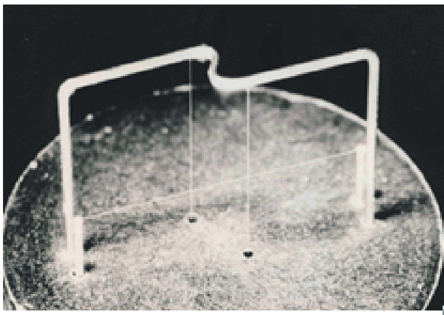
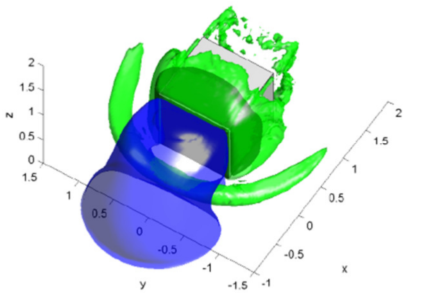
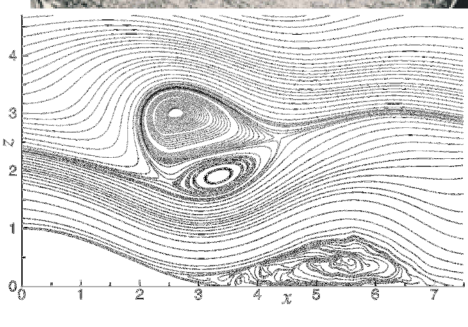
From bent layers to broken waves: studies in engineering and environmental fluid dynamics

Workshop in honour of Professor Ian Castro's 65th birthday

Chilworth Manor Hotel,
Southampton
28-29 March 2012



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Workshop in honour of Ian Castro's 65th birthday

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Wednesday 28 March:

11.00-12.00 Registration/Coffee

12.00-13.15 Lunch

13.15-13.20 Welcome

13.20-15.00 Session 1 (ND Sandham)

- 13.20 Keynote – JCR Hunt: *Interfacial shear layers in turbulent flows*
- 14.00 M Athanassiadou: *The use of inversion methods in the reconstruction of unknown sources of contaminants in the environment*
- 14.20 PF Linden: *Fluid mechanics of low-energy buildings*
- 14.40 JMR Graham: *Aerodynamic control of flexible structures in the natural world*

15.00-15.30 Tea

15.30-17.10 Session 2 (RD Sandberg)

- 15.30 Keynote – SI Chernyshenko: *Linearised Navier-Stokes equations and developed turbulence*
- 16.10 P Orlandi: *The importance of wall-normal Reynolds stress in transitional and turbulent rough channel flows*
- 16.30 GN Coleman: *The question of universality of turbulent axisymmetric wakes*

16.50-17.30 Coffee

17.30-18.50 Session 3 (TG Thomas)

- 17.30 PE Hancock: *Wind turbine wakes in stratified flow: some initial experience with wind tunnel simulations*
- 17.50 PW Bearman: *Vortex-induced vibration of circular cylinders and its suppression*
- 18.10 RP Hoxey: *Reynolds-number sensitivity of vortices in boundary-layer flows*
- 18.30 PH Alfredsson: *The streamwise turbulence intensity in wall bounded flows – is there an outer peak?*

19.30-22.00 Dinner (Toast: SI Chernyshenko; Speech: LJS Bradbury)

Thursday 29 March:

09.00-11.00 Session 4 (B Ganapathisubramani)

- 09.00 Keynote – SE Belcher: *The rough side of town – turbulent boundary layers over cities*
- 09.40 O Coceal: *Mean flow, turbulence and dispersion in a complex urban-like geometry*
- 10.00 S Leonardi: *Direct Numerical Simulation of a turbulent channel flow with 3D random roughness on a wall*
- 10.20 P-Å Krogstad: *Inner-outer layer interactions in rough-wall boundary layers*
- 10.40 JF Morrison: *Similarity and non-equilibrium effects in rough-wall channel flow*

11.00-11.30 Coffee

11.30-13.10 Session 5 (GN Coleman)

- 11.30 Keynote – AG Robins: *What did we do in Marylebone Road….did it all begin with the Marchwood cube?*
- 12.10 IR Cowan: *Engineering consultancy and rigorous fluid mechanics*
- 12.30 A Hunt: *Waves, slugs and ghosts in gas-liquid pipe flow*
- 12.50 M Schatzmann: *LES of accidental releases*

13.10-14.30 Close/Lunch

Interfacial shear layers in turbulent flows

Julian Hunt

Why do certain types of thin shear layers survive and control the outer edges of regions of intense turbulence within turbulent flows and at their outer edges? What is the overall effect of these layers and what happens within them? We can relate these ideas to some of the complex flow problems of wakes and shear layers, and their modelling, the subject of many pioneering studies by Ian Castro and his many colleagues.

The use of inversion methods in the reconstruction of unknown sources of contaminants in the environment

Maria Athanassiadou

Inversion methodology is the process of deducing the spatial and/or temporal distribution of sources of a tracer from concentration measurements. Vital to the process is a description of the way emissions are diluted in the atmosphere as they travel from sources to observation point i.e., knowledge of the transport. To close the system, a model is needed that connects the sources, transport and observations in a coherent way. Various inversion methods exist and choice of the most suitable depends on the problem, type and number of observations and available resources for the transport model. Typical environmental inverse problems do not have a unique solution, and therefore inversion modelling estimates the best solution from many possible solutions, along with a measure of confidence for the chosen solution. This talk presents a selection of different problems of relevance to environmental flows and describes a few of the most common inversion methods, giving some emphasis to Simulated Annealing.

Fluid mechanics of low energy buildings

Paul Linden

Buildings use large amounts of energy and contribute significantly to greenhouse gas emissions. In order to reduce these emissions, low-energy solutions are needed for heating and cooling buildings. In this talk I will describe two low-energy cooling systems, one using natural ventilation and the other an air conditioning system, that both exploit vertical stratification to remove warm air most efficiently from a space. As a result the internal flows are a combination of buoyant plumes driven by heating from occupants and other internal gains and the stratification of the air within the space. I will present models for these flows derived from and compared with laboratory experiments and discuss the implications for comfort and energy consumption.

Aerodynamic control of flexible structures in the natural world

Mike Graham

Infrastructure development in many parts of the world is leading to increasing numbers of large flexible structures which will be subject to significant wind, being erected. Two such types of structure, which are quite dissimilar in shape but share many similar aero-elastic problems, are large horizontal axis wind turbines and long-span suspension bridges. Both stand in the lower part of the Atmospheric Boundary Layer of the natural wind which is both highly turbulent and subject to significant mean shear. Both have a main wind-sensitive component which is aerofoil like and subject to buffeting by the turbulent wind, but in addition both can develop significant regions of separated flow during at least part of their operating life and hence a degree of self-buffeting.

In the case of wind turbines in wind parks wake impact from other upwind rotors can be a source of further high levels of unsteady loading on the rotor blades. These unsteady loads together with cyclic gravitational loads largely determine the fatigue life of the blades and this is a major design driver with a strong influence on the ultimate cost of the energy produced. The presentation will describe an investigation into the effectiveness of controlled trailing edge flaps in counteracting unsteady loads. The flaps may be of small chord (< 5% blade chord) if rapid activation is desired and numerical simulation and laboratory experiments will be described which have shown that short flaps can achieve as much as an 80% reduction in the amplitude of unsteady loading using the blade section lift as the control input. The possibility of using variable flexibility of the blade section camber as an alternative to flaps will also be discussed.

Long span bridges suffer similarly from buffeting but the dominant design constraint as spans become longer is the requirement to keep the bridge sufficiently stiff in torsion and heave that the critical flutter speed is well above the extreme 'once-in-fifty-year' gust speed for the site. The use of controlled flaps, which because of the possibility of winds from either direction will include leading edge flaps, will be shown to be theoretically capable of raising the critical flutter speed of these bridges significantly as well as reducing buffet loads. Results of wind tunnel tests at around 1:100 scale will also be shown.

Linearised Navier-Stokes equations and developed turbulence

Sergei Chernyshenko

Turbulence is a non-linear phenomenon. The most common situation when linearised equations can give useful information about the behaviour of a nonlinear system is the situation when the nonlinear terms are small. However, this is not the only situation when linearised approach can be justified. Consider for example a nonlinear system, say, an electronic device, containing a linear filter and a number of nonlinear elements. Suppose that in this system there are broadband fluctuations. Suppose also that the filter is a narrow-pass filter. Then, if at the input of the filter the signal is broadband then at the output of the filter the signal will be narrow-band, that is it will have a dominant frequency. Now, one can disassemble the device, take the filter into the laboratory, and study it there, separately. As a result of this linear analysis (the filter is linear, and no nonlinear components were brought into the laboratory) one will determine the band-pass and, hence, will be able to predict the dominant frequency at the outlet of the filter when it works as a part of the nonlinear system. For this, only a linear analysis is required, and the nonlinear effects in the full system need not be small.

The reason why the Navier-Stokes equations linearised about the mean turbulent velocity provide useful information about nonlinear turbulence in spite of non-linear effects not being small is because the linearised equations have strong filtering properties.

This talk will discuss the idea of filtering in more detail for the case of a developed turbulent flow. In particular, we will consider how selective the Navier-Stokes equations linearised about the mean turbulent velocity profile actually are. Then we will turn our attention to the significant variation of the selectivity, or filtering properties depending on what particular flow characteristic is considered as the output of the filter. Third, we will discuss how these ideas can be used for developing predictive tools.

Then, a number of recent results based on linearised equations will be discussed, in particular the velocity and passive scalar streak properties, the patterns in the turbulent flow past an oscillating wall in the regime with drag reduction, and the drag reduction magnitude itself.

The importance of wall-normal Reynolds stress in transitional and turbulent rough channel flows

Paolo Orlandi

In the present paper the focus is on the effects of wall-normal stress on rough flows, then it has been first demonstrated that the present second-order accurate method reproduces the pseudospectral DNS profiles for smooth channels at high Reynolds number. Furthermore the same Reynolds number dependence in the experiments of flow past transversal square bars with *w/k* = 3 implies that the immersed boundary technique used to reproduce the effects of rough surfaces is a valuable tool. The importance of the wall-normal stress can be stressed by observing that the wall-normal momentum equation for fully developed turbulent channel flows implies a balance between $\langle p \rangle$ and $\langle u_2'^2 \rangle$. In addition, averaging the Poisson equation for pressure $-\nabla^2 p = s_{ij}s_{ji} - \frac{\omega_i \omega_i}{2} = -Q$, bring to the interesting outcome that $\frac{\partial^2 \langle u_2^2 \rangle}{\partial x_2^2}$ controls the topology of the turbulent structures. Points where $Q > 0$ are associated with tube-like vorticity distributions, whereas points where $Q < 0$ are associated with the occurrence of sheet-like vertical structures. In non-homogenous turbulent flows $\frac{\partial^2 \langle u_2^2 \rangle}{\partial x_2^2}$ accounts for the disequilibrium between $\langle s_{ij}s_{ji} \rangle$ and $\langle \omega_i \omega_i / 2 \rangle$; and thus te term $\frac{\partial^2 \langle u_2^2 \rangle}{\partial x_2^2}$ can be regarded as a measure of the number of sheet-like structures, which are inherently unsteady, and roll-up producing turbulent kinetic energy. the effects of the roughness on $\frac{\partial^2 \langle u_2^2 \rangle}{\partial x_2^2}$+ show a reduction in the size of the regions with sheet-like structures, which is a further indication that the roughness affects only a small layer near the plane of the crests, and the shape of the structures in this layer depends on the type of roughness of the surface.

It has also been demonstrated that $\widetilde{u_2'}|_w$ also controls the transition between laminar and turbulent flow conditions. Figure 1a indicates that $\widetilde{u_2'}|_w^+$ remains small up to $Re = 2500$, then it jumps to values greater than 0.6 when the flow is turbulent, and the Re dependence increases at high Re. The interesting outcome of Figure 1a is that, independent of the type of disturbance, in plane channels a fully turbulent regime is sustained if that maximum of $\widetilde{u_2'^+}$ is close to 1. This implies that the maximum of $\widetilde{u_2'}$ is directly proportional to the friction velocity.

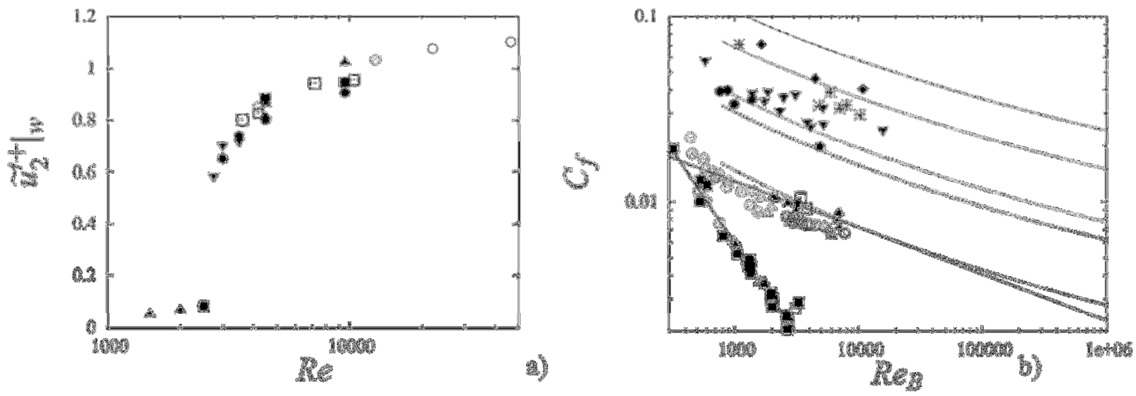

Figure 1: a) $\widetilde{u}_2'^+|_w$ versus Reynolds number, for different rough surfaces. b) C_f versus Re_B Solid symbols give the C_f of different surfaces from DNS the lines are obtained with different values of $\widetilde{u}_2'|_w/u_B$ starting with $\widetilde{u}_2'|_w/u_B = 0$ and with a 0.06 increment; the two dotted lines are at $\widetilde{u}_2'|_w/u_B = 0.06$, the thin with $U_W = 0$, the thick one with $U_W = 0.2$

The DNS provides diagrams of $C_f(Re_B)$, but the range of Reynolds numbers is smaller than that encountered in practical engineering applications. Thus it could be interesting to make an attempt to create a practical diagram of $C_f(Re_B)$ from the data at low Re. In this diagram, analogous to the classical Moody diagram, the equivalent sand-grain height is replaced by $\widetilde{u_2'}|_w$, which, interestingly, is also a boundary condition for RANS closures, appears. The new diagram is obtained following the same procedure described in the book of Schlichting, based on the assumption that the defect velocity profile $(U_H - U)/u_{\tau R}$ fits the law $\kappa^{-1}\log(H/y)$ in the outer layer, for any type of roughness. It has also been used the expression of the roughness function $\Delta U_W^+ = B\frac{\widetilde{u_2'}|_W^+}{\kappa}$ entering in the log law expression for U^+. the friction curves $C_f(Re_B)$ in figure 1b are then obtained, from the non-linear equation, for each value of $\widetilde{u_2'}|_w$. In the classical Moody diagram the curves move upward by increasing the size of the equivalent roughness eight, then it can be asserted that the effect of an increase of the size of the roughness elements leads to an increase of u_2 fluctuations at the plane of the crests. Since the curves in figure 1b extend into the range of Reynolds numbers for real applications, the equation obtained with $\Delta U^+(\widetilde{u_2'}|_W^+)$ can be of practical utility.

The question of universality of turbulent axisymmetric wakes

John Redford, Ian Castro and Gary Coleman

The aim of this study is to test the validity of the Townsend hypothesis that, irrespective of the details of how they are created, all boundary-free turbulent shear flows eventually reach a universal state. Although plausible and conceptually attractive, the idea of universal self-similarity for free shear flows is currently somewhat controversial. It has been called into question, for example, by the measurements of Bevilaqua & Lykoudis (1978), who found that the wakes downstream of two axisymmetric bodies (one a sphere, the other a porous circular disk) were both self-similar but not uniquely so – despite both bodies producing the same drag. More recently, George and co-authors have developed a generalised similarity analysis (e.g. George 1989) that can account for the effect of the structural details of the initial conditions on the far field of various free shear flows. They point to the experimental and numerical simulation data that show the far-field statistics, such as mean growth rates, can remain initial condition dependent very far downstream of the point at which the wake was created. However, the possibility that the initial-condition dependence eventually fades cannot be ruled out. Bevilaqua & Lykoudis stress the difference between universality and self-similarity, and suggest non-universal forms of the latter may in time tend asymptotically towards the former (see also Narasimha 1992).

The question of universality is examined here by comparing 'far field' (i.e. very late) results from direct numerical simulation (DNS) of two time-developing axisymmetric wake flows, initialised such that they contain qualitatively very different turbulence structures but the same net momentum defect. The first of the two initialisation strategies (denoted VR) invokes a nonlinear/bypass transition, by specifying a series of vortex rings and perturbing them slightly, via radial/geometric displacement of the core location (see figure 1). The other initialisation (Case VRX) adds low-level random disturbances to the axisymmetric mean velocity deficit taken from Case VR, so that the turbulence is the result of growth and interaction of the linearly unstable modes of the parallel-flow axisymmetric shear layer. The DNS results indicate that after a period of non-universal self-similarity, for which each flow exhibits its own distinct mean spreading rate (figure 2a), the two cases eventually converge to a universal state and enter the 'Townsend regime', characterised by similar turbulence structure and mean-flow evolution (figure 2b).

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Bevilaqua, P. M. & Lykoudis, P. S. 1978 Turbulence memory in self-preserving wakes. J Fluid Mech. 89 589–606.
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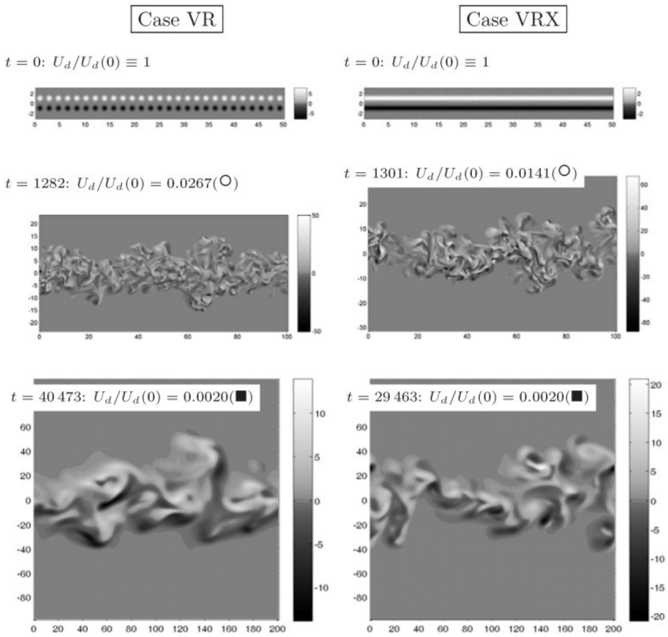

Figure 1: Evolution of vorticity contours for Cases VR and VRX.

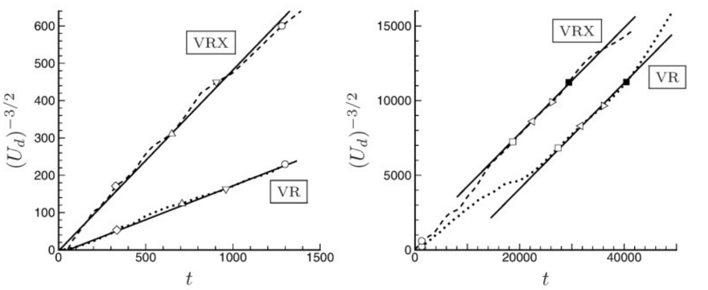

Figure 2: Similarity diagnostics for time-developing axisymmetric wakes: ········ , Case VR; - - - -, Case VRX. Variables normalised by initial maximum wake defect U_d and initial integral wake-width scale $\rho_* = [(\ln 2/\pi)(I_d/U_d)]^{1/2}$ where $I_d = 2\pi \int_0^\infty (U_\infty - U) r \, \mathrm{d}r$.

Wind turbine wakes in stratified flow: some initial experience with wind tunnel simulations

Philip Hancock

A programme of work is being undertaken on wind turbine wakes in the context of large off-shore wind farm arrays, of 5MW-sized turbines. Part of the EPSRC-Supergen-Wind consortium, the Surrey work itself is concerned with wake development, wake-wake and wake-turbine interactions, in neutral, stable and unstable atmospheric wind flows. Existing wake models, especially those for practical engineering purposes, are based on neutral wind flows. However, offshore atmospheric boundary layer (ABL) field data indicates that ~75% of the time the wind flow is stable, unstable or very unstable.

Currently, work is in hand on the effects of stable and unstable stratification on the wake of single wind turbines, and has required the extension of the capability of the EnFlo wind tunnel. This wind tunnel is one of a few globally that is able to simulate both stable and unstable stratification at a scale that is large enough to adequately represent large wind turbines. Stratification is achieved by cooling or heating the floor - and inlet heaters provide control of the imposed conditions above the ABL - so as to produce the desired balance between buoyancy and inertial forces.

The offshore case is particularly challenging as the sea-surface aerodynamic roughness is relatively low, leading to greater difficulty in roughness scaling than arises in rural or rougher-surface flows. The offshore stable case is even more challenging. For instance, the upper part of the rotor disk can be influenced by the outer part of the ABL, where the imposed condition is important, while the lower part is more likely to be influenced by the surface condition. A sufficiently strong imposed stable condition (and only weak surface stability) can lead to no vertical growth in the wake.

Designed by Alan Robins and built by the CEGB in the 1980's for dispersion studies, the wind tunnel was brought to Surrey in 1992 in a campaign led by Ian Castro, to form the major part of the EnFlo lab. The presentation is with this in mind, of that forward-looking initiative.

Vortex-induced vibration of circular cylinders and its suppression

Peter Bearman

Recent results of research on vortex-induced vibrations of isolated circular cylinders and the flow and vibration of circular cylinders in a tandem arrangement will be presented. Vortex-induced vibrations (VIV) are a continuing problem, particularly in offshore operations. The influence of Reynolds number on the response of isolated cylinders is discussed and the response of a cylinder free to respond simultaneously in the in-line and transverse directions is contrasted with that of a cylinder responding in only one direction. The interference between two circular cylinders is presented and prominence given to the case of cylinders in a tandem arrangement. The origin of the time-mean lift force on the downstream cylinder is considered together with the cause of the large amplitude transverse vibration experienced by the cylinder above vortex resonance. This wake-induced vibration is shown to be a form of vortex-induced vibration.

A widely used method for suppressing VIV, developed originally in the wind engineering field, is the attachment of helical strakes. However, strakes suffer from two major problems: the first being that they increase drag and the second that their effectiveness reduces with decreases in the response parameter $m^*\zeta$, where m^* is the ratio of structural mass to the mass of displaced fluid and ζ is the fraction of critical damping. It is known that if vortex shedding from a rigid cylinder is eliminated, say by the use of a long splitter plate, then drag is reduced hence conceptually an effective VIV suppression device should be able to reduce drag rather than increase it. This simple idea is the motivation for some of the work to be described. Rather than try to promote three-dimensionality, as with helical strakes, two dimensional solutions are proposed that are shown to suppress vibrations down to very low values of mass and damping.

Reynolds number sensitivity of vortices in boundary-layer flows

Roger Hoxey, Peter Richards, Adam Robertson and Andrew Quinn

A wind-tunnel study at the University of Southampton, linked to full-scale measurements at Silsoe Research Institute, was the basis of an EPSRC funded project with Ian Castro as the proposer and principal investigator. Ian and Alan Robins had been responsible for earlier, fundamental work on cubes immersed in uniform turbulent streams (Castro & Robins 1977, cited in over 230 reports that we know about), and the more recent work, 2002 – 2006, took another look at cubes in fully-developed, boundary-layer flow to explore scale effects.

Some of the findings of the recent study were presented in a JFM report (Lim, Castro & Hoxey 2007, denoted herein by LCH) where scale effects were observed in regions of the flow over the cube near strong, edge-generated vortices. Experiments were conducted at the University of Southampton in both the R J Mitchell wind tunnel (working section 3.4m x 2.5m x 8m long) and in the much smaller (0.9m x 0.6m x 4.5m) open-circuit tunnel. The full-scale cube (h = 6m) was scaled at 1:25 (h = 240mm) and 1:75 (h = 80 mm) in the large and small tunnels respectively with appropriately simulated boundary-layer flow. Full details are in LCH and only one result is extracted here of the mean pressure coefficient at a point on the top of the cube for a flow incident at 45 degrees to the cube. The tapping point is 0.069 h from the leading edge, and is under the delta-wing type vortex. Figure 1 shows the pattern of the mean pressure coefficient with respect to *Re* found in the three experiments.

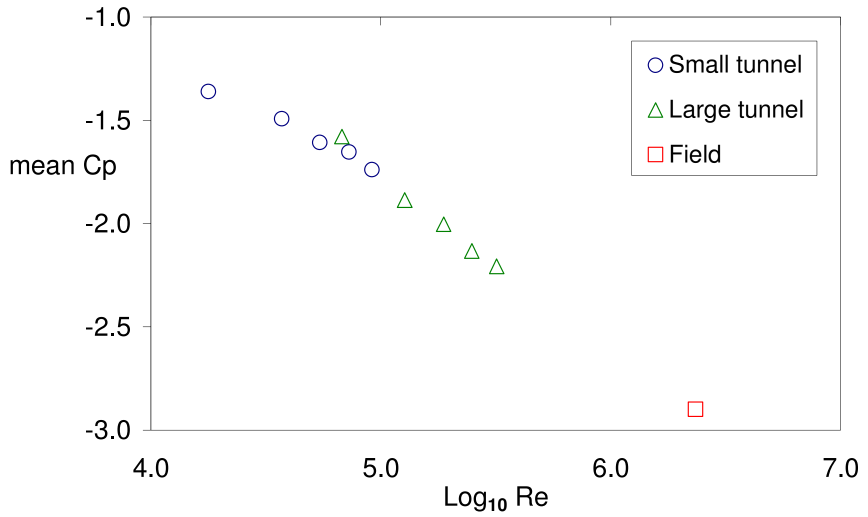

Figure 1 Mean surface static pressure under the vortex generated from the leading edge of a cube set at 45 degrees to the mean flow (position 0.069 h from leading edge, 0.356 h from side)

The mean pressure coefficients for the cube at 0 degrees showed no significant *Re* effect and led to the observation in LCH that 'where strong concentrated vortices exist …. clear *Re* effects do exist in the mean-flow field'.

The work at Southampton and at Silsoe shows significant *Re* dependency on surface pressure associated with recirculation regions on bluff bodies. The strongest effect is found where stable vortices are generated such as the 'delta-wing' type vortex which can be seen when a bluff body is yawed to the mean flow. It is argued here that the vortices generated in the atmospheric boundary layer (ABL) are also *Re* sensitive, as it is a reasoned extension to assume that viscosity will have a similar effect here too, although it has not been possible to find definitive evidence. There is circumstantial evidence in that a well-modelled, wind-tunnel generated boundary layer will have generally lower turbulence than the full-scale boundary layer, which is indicative of reduced vorticity. There are also many model-scale experiments that fail to reproduce the extreme surface pressure suction peaks found at full-scale.

There are observable static pressure variations within the ABL associated with vorticity and these variations contribute to the surface static pressure on a building as sensed at a tapping point. It is also evident from spectral analysis that the static pressure fluctuations contribute more to the surface pressure at the higher frequencies as the spectrum of the fluctuations increase as shown by a -4/3 logarithmic decay rate, compared to a -5/3 rate for dynamic pressure. This spectral observation has in the past been explained as contributions to tapping pressure fluctuations from building-induced turbulence: this explanation is now called into question.

The vortical elements in the turbulent boundary layer reduce the pressure on the surface of a building; these are not necessarily related to the instantaneous dynamic pressure, ½ $\rho u2$, but are related to turbulence in the flow. The magnitude of these pressures, which contribute to the wind load on a building, are not quantified here but in some cases this 'static pressure' term may exceed the conventional *C*p term. Further work is required to establish appropriate information for the design of structures.

As far as we are aware there is no database available that contains meteorological information on fluctuations and extremes of static pressure in the ABL, akin to that available for wind speed.

The corollary to these observations is that it may not be possible to generate the small scale vorticity found in the ABL at model scale because of viscous effects, and that the extreme negative pressures are underestimated. This may also apply to full-scale measurements that are made at low wind speeds where the vortical contribution to surface pressure may be reduced by viscous dissipation.
These findings are tentative and should form the basis of a discussion at the workshop.

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The streamwise turbulence intensity in wall bounded flows – is there an outer peak?

P. Henrik Alfredsson

Recently the existence of a second, outer peak in the streamwise turbulence intensity in wall bounded turbulent flows, seen only at high Reynolds numbers, has been discussed. A problem associated with turbulence measurements using hot-wires at high *Re* in laboratory flows, is the spatial resolution associated with the finite sensor length. It has been shown that this may give rise to a false outer peak in the rms distribution of the streamwise velocity fluctuations. A simple analysis will be demonstrated that can show whether a measured outer maximum is real or due to spatial averaging.

Furthermore a composite profile of the streamwise turbulence intensity, sometimes known as the diagnostic plot, will be shown to predict such a maximum above a certain, high, Reynolds number for smooth boundary layer flows. The diagnostic plot uses neither the wall position nor the friction velocity to plot the streamwise rms-distribution, but instead the fluctuations are normalized by the local mean velocity and given as a function of the ratio between the local velocity and the free stream velocity. Finally it will be shown that the use of the diagnostic plot by Prof. Ian Castro on some of his rough boundary layer data, gives a remarkable collapse of the data indicating that the suggested profile description originally developed for smooth boundary layers may be useful also in other flows.

Acknowledgement: The results presented here are based on joint work with Drs. Antonio Segalini and Ramis Örlü at KTH, and with an interesting additional contribution by Prof. Ian Castro.

The rough side of town – turbulent boundary layers over cities

Stephen Belcher

Atmospheric boundary layer flow over cities is a case of extremely rough wall boundary layers. Over the last 10 years or so there has been great interest in these flows both because of the practical interest in the effects of cities on weather and climate, but also because of the theoretical interest in rough wall flows. Measurements in the atmosphere, in wind tunnel modelling and high resolution simulations (including LES and DNS) are providing insights and data to test various theoretical frameworks for setting these flows. And it turns out Ian Castro was there very early on!

Mean flow, turbulence and dispersion in a complex urban-like geometry

Omduth Coceal

Characteristic flows in urban areas are complex for two main reasons: the geometry is complicated, and the flows are highly turbulent. How are the flow features related to the building geometry, and how do they affect the dispersion of passive scalars? These questions are explored using results from direct numerical simulations and large-eddy simulations, and discussed in the context of experimental findings in the literature. For a regular arrangement of buildings, it is shown that generic dispersion processes can be identified, and that they can be linked to features of the geometry, mean flow and turbulence. Essentially, this includes advection effects within the building geometry due to mean flow channelling, 'topological' splitting of the plume around buildings, and turbulent vertical transfer as a result of predominantly unsteady exchange processes. Secondary sources, resulting from entrainment of material in building wakes and their subsequent re-release, modify both the near-source concentration pattern and its subsequent evolution. Further effects come into play when the non-regular aspects of real urban geometries are taken into account. This includes mechanisms that enhance vertical scalar transfer induced by variations in building heights, as well as the skewing of the dispersion plume with height as a result of asymmetries in the flow. Implications for predictive urban dispersion modelling at street and neighbourhood scales are briefly discussed.

Direct Numerical Simulation of a turbulent channel flow with 3D random roughness on a wall

Stefano Leonardi

Turbulent flows over rough surfaces are often encountered in engineering. Paint and corrosion, accumulation of living organisms (bio-fouling) or non-living substances and spallation are different type of roughness which can be found on the ships. At high Reynolds numbers pipes and ducts cannot be regarded as hydraulically smooth. In the atmosphere and ocean, the underlying surface is usually rough. Since the roughness can seriously degrade the performance of airfoils, turbomachinery blades, and determine an overall drag increase, the ability to predict its effect is important. In the last two decades several numerical and experimental studies have tried to explain the physics of the flow over rough surfaces. Most of the studies have dealt with idealized roughness: square bars, sand grain, meshes, rods, cubes, chopped transverse bars. However, "an understanding of idealized roughness may not properly extrapolate to more practical cases of highly irregular surface roughness" (Bons 2002). Some research groups have considered random (or irregular) roughness, from the pioneering work of Xie & Castro (2006) to the recent contributions of Anderson & Meneveau (2011) Mejia-Alvarez & Christensen (2010) and Flack & Schultz (2010).

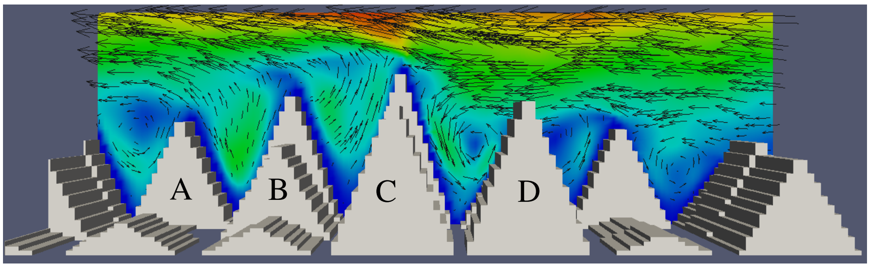
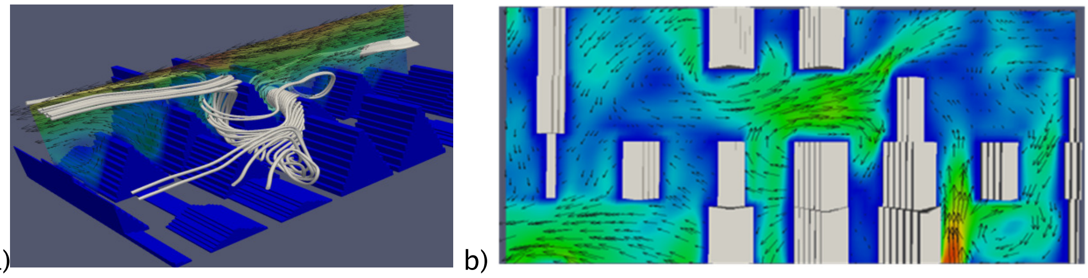


Figure 1 Velocity vectors superimposed to colour contours of streamwise velocity

In the present paper we discuss Direct Numerical Simulation results of the turbulent flow over a rough wall made of 3D wedges of random height (Fig.1). In addition, two other simulations have been carried out to assess the effect of the geometry on the overlying flow. In the first simulation, the elements in the wake of higher wedges were removed while in the other, a uniform distribution of wedges with the same area was used. A wedge is considered in the wake of another element when the line joining the crests is steeper than 45 degrees. The bulk Reynolds numbers is 7000 which correspond in case of smooth walls to Re_τ=300. Periodic boundary conditions apply in the streamwise and spanwise direction, while no slip conditions are imposed on the upper boundary of the computational box. Figure 1 shows velocity vectors superimposed to color contours of streamwise velocity in a vertical section. While on 2D transverse bars or uniform cubes the flow structure is rather uniform, over 3D irregular roughness even similar geometrical elements present different flow features. For example, between the wedges "C" and "D" a recirculation similar to those occurring over transverse rods can be observed. On the other hand, between "A" and "B" or "B" and "C" ejections are observed. This is due to two streams of fluid coming from the sides, merging in the cavity and causing an ejection.

The onset of a strong and irregular spanwise motion can be observed in Fig. 2. Streams of fluid moving in the spanwise direction between the "canyons" formed by the wedges can be observed. Recirculations in horizontal planes show the complexity of the flow structure over irregular roughness geometries. The pressure distribution on the walls of the wedges not surprisingly is correlated to the flow field.

Therefore, similar elements may have different contribution to the form drag of the surface, depending on the position within the irregular array of elements. The pressure drag is about 80% of the overall drag.



a) b)

The Reynolds stress budgets showed a redistribution of energy between the streamwise velocity to the normal wall and spanwise velocity components. The main sink in the budget of <uu> is not the dissipation but rather the pressure-velocity correlation and the turbulent diffusion. At the conference a comparison of the 3 surfaces will be discussed.

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Inner-outer layer interactions in rough-wall boundary layers

Per-Åge Korgstad

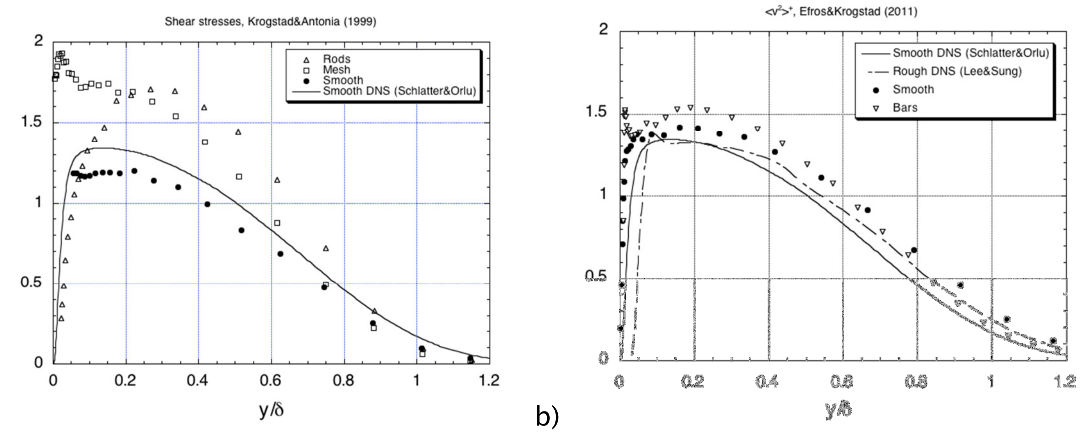
The question of how the inner layer interacts with the outer part of a turbulent boundary layer over rough surfaces has been receiving considerable attention for some time. The main reason for this has been due to the fact that the many experiments and simulations performed have not been able to give very convincing answers. In some cases the surface roughness has been found to make significant changes to the turbulent structure in the outer layer (e.g. Krogstad & Antonia, 1999, Lee & Sung, 2007, Volino et al., 2009) while others have provided equally strong evidence to say that the outer layer is not influenced by surface roughness when the variables are properly scaled (e.g. Amir & Castro, 2011, Flack et al., 2005, Krogstad & Efros, 2010).

Various explanations for the differences in the observed effects have been offered. It has been suggested that spanwise bars provide a type of perturbation that is very efficient in enhancing the communication between the inner and outer layers by constantly feeding information into the flow at a particular wave number. Many experiments, but also DNS simulations, have shown significant outer layer modifications in flows over this type of surface (e.g. Lee & Sung, 2007, Volino et al., 2009). However, the combined experiment and DNS study of Krogstad et al. (2005) for the flow in a channel could not verify the outer layer changes that had previously been observed in boundary layers over the same surface geometry. Also for flows in rough pipes it has been suggested that the core region is unaffected by the surface roughness. This has raised the question of whether internal flows might react differently to surface roughness than boundary layers.

The best explanation for the observed differences in surface roughness effects has probably been put forward by Jimenez (2004). He suggested that part of the controversy observed for boundary layers may have been caused by lack of scale separation between the roughness length, k, and the boundary layer thickness, δ. Based on simple estimates of how the roughness affects the logarithmic layer and therefore turbulence production, it was suggested that for the roughness elements not to act as individual obstacles submerged in a boundary layer, but to be a perturbation to the surface boundary condition only, there should be a separation of scales between δ and k of at least $\delta/k > 40$.

To investigate this criterion in some detail, the two-dimensional bar experiment of Krogstad & Antonia (1999) (Figure 1a) was repeated in a much thicker boundary layer that allowed Jimenez criterion to be fulfilled with good margin. Figure 1a shows the wall normal stress, $\langle v^2 \rangle^+$, which was found to be the most sensitive of the Reynolds stresses for the first experiment. Also included is data from an experiment over a surface covered with a stainless steel woven mesh which had the same roughness height. For both surfaces it is seen that the stress level is increased significantly all through the boundary layer, suggesting a very strong interaction between the inner and outer layer. In this experiment $Re_q = 4800$ in the rod case with a roughness scale of $k^+ = 43$ and δ/k was about 47, close to the limit given by Jimenez (2004). Krogstad & Antonia (1999) demonstrated the flow satisfied the criteria for fully developed rough wall boundary layers.

In the repeated, thick boundary layer experiment reported in Efros & Krogstad (2011), the Reynolds number was increased almost by a factor 10 to Re_q = 32600. In this experiment the roughness scale was about k^+ = 100, so from a roughness effect point of view the two flows should be comparable. The boundary layer thickness was about three times as high as in the first case. Therefore, with roughly the same bar height, the ratio of length scales was now increased to δ/k = 131. Figure 1b shows that the outer layer effect is now much smaller with hardly any changes from the smooth wall measurements for $y/\delta > 0.4$. Also included are the smooth wall DNS of Schlatter & Orlu (2010) and the rough wall DNS of Lee & Sung (2007). The two DNS calculations show a much larger outer layer change than found in the experiment. This is probably due to the much lower Reynolds numbers and a significanly lower range of scales, δ/k. Comparisons with other turbulence quantities will be presented and it will be shown that up to third order moments the outer layer perturbations are small when δ/k is increased well above the limit suggestion put forward by Jimenez (2004).



a) b)

Figure 1. (a) Krogstad & Antonia (1999), (b) Efros & Krogstad (2011)

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Similarity and non-equilibrium effects in rough-wall channel flow

Jonathan Morrisson and David Birch

The streamwise and surface-normal velocity components in fully developed turbulent channel flow and studied for two fully rough surfaces ($k^+ \approx 200$) and a smooth surface at Reynolds numbers, $Re_\tau \approx 5000$. One rough surface comprises sparse and isotropic grit with a highly non-Gaussian distribution. The other is a uniform mesh consisting of twisted rectangular elements forming a diamond pattern. The mean velocity profile over the grit surface exhibits self-similarity (in the form of a logarithmic law) within the limited range of $0.04 < \frac{y}{h} < 0.06$, but the profile over the mesh surface does not, even though the mean velocity deficit and higher moments (up to fourth order) all exhibit outer scaling over both surfaces. The distinction between self-similarity and outer similarity is clarified and the importance of the former is explained.

Surprisingly, the energy balance within the supposed log region on the grit surface does not conform to the local-equilibrium approximation: the log-law matching procedure defines a roughness lengthscale and a zero-plane displacement, $d^+ = 130$ for $\kappa = 0.41$. Although the zero-plane displacement is somewhat smaller than that required for the measured shear-stress gradient to match the linear variation required by the momentum equation, $d_m^+ = 237$: when this offset is used in the log law, the data no longer provides a region in which the velocity varies logarithmically. The reasons for this are discussed and the behaviour of the turbulence in the log region is examined, with particular reference to the maximum in the Reynolds shear stress, y_p^+, which sensibly appears below the log region, $\left(y_p - d\right)^+ \approx 45, \left(y_p - d_m\right)^+ \approx 75$. Scaling of the velocity spectra and second- and third-order structure functions is examined: the energy balances in the log region and at the centre-line where estimates of the dissipation rate can be made are also examined.

Single- and two-point velocity correlations reveal the presence of large-scale streamwise structures with circulation in the plane orthogonal to the mean velocity.

What did we do in Marylebone Road…..did it all begin with the Marchwood cube?

Alan Robins

The DAPPLE experiments in the streets around Marylebone Road and the associated and subsequent wind tunnel and modelling work addressed many issues surrounding flow and pollutant dispersion in cities, a selected sample of which will discussed in my talk. One major aim was data collection and that was successfully met; important though that was, the talk will concentrate mainly on case studies. Firstly, what did we learn about flow in the street network and how did this correspond to previous descriptions based on wind tunnel and computational work? Some more recent extensions of the wind tunnel work will be discussed, in particular attempts to establish mass flux balances at intersections. With some understanding of flow conditions, we can look to the implications for dispersion and ask if the tracer dispersion experiments matched or exceeded our expectations. Some of the more unconventional effects, at least for those accustomed to normal dispersion behaviour, will be illustrated, again using field and laboratory results. This will include lateral and upwind dispersion and some aspects of the role of traffic movement in these processes. The final case study will concern variability in the dispersion processes. The DAPPLE work could be thought of as a promising start, but one that created many more questions than it answered. One such question, which that will be returned to throughout the presentation, enquires of the ability of commonly used dispersion models?

Engineering consultancy and rigorous fluid mechanics

Ian R Cowan

Fluid Mechanics has long been an important discipline in the industrial sector, both from a performance perspective (improving plant performance and reliability) and a safety perspective (protecting human life and the environment). With the rise of cheap computing over the last decade, Computational Fluid Dynamics (CFD) is now no longer the preserve of universities and large automotive companies with their Cray supercomputers, but indeed can be run economically by anyone with access to a run-of-the-mill desktop PC.

Software vendors have, to their credit, expended huge effort to transform the inaccessible Fortran CFD codes of the early '90s into user-friendly, function-rich, software packages which are very easy and intuitive to use, for users of all backgrounds. These are powerful tools, which are now used daily across the world, helping engineers design new facilities and improve and maintain existing plant. As an example, a very brief description will be provided of an exciting new development in the area of floating liquefied natural gas (LNG) production, and of the way that CFD is being used to guide the design of what will be the world's largest floating object.

As the CFD codes become easier to use and accessible to a wider cross-section of (typically non-academic) users, it is reasonable question to ask – what sort accuracy might one expect from the CFD model predictions? This is a question that Prof. Ian Castro, Prof. Alan Robins and myself examined over 15 years ago, as part of my post-doc placement with them, in a project on modelling uncertainties (Project EMU). The purpose of this brief talk is to provide an update, 15 years on, with an example application, and to see whether the improved usability and functionality of the modern CFD codes are enough to fill the knowledge gap for today's users, or whether there is still a need for rigorous Fluid Mechanics understanding, to underpin the use of the CFD modelling – of the sort that Prof. Castro taught and practiced. The conclusion should not come as a huge surprise.

Waves, slugs and ghosts in gas-liquid pipe flow

Andy Hunt

The flow of gas and liquid in a pipe exhibits many and varied structures, often wavelike in form in common with other free surface flows. Because of the restriction of the pipe surface surrounding the flow, the waves are bound to this circular geometry and form other structures that from the outside of the pipe may appear visually to fill it. Measuring the internal detail of such structures requires non-intrusive measurements and offers an interesting challenge, and electrical capacitance tomography (ECT) is one method of visualising the entire flow field across the pipe.

Comparisons between measurements using various combinations of imaging and other sensors in two-phase flows have been made in the past including: ECT and gamma-ray densitometers (Hunt, Pendleton and Ladam 2004); wire-mesh sensor (WMS) and ECT (Azzopardi, Hampel and Hunt 2009; Hunt, Abdulkareem and Azzopardi 2012); WMS and x-ray tomography (Prasser et al 2005); ECT and weigh scales (Hunt, Pendleton and Byars 2004). These comparisons have shown that for measuring dynamic properties of local flow ECT is fast (up to 5000 frames of data per second), accurate, non-intrusive but with low spatial-resolution.

Atout Process Ltd in collaboration with Tomoflow Ltd is developing ECT as a mass flowmeter for complex multiphase flows in industrial applications, but in the course of our development we have observed many interesting structures in the flows. Our results demonstrate that ECT can measure volume fraction accurately, but that the velocity measurement based on cross-correlation does not measure a particular phase velocity but actually measures flow 'structure' velocity. In gas-solids flows those structures may be large solid lumps or clusters of solid particles, and in gas-liquid flows they may be small bubbles, large 'churn' bubbles, waves or slugs. Given the capabilities of ECT to measure concentration and velocity non-intrusively we are able to show detailed void fraction and velocity profile information.

In this paper we concentrate on two interesting structures in gas-liquid flows. The first type, observed in horizontal pipelines, is a solitary travelling wave that is so quiet in its passage along the pipeline that the project technicians named it 'the ghost'. The second type is the 'huge wave' (named by Sekoguchi and Mori 1997) involved in the transition from annular flow to churn flow in vertical flow.

For the 'ghost' flows, visual observations show what appears to be a frothy 'slug' occupying the entire pipe, moving individually at very long wavelength, essentially solitary. ECT measurements show that in fact the structure has an air core and is effectively a cylindrical wave wrapped around the pipe perimeter. This structure does not appear to be part of a coherent transition between flow regimes.

In vertical gas-liquid flows we observed three types of flow: dispersed bubble, plug and huge wave. In dispersed bubble flows at higher liquid velocities and low gas flowrate the velocity profile exhibits a centre-peak, while for plug flows we see a flat velocity profile. An important transition is seen at a gas superficial velocity of about 1 ms-1 as huge waves become the dominant feature with a significant centre peak to the velocity profile. At this transition the velocity of the wave structure is about 2ms-1 and the transition is clearly measurable by the frequency of flow structures. Below the transition (in plug flow) the frequency increases with gas superficial velocity while above the transition (with huge waves dominant) the frequency is approximately constant. Below the transition point the bubbles are large, irregular 'churn' bubbles that seem to 'tunnel' up the pipe into the fast-moving wake of the bubble in front. We believe that the transition point is associated with the moment at which gas from one plug structure 'breaks through' the liquid barrier to the higher one and a continuous gas core starts to exist in the flow.

LES of accidental releases

Michael Schatzmann

Manufacturing, storing and transportation of flammable and toxic gases involves the risk of accidental spills. Releases of major concern occur in urban or industrial environments, with the consequence that the dispersion is heavily influenced by buildings and other obstructions. Dispersion models of different complexity have been developed in the past. Although they have been reasonably successful in some cases, most of them are still limited in scope. Especially in cases where obstacle effects dominate the dispersion of the hazardous cloud, these models are either too simplistic and thus unable to cope with the geometric complexity, or they are much too slow and thus not able to provide immediate guidance for the persons in charge of the rescue operations. First responders, however, need a more or less instant estimate of danger zones resulting from accidentally released hazardous materials in order to take immediate action, to coordinate rescue teams and to protect human population and critical infrastructure.

Recent progress in the fields of computer hardware development, numerical mathematics and scientific computing opens up the potential for improvements. In an effort jointly carried out by the Ministry of the Interior of the Free and Hanseatic City of Hamburg, by the US Naval Research Laboratory in Washington, DC, and by the Meteorological Institute of the University of Hamburg, a new emergency management tool for the Hamburg inner city area has been developed. This tool provides, nearly instantaneously, the space-time-structure of airborne hazardous clouds. It is based on a high- resolution LES contaminant transport model (FAST3D-CT) which provides the detailed velocity and turbulence fields within the urban domain. This database is then converted to an efficient form suitable for use in a second model (CT-Analyst) which runs on a laptop and comes with an interface as is common in computer games.

The system is fast because results are pre-computed for a large number of meteorological situations. In case of an accident predictions are based solely on already existing knowledge. The system is easy to handle due to its user-friendly interface. A typical example of such an approach adjusted to the geometry of the Hamburg inner city area will be presented. Special emphasis will be laid on the validation of modeled results.

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