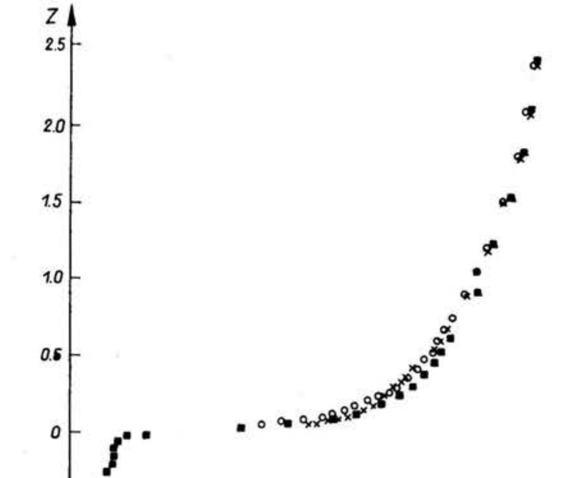

FIG. 8. Verical profile of U at $\mathrm{Re}_C = 5080$, × section A-A, ■ section B-B, ○ section C-C.

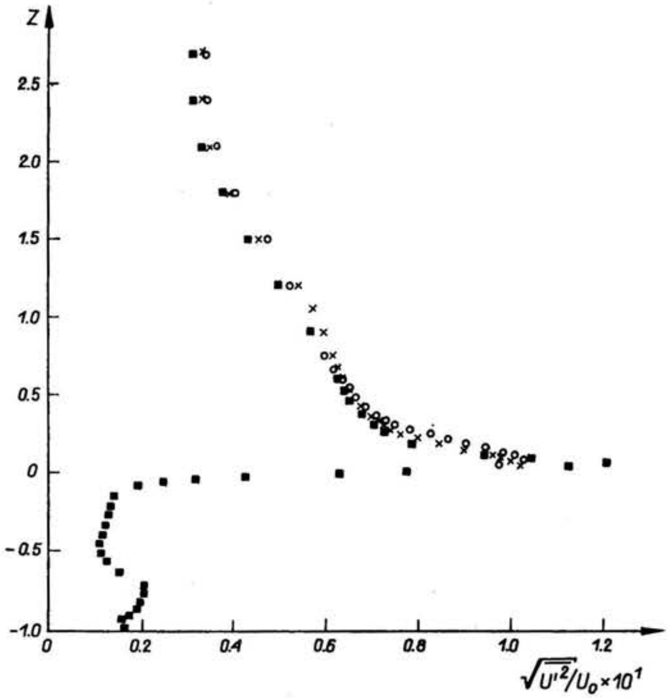

FIG. 9. Vertical profile of $\sqrt{\overline{U'^2}}/U_0$ at $\mathrm{Re}_C = 5880$, × section A-A, ■ section B-B, o — section C-C.

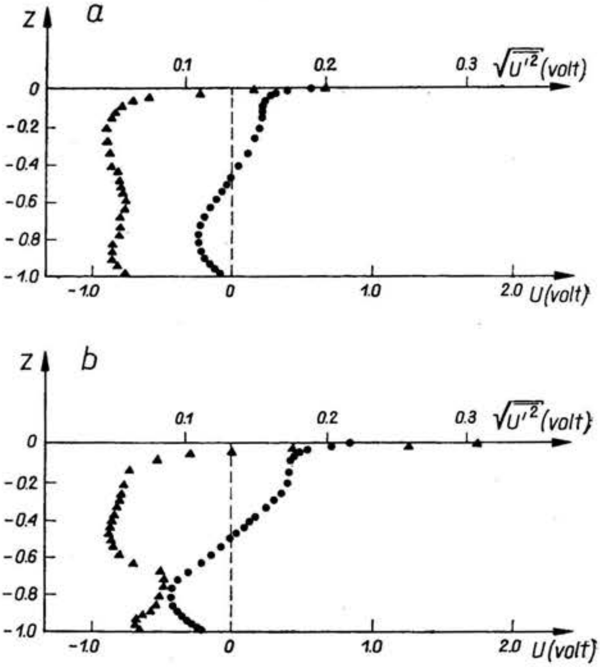

FIG. 10. Vertical profile of U and $\sqrt{\overline{U'^2}}$ in Volt at the section B-B, inside the cavity; a) $\mathrm{Re}_C = 3340$, b) $\mathrm{Re}_C = 5080$.

gives a smaller drag, this can be shown by comparing the profiles at the sections A—A and C—C. At the section B—B the horizontal velocity profile shows a higher gradient at the center of the cavity, the same position of the inversion point and a higher negative value which assumes, as for $\mathrm{Re}_C = 3340$, a value equal to that found where $dU/dz = 0$.

The turbulent intensity at $\mathrm{Re}_C = 5080$, Fig. 9, has a sharp maximum above the interface and diminishes very quickly until it reaches the minimum value at the center of the cavity. Inside the cavity (Fig. 10b) the effects of the velocity gradients on turbulence diffusion overcome the wall effects; thus the maximum turbulence level is located between the two maximum velocity gradients. On the contrary, at $\mathrm{Re}_C = 3340$ (Fig. 10a) the wall effect is predominant, thus the maximum turbulence level is located near the wall.

5. Conclusions

The experimental investigation of a turbulent boundary layer flowing over a cavity has been carried out in an experimental apparatus which does not give a completely developed and purely two-dimensional flow. These conditions do not lead to a right comprehension of the phenomenon but in a first approximation it can be concluded that inside the cavity the turbulent intensity is lower than in the boundary layer, the higher value being established at the interface. The most interesting fact is that the laser Doppler anemometer can be used in a satisfactory way to measure the flow's properties in a recirculating region.

Further investigations should be carried out using an experimental apparatus with a higher length to height ratio and with a higher aspect ratio in such a way as to have a fully developed and two-dimensional flow. Moreover, it will be useful to correlate experimental and theoretical investigations through the use of a mathematical turbulent model applied in a flow of a simpler nature.

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