# THE EFFECT OF LARGE-SCALE TURBULENT STRUCTURES ON A SIMPLE 2-D CANYON-TYPE FLOW

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**Abstract.** This paper is concerned with a preliminary experimental investigation of the interaction between large turbulent structures, generated in the wake of a circular cylinder, and the rough-wall turbulent boundary layer separated flow immediately downstream of a simple street canyon type geometry represented by backward-facing step. The motivation for the work was to provide some initial data for the validation of a 3-D k-ε turbulence model used for the prediction of flows and pollutant dispersion within the urban canopy. The aim has been to assess the extent of the perturbation of a simulated street canyon caused by regular large-scale eddies generated upstream. The research has involved the use of thermal anemometry to determine mean velocity and turbulence characteristics both upstream and downstream of the step, together with the mean reattachment length for the recirculating flow. The results indicate that the presence of the cylinder in the flow reduces the reattachment length. In addition, the periodic structures generated in the cylinder wake are rapidly mixed with the turbulence in the step shear layer such that no periodicity is detected at the reattachment zone.

**Key words:** large-scale turbulence, backward-facing step, shear layer, canyon flow

## 1. Introduction

A better understanding of the flow and pollutant dispersion characteristics within urban street canyons is important if air quality is to be improved and town centres designed to minimise adverse environmental conditions. The complexities of the urban climate have been extensively reviewed (Mestayer and Anquetin, 1995) and investigations of the problem have involved model scale experiments and numerical turbulence modelling of relatively simplified urban geometries and flows, coupled with limited field experiments.

In experimental and numerical modelling the street canyons are normally treated either as essentially 2-D rectangular cavities or backward-facing step flows, with the approaching fully-developed turbulent boundary layer separating at the leading edge. Such investigations have yielded useful results, particularly concerning the effects of canyon geometry (Oke, 1988, Mestayer *et al*, 1995, Sini *et al*, 1996) and solar-induced canyon wall temperatures on the flow velocities, pollutant levels and dilution times within the cavity (Mestayer *et al*, 1995, Sini *et al*, 1996). The general

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perception of the canyon flow is that it is dominated by a single, stable, large, rotating flow vortex whose axis is parallel to the street direction. For narrower streets this becomes a series of two or three contrarotating vortices, one above another. However, the reality is much different. From investigations of 3-D rectangular cavities, associated with aircraft aerodynamics (Savory *et al*, 1993, 1997b) one of the present authors has noted how the flow is always highly 3-D in nature, particularly when the incident flow is not normal to the main canyon axis. Indeed, the cavity flow is strongly dependent upon geometrical aspect ratio, with particular cases giving rise to increased flow unsteadiness, enhanced momentum exchange with the external flow and strong circulations in the horizontal plane. It is possible that some of these features may be extrapolated to the larger-scale street canyon regime. In addition, in practical urban applications such flows are likely to be strongly perturbed by larger scale eddies either impinging on the boundary layer from higher levels in the urban atmosphere or generated by the flows over upstream canyons. This mesoscale flow field above the city may be modelled using a large eddy simulation, whilst conventional turbulence models may be used for the flow within the street canyons. It is anticipated that some form of coupling of these two numerical modelling approaches will be necessary for the development of a comprehensive urban canyon simulation.

Hence, the aim of the present work has been examine the flow over a rough-wall backward-facing step with a thick separating turbulent boundary layer both with and without the perturbations caused by the influence of large external flow structures. These structures were generated by a circular cylinder positioned in the freestream upstream of the step at a location that produces large eddies of a diameter equivalent to the boundary layer thickness at separation. This simple test case has been chosen in order to validate the urban canyon flow turbulence model CHENSI (Mestayer *et al*, 1993). Although it is recognised that the large-scale turbulence above the urban canopy is likely to be dominated by streamwise, rather than lateral, vorticity, the present test arrangement was used since it presented a convenient and valid method for introducing large-scale, periodic perturbations for model validation purposes.

The backward-facing step flow regime has been the subject of numerous investigations and is a standard test case for numerical modelling. In the case of smooth-wall flows, with a turbulent boundary layer at separation, a number of authors have studied the effects of Reynolds number on the reattachment length (Eaton *et al*, 1979, Durst and Tropea, 1982, Adams *et al*, 1984), whilst others have ascertained the influence of boundary layer thickness (Bradshaw and Wong, 1972, Adams and Johnston, 1988) and turbulence intensity at separation (Isomoto and Homani, 1989) on the subsequent reattachment. The flow downstream of a step with a rough-wall boundary layer has received relatively little attention, notably the research reported in (Badri Kusuma, 1993) and the present research is a continuation of that study. The next section of this paper briefly outlines the facilities and configurations used in the present investigation. The ensuing section discusses some of the results obtained from the study and, finally, some conclusions are drawn.

## 2. Experimental Details

### 2.1. WIND TUNNEL AND MODEL ARRANGEMENTS

The experiments were carried out in the low-speed boundary layer tunnel at ECN which has working section dimensions of 4m length x 2m width x 0.5m height. In the present experiments a nominal upstream freestream reference velocity (Uref) of 6.4m/s was used. The basic arrangement for the test geometry is shown in figure 1

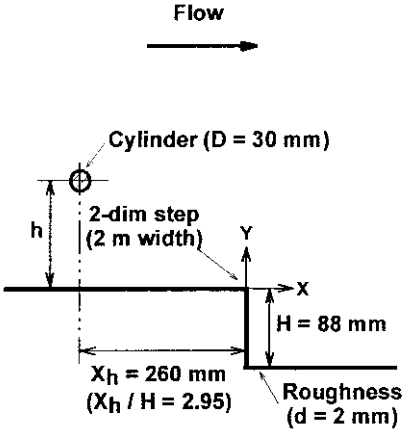

*Figure 1.* Diagrammatic layout of step and cylinder model (not to scale)

which also gives the principal dimensions. A step height (H) of 88mm was adopted since this was the value used in an earlier study (Badri Kasuma, 1993). The gravel roughness of 2mm diameter was utilised for the same reason. The following parameters for the boundary layer at the step agreed well with an analysis of the data from the earlier study; boundary layer thickness, $\delta$=79.9mm, roughness length, $y_0$=0.65mm, shear velocity, $U_*$/Uref=0.0800. The cylinder model was a smooth-walled aluminium tube with an outside diameter (D) of 30mm, giving D/H=0.34. The cylinder spanned the width of the tunnel and graded, narrow supports were provided

provided to allow the model to be set at the desired height above the ground. The cylinder position for the initial measurements was chosen so that at the step the eddies shed by the cylinder had a diameter approximately the same as the thickness of the separating boundary layer and occupied the upper quarter of the boundary layer.

### 2.2. HOT-WIRE ANEMOMETRY

The measurements were carried out using a single hot-wire anemometer system, with the probe mounted in an aerofoil section, together with a pitot-static tube, which was itself attached to the end of a cylindrical rod vertical traversing mechanism. The hot-wire was operated with an overheat ratio of 0.5 and a freestream calibration against the pitot-static tube was carried out prior to each vertical traverse in order to minimise drift due to ambient temperature changes. Although data obtained from such an instrument in regions of high turbulence intensity or flow recirculation are grossly in error the results do permit an assessment of the effects of cylinder model location on the backward-facing step shear layer development.

### 2.3 FLOW REATTACHMENT PROBE

It is not possible to use a single hot-wire anemometer probe to determine the location of reattachment downstream of a step since such a device is not capable of resolving flow direction. A number of flush surface-mounted devices have been developed for determining flow direction and reattachment, such as a thermal tuft (Eaton *et al*, 1979). However, many of these instruments are not readily suited for use in rough-wall boundary layers and so a new probe was constructed for such a purpose (Savory *et al*, 1997a). Briefly, the reattachment probe consists of a conventional single hot-wire anemometer operated in constant temperature mode. At right angles to and approximately 1mm equidistant from the wire are the two junctions of a copper/constantan thermocouple. The principle of operation is simple and works on the basis that in a flow field there will be a positive or negative potential difference between the junctions if there is a net flow velocity in either of the two normal flow directions, which results in a net temperature difference at the junctions. In a reattachment zone the mean velocity near the surface tends towards zero and so the thermocouple e.m.f. also tends toward zero. However, in practice, it was necessary to develop an appropriate methodology in order to ensure that the probe gave reliable and repeatable results (Savory *et al*, 1997a).

### 2.4 SCOPE OF THE MEASUREMENTS

At the nominal freestream reference velocity of 6.4m/s the Reynolds number for the step was $Re_H=3.88 \times 10^4$ and the Reynolds number for the cylinder was $Re_D=1.32 \times 10^4$. The frequency of the periodic vortex shedding from the cylinder was

$Re_D=1.32\text{x}10^4$. The frequency of the periodic vortex shedding from the cylinder was 43 Hz. The range of measurements were; (1) Velocity time-histories in vertical profiles at X/H=-0.4, 0, 1, 3 and 5 without the cylinder and with the cylinder set at a heights h=90, 110 and 130mm (giving h/H=1.02, 1.25 and 1.48), (2) Reattachment probe data between X/H=1.5 and 7 without the cylinder and with the cylinder at heights of h=90, 100, 110, 120, 130 and 140mm (h/H =1.02 to 1.59).

## 3. Results and Discussion

From consideration of the step and cylinder geometry, together with an assumed half-angle for the growth of the cylinder wake of 17 degrees, it is estimated that an undisturbed cylinder wake would reach the ground plane downstream of the step at X/H=4.6 for the case where h/H=1.48 and at X/H=3.1 for the case where h/H=1.02.

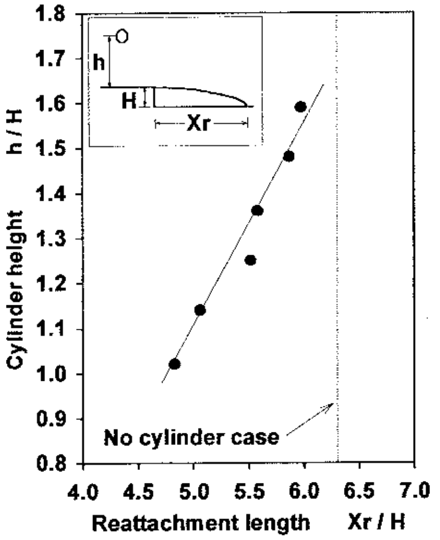

*Figure 2.* Variation of reattachment length with cylinder height

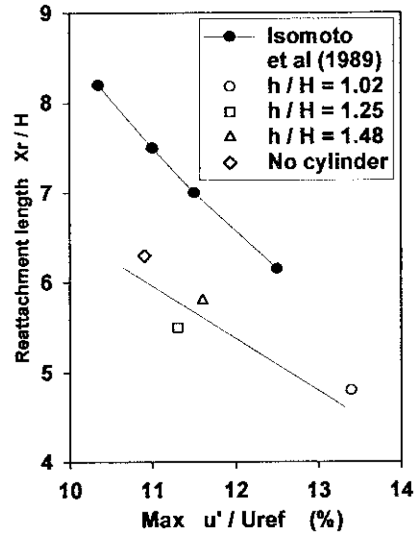

*Figure 3.* Variation of reattachment length with max. turbulence intensity at separation

The lowest cylinder height was chosen in order to produce a configuration which would, it was estimated, produce vortices that first impinge upon the ground plane at the upper edge of the step. The results from the reattachment probe for all of the cylinder locations are given in figure 2, together with the case of no-cylinder in the flow. The data suggest that the reattachment length of 6.3H in the absence of the cylinder is reduced slightly to 6.0H by the presence of the cylinder at h/H=1.59 and then reduced massively to 4.8H by the cylinder located at h/H=1.02. Previous work

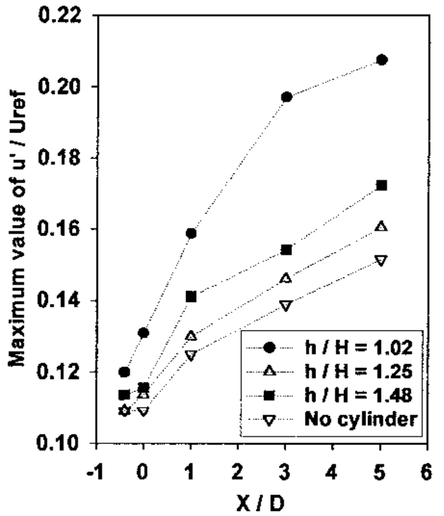

*Figure 4.* Variation of max. turbulence intensity with downstream distance for different cylinder locations

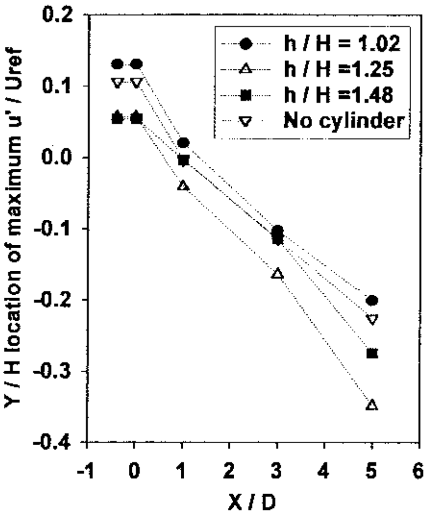

*Figure 5.* Variation of position of max. shear layer turb. intensity with downstream distance for different cylinder locations

(Isomoto and Honami, 1989) has shown that an increase of 2% in the boundary layer turbulence intensity at step height can reduce the reattachment length by as much as 2H. Figure 3 shows the results from the present work, together with the earlier data (Isomoto and Honami, 1989). It may be seen that the trends in the two data sets are broadly similar, with the difference in turbulence intensity between the no-cylinder case and the cylinder at h/H=1.02 being 2.5%, resulting in a reduction in reattachment length of 1.5H. The differences may be attributed to the fact that the cylinders used by the earlier authors were relatively small ($D/H \leq 0.12$) and that, in the present work, the large cylinder, coupled with the wall roughness, introduced much larger scale turbulence into the flow.

The development of the turbulence intensity profiles downstream of the step for the different cylinder locations are shown in figures 4 and 5. The maximum value of the streamwise turbulence intensity in each vertical profile is given in figure 4 and these clearly show that the shear layer turbulence is greatly increased throughout its length when the cylinder is at the lowest position (h/H = 1.02) when compared to the other cases. The other cylinder positions show small increases in the maximum turbulence levels, when compared to the no-cylinder case, although the rates of increase in the downstream direction are similar in all three cases. The location above the ground plane of the point of maximum turbulence intensity is shown in figure 5. It is surprising to note that the variations in vertical location of the turbulence maxima with downstream distance are very similar in all four cases, with no distinct

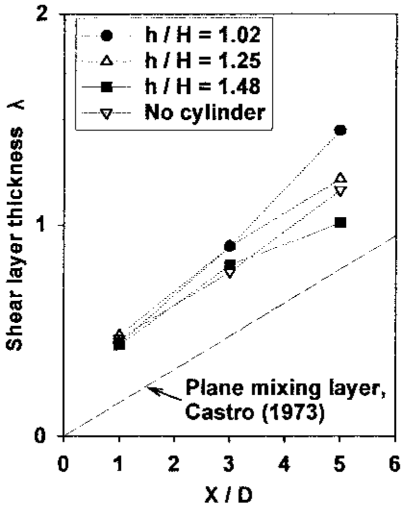

*Figure 6.* Variation of shear layer thickness with downstream distance for different cylinder locations

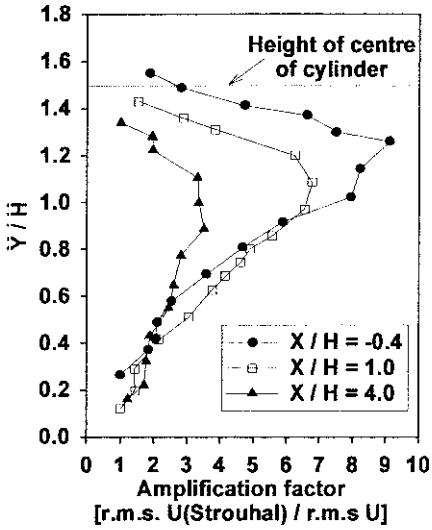

*Figure 7.* Profiles of Amplification Factor at vortex shedding frequency (43Hz) due to cylinder at h/H=1.48

trends with cylinder location. Hence, it would seem that the earlier reattachment which occurs is due to a small degree of shear layer thickening rather than any dramatic change in the curvature of the shear layer centre-line.

This appears to be borne out in figure 6 by the variation of shear layer thickness ($\lambda$) with downstream distance, estimated from the mean velocity profiles and defined as; $\lambda = (U_{ref} / H).(\partial Y / \partial U)_{max}$, where $(\partial Y / \partial U)_{max}$ is the maximum slope in each profile. The lower two locations of the cylinder appear to produce a thicker shear layer as reattachment is approached, with growth rates that are slightly larger than a conventional plane mixing layer (Castro, 1973).

Figure 7 shows how the energy associated with the vortices shed from the cylinder attenuates rapidly through the recirculation region, such that it is not detectable at reattachment (X/H>4). Here, the energy is expressed as an amplification ratio, defined as the ratio of the r.m.s. streamwise velocity fluctuation at the shedding frequency to the r.m.s. velocity in the energy spectrum at that frequency but excluding the vortex shedding peak.

Although only the case of the cylinder at the highest location is shown here, the same result pertains for all the cylinder settings, demonstrating that these well-defined turbulent structures appear to be rapidly mixed into the shear layer since they are not detectable within the body of the shear layer or in the recirculation region.

## 4. Concluding Remarks

Clearly, the presence of the cylinder greatly alters the mean flow since it generates a large wake which mixes with the separated boundary layer. The effect of this is to increase the mean velocity beneath the wake and through the step shear layer. The turbulence intensities in the outer shear layer do not appear to be effected by the cylinder wake but the peak intensities in the centre of the shear layer are greater with the cylinder present. The presence of the cylinder, located at a height of Y/H=1.59 reduces the reattachment length from 6.3H to 6.0H. With the cylinder set at increasingly lower levels the reattachment length is reduced still further, to 4.8H when Y/H=1.02. It would appear that the increased turbulence intensities in the shear layer, coupled with the increased velocities, has the effect of causing earlier reattachment through a small shear layer thickening. The effect on reattachment of the step height turbulence intensity increase at separation is similar to that found in earlier work.

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