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THE EFFECTS OF WALL ROUGHNESS AND THE EXTERNAL FLOW STRUCTURE ON BACKWARD-FACING STEP FLOWS

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ABSTRACT

This work concerns with the laboratory experimental study of the backward facing step flows where the final results will be used as a basis for numerical model validation. The complexities of this flow field made us divide the experiments in stages. The experiment analyses of this preliminary work where the flows were produced by wall-jet incoming flows are presented here (see figure 1a). We particularly analysed the influence of the wall roughness and of the external flow structure based on both qualitative and quantitative measurements. We used the laser visualization technique for the qualitative measurements and hot-wire anemometry for the quantitative measurements. The analysis is done by comparing the mean velocity profiles, the turbulence intensity profiles and the reattachment length in various experimental configurations. The AFOSR-Stanford conference criterias for the geometry and flow conditions of the backward facing step flows experiment as described below are respected. The experimental results in jet-wall configuration is presented in this basis manuscript. The rest of the experiment results will be presented at the conference. It seems that the reattachment length is more affected by the turbulence of the external flow than by the wall roughness. The difficulties of having references for the jet case made us use our visualizations as a basic reference. Based on these results we are now advancing the second experimental stages in a larger wind tunnel (see figure 1b.).

NOTATION

B	= Width of the canal jet.
H	= Step height.
δ	= Boundary layer height.
X_r	= Reattachment length.
X	= Abscisse from the step.
Y	= Height of a measurement point.
R_{eH}	= $U_{ref}\,H/\nu$
U_{ref}	= Mean velocity reference (m/s)
U	= Mean velocity (m/s)
U_{max}	= Local max. of mean velocity (m/s)
u'	= Fluctuation velocity (m/s)
d	= Height of the jet mouth (cm)
ℓ	= Height of the point where $U=U_{max}/2$

1. INTRODUCTION

Environment is the most precious system of our world that depends on many complex parameters. There are three larges mediums : the atmosphere, the ocean and the land surface where these parameters construct the environment conditions. One of the region where the exchanges between these medium take place is the atmospheric boundary layer. In view of studying the dynamics of the urban atmosphere, the exchanges between the atmosphere and the urban canopy became one of the most attracting research in the recent years. Our interest in this study is the assessment of the influence of the wall roughness and of the external turbulent macro-structures on the flow dynamics inside the canyon streets. For that purpose we use the backward facing step flows as a basic experimental tool of analysis.

The structure of the backward facing step flows is shown in fig.2a[1] and fig.2b[1] . The zone 1 is an ordinary boundary layer that creates the initial conditions for the rest of the flows. Therefore its features are very importants. Bradshaw and Wong (1972) divided this region into three regimes : overwhelming perturbation ($\delta/H<1$) where the free shear layer structure quickly erases all traces of the upstream flow, strong perturbation ($\delta/H=1$) where the free shear layer is affected by the upstream flow but not dominated by it, and small perturbation ($\delta/H>1$). The zone 2, which resembles a free shear layer in the absence of wall[10,6], transforms gradually into a mixing layer in the frontier of zone 4. Chandrasuda and Bradshaw (1981), and Eaton and Johnston (1981) found that the recirculation zone (3), where the maximum mean velocity of the reverse flow is of the order of 20% of U_{max}, is not a dead air zone. The large eddies are affected by the wall roughness and the turbulence of the external flows. Previous studies proved that the logarithmic law not be obeyed in the recirculation and reattachment zones. The reattachment zone (4) is defined as the region where the large eddies impinge on the wall[1,4,8], are swept downstream or upstream of the reattachmert point[1,8] and are torn in two directions : one to the upstream and one to the downstream of the reattachment point[1,4]. Chapman (1958) suggested that the reattachment length directly depends on the balance between the flows entrained by the free shear layer from zone 3 to zone 2 and the flows inversed by pressure gradient from zone 4 to zone 3. Thus the separation line can be defined as the line where there is an equilibrium between the regions 2 and 3. The flow begins to redevelop its initial structure in the recovery zone (5). In divergent and canal cases the zones 6 and 7 are inviscid layer and zone 8 is an ordinary boundary layer under the upper plate. For the jet case the zones 6 and 7 remain free shear layers. Based on the reattachment length, which is the most important dependent parameter to characterize the individual flow field[9]. J.K. Eaton et al (1981) determined 5 independent parameters that totally define the flow structure : the boundary layer initial condition, the boundary layer thickness, the external turbulent flow, the pressure gradient and the aspect ratio (B/H). But for the jet case, the boundary layer thickness is not as important as the external turbulent flow.[1]

2. EXPERIMENTAL STUDY

2.1 Experimental Set-Up

The plane wall-jet shown in figure 1a is created by an axisymetric jet blower that has a 3 cm slot height (d), 70 cm

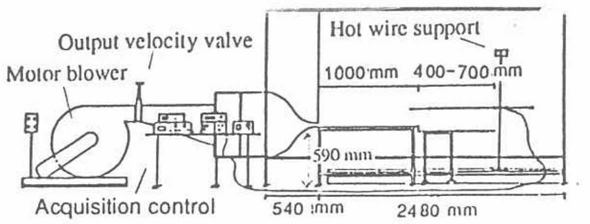


Fig. 1a.. Wall jet experiment

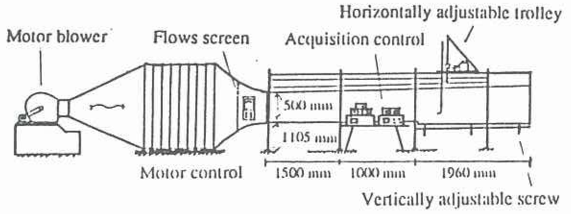


Fig. 1b. Atmospheric wind tunnel

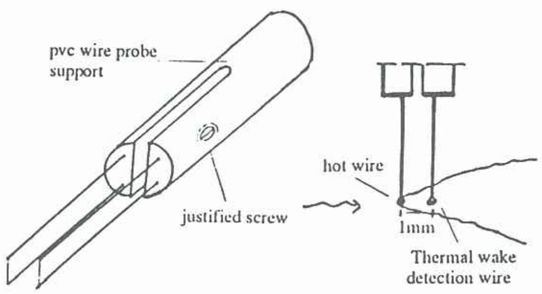


Fig. 1c. Two parallel wire probe

Fig.1 Schematics of the experimental Facilities.

width and 6.5 m/s maximum mean output velocity. The bottom plate is a wooden plate covered by a hard-smooth surface. This plate is divided into two parts by an adjustable step. The maximum height of the step is 10 cm. The upperstream is 100 cm long and the downstream length is adjustable between 40 cm and 70 cm. The upperside plate is in plexiglas to allow for the illumination with the laser beam. This plate is hinged in the jet mouth/slot with an adjustable angle between 0 and 90 degree. One side of the canal wall is also made from plexiglas to allow flow visualization.

For the visualization we use an adjustable turning mirror at 50 Hz (AID 82.03) placed above the upper plate, an argon 5 watt tomography laser of Spectra Physics series 2000 placed downstream of the jet, an aerosol (DOP, D870) as a tracer of the flows, a Sony V8 video camera and a Cannon photo camera . The quantitative measurements are done with hot-wire ($\phi = 5\ \mu m$) which is calibrated in the potential zone versus a pitot tube, supported by a CTA anemometer DISA 55M10, a Lineariser DISA 55D10 and a Voltmeter (JM 1860, Solartron/Schlumberger). A spectral analyser is also used. King's law is used for calibrating the hot wire. Some 2 mm grading gravels are used to produce the wall roughness. A two parallel wire probe is developed as an alternative solution for detecting the flow direction in recirculation zone (see figure 1c.). The flow direction is determined by detecting the thermal wake of the upstream wire on the other one. This can be done by measuring the temperature fluctuations behind the wire, ie operating the wires alternately as hot- and cold-wires.

The larger wind tunnel, designed for simulating the atmospheric boundary layer, is used for the second stage. It will be modified to provide the wall jet case experiments and a vortex generator will be added to create additional external flow structures.

2.2 Flow Conditions and Measurements

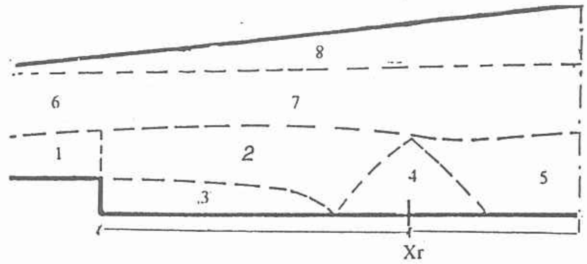
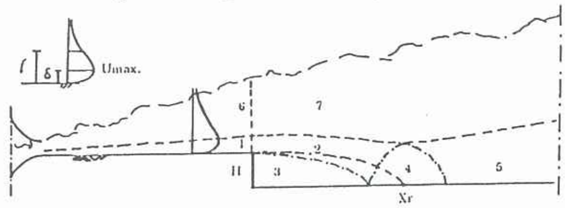


Fig. 2a. Divergent case (canal case $\alpha = 0$)



1. Ordinary boundary layer
2. Free shear layer
3. Recirculation Zone
4. Reattachment zone
5. Recovery zone
6. & 7 Free shear layer (Jet case)

Xr : Reattachment point for div. & cana cases :
6 & 7 Inviscid layer.
8Attached boundary layer

Fig. 2b. Wall jet case

Fig. 2. Experimental configurations and flow structures

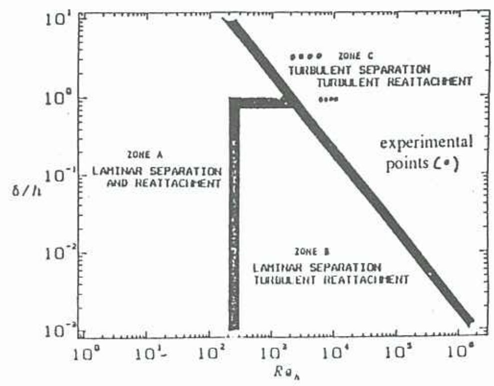


Fig. 3 Experimental Parameter space

The measurements were made in 3 configurations : canal case, divergent case and jet case, from which we expect to predict the effect of the external structure. The Stanford criteria such as : $B/H > 10$, $R_{eH} > 1000$ and $u'/U_{max} < 0.5\ \%$ are respected. The wall roughness follows the Nikuradse criteria. The mean velocity and r.m.s fluctuation profiles are measured every step-height downstream of the step and in 2 points upstream of the step. The input velocity of the jet is varied from 0.8 to 6.5 m/s for the visualizations and fixed at 6.5 m/s for the hot-wire measurements. The step height is varied from 5 to 0.6 cm to explore the range $0.9 < \delta/H < 3.2$. This condition allowed us to have $2250 < R_{eH} < 12000$ and $20 < B/H < 116$. The separation line is defined as the line where the mean velocity profile deflects and inverses its gradient. The reattachment point is defined as the point where the mean velocity gradient is zero or minimum in first approximation. The recirculation zone is defined as the zone where a wrong direction of the mean velocity gradient is captured by hot wire. Uncertainty remains from measurements with a single hot-wire in recirculation zone. This made us unable to predict the exact near wall structure in the recirculation zone so that the effect of the wall roughness is well analysed only for the flows outside the recirculation zone. Detailed analysis of this recirculation zone is expected from the second stage of the experiment where we will use the two-parallel wire probe to improve the measurements, as described above.

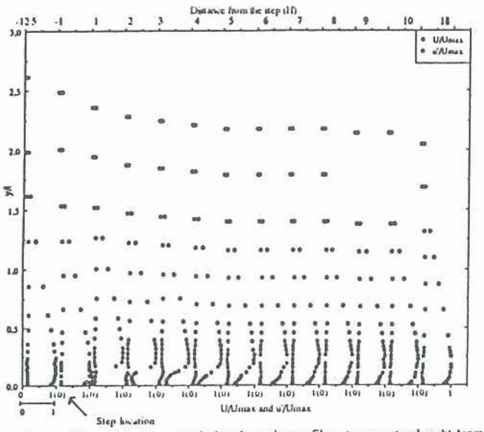


Fig. 4 Mean Velocity and turbulent intensity profiles at every step height from the step (smooth wall jet case at δ/H = 0.9)

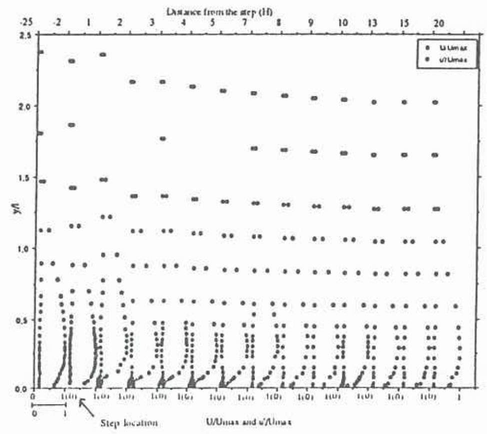


Fig.7 Mean velocity and turbulent intensity profiles at every step height from the step (rough wall jet case at δ/H = 3.2)

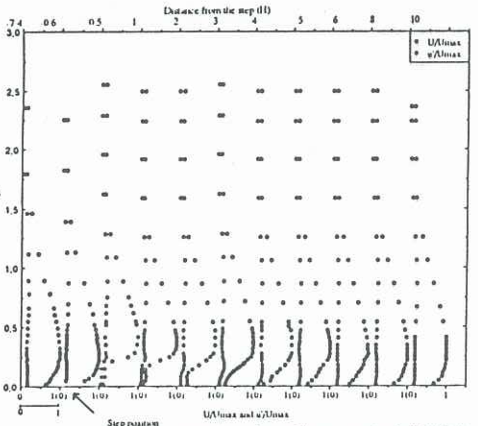


Fig.5 Mean velocity and turbulent intensity profiles at every step height from the step (rough wall jet case at δ/H = 0.9)

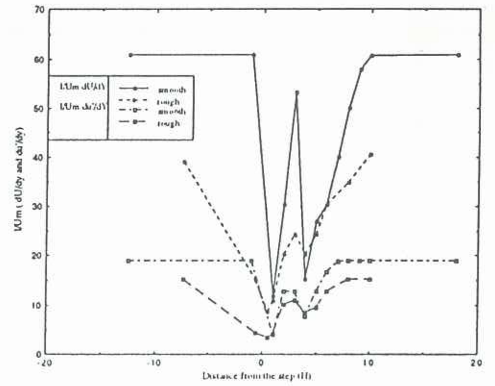


Fig.8 Longitudinal evolution of the gradients of mean velocity and turbulent intensity near the wall

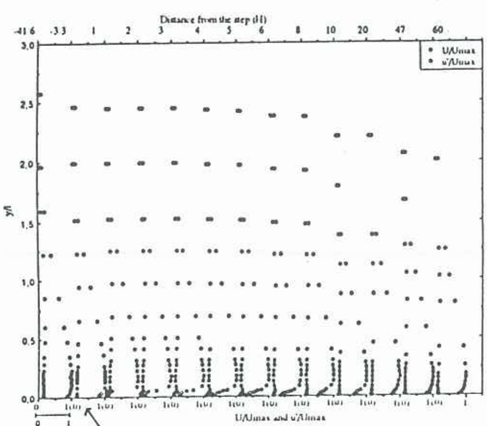


Fig.6 Mean velocity and turbulent intensity profiles at every step height from the step (smooth wall jet case at δ/H=3.2)

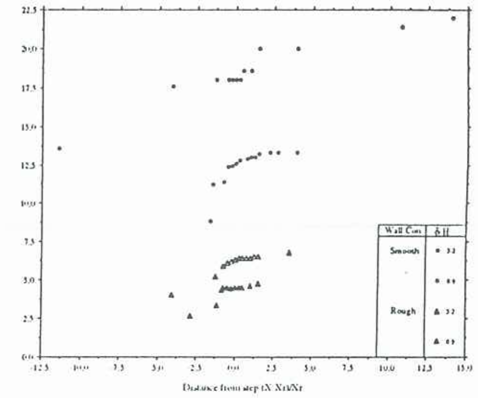


Fig 9 Longitudinal evolution of l for the jet wall cases

2.3 Experimental results

A part of the results of the visualization experiment was already presented at the Euromech 276 Symposium[1]. The large eddies impinge on the wall and then sweep downstream the reattachment point in the canal case, and they also sweep upstream the reattachment point and some times are torn in two direction : one to the upstream and one to the downstream of the reattachment point in the divergence case, and they also destroy all the traces of the upstream flow and fall down to the reattachment zone in the jet case. Bursting phenomenon is found in the divergent and jet cases. The detailed discussion are available in the visualization report[1].

The turbulent intensity of the external flow increases the dimension of large eddies and decreases the reattachment length. The mean velocity and fluctuation profiles are normalized by U_{max} and the heights by H (or ℓ for the jet case). With the limitation of the manuscript, only few of the experiment results can be shown here, so that the rests will be presented in the seminar. Figures 3 to 13 show the results for the jet case with $\delta/H = 0.9$ and $\delta/H = 3.2$. No contradiction is found between the visualization results and the quantitative results. As predicted the mean velocity and turbulence profiles are deflected at the separation line, the logarithmic law is not obeyed in the recirculation zone.The near wall structure in the recirculation zone are affected by the wall roughness but this need to be confirmed by the

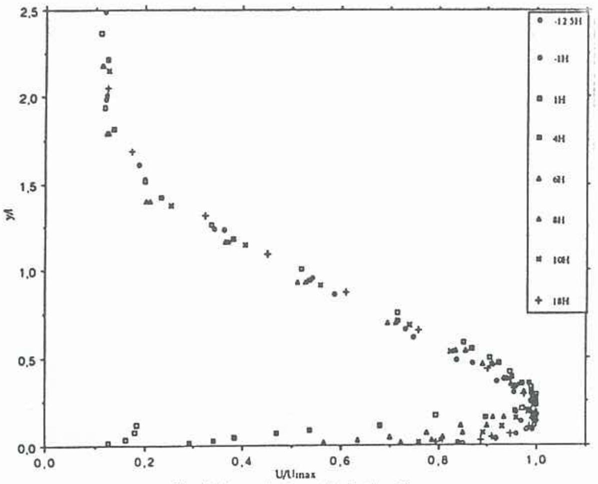


Fig. 10 Mean velocity profiles in the self similarity form (smooth wall jet case at δ/H=0.9)

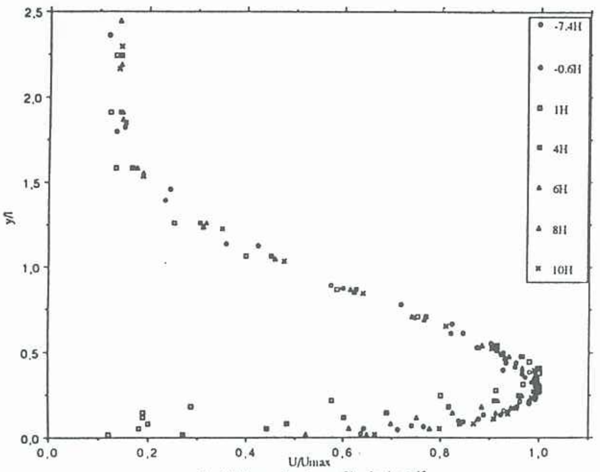


Fig 11 Mean velocity profiles in the self similarity form (rough wall jet case at δ/H =0.9)

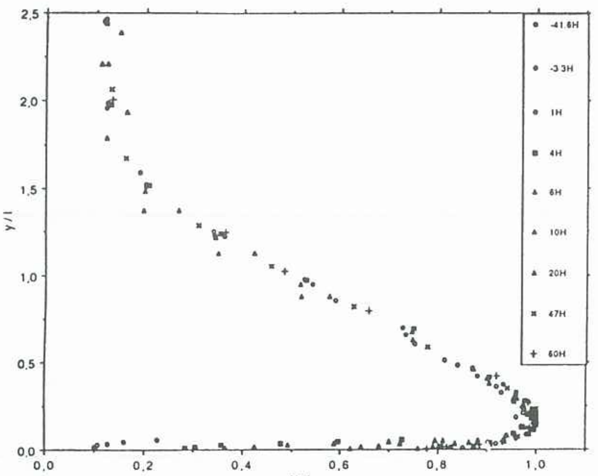


Fig 12 Mean velocity profiles in the self similarity form (smooth wall case at δ/H=3.2)

detailed measurements and analyses in the second stages of the work. This second stages work is expected to be finished in december 1992. It seems that self similarity of the mean velocity and turbulent intensity profiles is recovered more rapidly in the jet case than in the other cases. It is importants to remark the difference in the effects of the wall roughness and of δ/H for the jet case on the one hand and for the other cases on the other hand. In the jet case the reattachment length is found practically constant for both smooth and rough wall case, and independent of δ/H. In the other cases the reattachment length varies with both the wall roughness and δ/H.

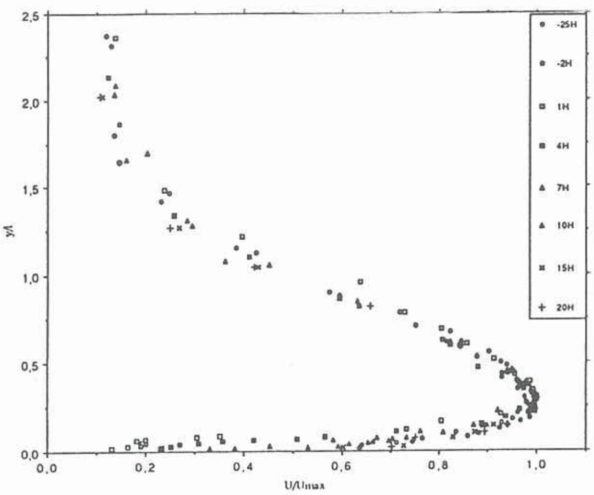


Fig. 13 Mean velocity profiles in the self self similarity form (rough wall case at δ/H=3.2)

3 CONCLUSION

The results indicate that the effects of wall roughness are dominated by those of the external turbulent flows. As expected, only a weak conclusion can be made for the recirculation zone in this preliminary stage. The use of the near wall velocity gradient to determine the reattachment length seems a good method. But with single hot wire measurements these results must be regarded as a first approximation. The measurement uncertainty is found especially in the recirculation zone where the flows are reversed by the adverse pressure gradient. This problem might be solved by using the double wire that can detect the flow direction. Regarding the statistic problem of the particle injection for the laser measurements, this alternative solution can give a good enough prediction of the flows. The visualization is needed to predict the structure of the flows and to support the quantitative measurement.

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