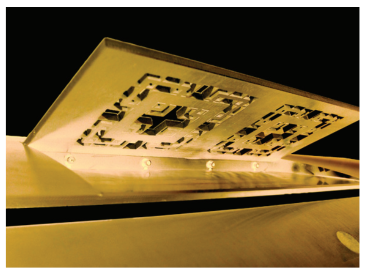
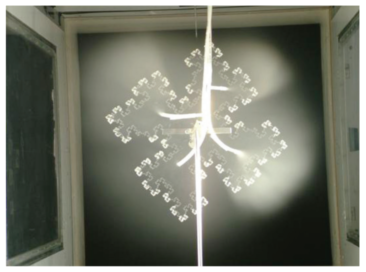
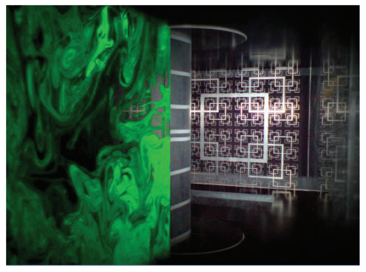
1ST UK-JAPAN BILATERAL WORKSHOP
28-29 March 2011
Department of Aeronautics | Imperial College London

S. Laizet, Y. Sakai, J.C. Vassilicos

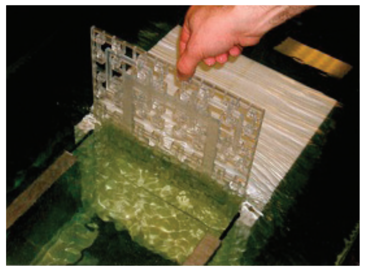


Turbulent flows generated/designed in multiscale/fractal ways: fundamentals and applications





FINAL PROGRAMME



Imperial College London | Nagoya University

Programme

MONDAY 28 MARCH 2011

8.30-9.00: *Arrival and Registration (free entrance)*
9.00-9.15: *Introduction by J.C. Vassilicos (Imperial College London, UK)*

FIRST SESSION: FUNDAMENTALS
9.15-9.50: W.K. George (Imperial College London, UK) *Freeing turbulence from the tyranny of the past*
9.50-10.25: M. Oberlack (TU Darmstadt, Germany) *Beyond mean flow scaling laws - how to obtain higher order moment scaling from new statistical symmetries*
10.25-11.00: S. Goto (Okayama University, Japan) *Multiscale self-similar coherent structures in developed turbulence*
11.00-11.30: COFFEE BREAK

SECOND SESSION: DIFFERENT WAYS OF GENERATING TURBULENCE
11.30-12.05: N. Sekishita (Toyohashi University of Technology, Japan) *Successful attempts of large scale-turbulence realization by a Makita-type turbulence gen- erator and a buoyancy jet in a cross wind*
12.05-12.40: T. Ushijima (Nagoya Institute of Technology, Japan) *Mean flow development of wake behind the Sierpinski tetrahedron*
12.40-14.15: LUNCH
14.15-14.50: K. Nagata (Nagoya University, Japan) *Reexamination of fractal-generated turbulence using a smaller wind tunnel*
14.50-15.25: P. Valente (Imperial College London, UK) *Decay of homogeneous turbulence generated by a fractal square grid: wind tunnel experiments*
15.25-16.00: P. Lindstedt (Imperial College London, UK) *Fractal generated turbulence in isothermal and reacting opposed jet flows*
16.00-16.30: TEA BREAK

THIRD SESSION: MULTI-POINTS STATISTICS AND INTERMITTENCY
16.30-17.05: J. Peinke (University of Oldenburg, Germany) *A new class of turbulence - insights from the perspective of n-point statistics*
17.05-17.40: C. Keylock (Sheffield University, UK) *The wake structure, energy decay and intermittency behind a fractal fence*

TUESDAY 29 MARCH 2011

FOURTH SESSION: FLOW DESIGN FOR APPLICATIONS
9.15-9.50: Y. Sakai (Nagoya University, Japan) *Mixing of high-Schmidt number scalar in regular/fractal grid turbulence: Experiments by PIV and PLIF*
9.50-10.25: J. Nedic (Imperial College London, UK) *Aero-acoustic performance of fractal spoilers*
10.25-11.00: COFFEE BREAK
11.00-11.35: N. Soulopoulos (Imperial College London, UK) *A turbulent premixed flame in fractal-grid generated turbulence*
11.35-12.10: T. Sponfeldner (Imperial College London, UK) *A parametric study of the effect of fractal-grid generated turbulence on the structure of premixed flames*
12.10-13.30: LUNCH

FIFTH SESSION: SIMULATIONS
13.30-14.05: B. Geurts (Twente University, Holland) *Turbulence modulation through broad-band forcing*
14.05-14.40: S. Laizet (Imperial College London, UK) *Direct Numerical Simulation of multiscale generated turbulence*
14.40-15.00: TEA BREAK
15.00-15.35: M. Pettit (Imperial College London, UK) *LES/DNS of Opposed Jet Flows Employing Fractal Turbulence-Generating Plates*
15.35-16.10: H. Suzuki (Nagoya University, Japan) *DNS on spatially developing fractal generated turbulence with heat transfer*
16.10-16.30: Discussion/Conclusion

Introduction

After more than a century of exhaustive research on the aerodynamics and hydrodynamics of geometrically simple shapes, whether streamlined as in wings or bluff as in spheres and cylinders, it is blindingly natural to expect much of the future in fluid mechanics to lie in the aerodynamics and hydrodynamics of geometrically complex, and thereby multiscale, shapes.

The simplest cases of multiscale shapes are fractal shapes, which is why they have been a good start. These are multiscale shapes with a complex appearance which can nevertheless be defined with only a small number of scaling parameters.

To my knowledge, the study of turbulent flows generated/designed in multiscale/fractal ways started in the UK with an experimental publication in 2001. These multiscale/fractal ways include multiscale/broadband forcings as well as multiscale/fractal boundary and/or initial conditions. The first computational model of turbulence subjected to fractal/broadband forcing which was neither motivated by nor limited to intricacies of Renormalisation Group theory appeared in 2002, also from the UK.

The idea was to interfere with the multiscale dynamics, inner geometry and topography of the turbulence itself and find out whether qualitatively different types of turbulence can be created. Whilst this idea is perhaps easy to accept for multiscale/broadband forcings it is less easy to accept for multiscale/fractal initial/boundary conditions.

This is where the work of William K. George over the past quarter century fits in and gives meaning to the endeavour, in particular his work on the importance and imprint of initial/boundary conditions on turbulent flows. If turbulent flows keep a degree of memory of the conditions which generate them, then the possibility exists of designing bespoke turbulent flows taylor-made for particular applications. This is far better than turbulent flow control if it can be achieved. Multiscale/fractal generation/design is about using multiscale/fractal objects (such as grids, fences, profilers etc) to shape the nature of the resulting turbulent flow over a broad range of scales for a broad range of applications. Below is a list of applications touched upon in this 1st Japan-UK meeting. More applications will be discussed in the 2nd Japan-UK meeting one year from now.

1. Fractal mixers: fractal grids can be used to design turbulent flows with low power losses and high turbulence intensities for intense yet economic mixing over a region of designed length and location.

2. Fractal combustors: the fractal design of a long region of high turbulence intensity and its location are of great interest for premixed combustion and may pave the way for future fractal combustors particularly adept at operating at the lean premixed combustion regime where NOx emissions are the lowest. In fact results recently obtained at Imperial's Mechanical Engineering Department suggest that fractal design seems to generate turbulent flame speeds which increase by even more than the increase in turbulence intensities!

3. Fractal spoilers and airbrakes can have significantly reduced sound pressure levels without degrading the lift and drag characteristics of the wing system.

4. Fractal wind breakers and fractal fences: a fractal fence, for example, can have increased resistance because of all its empty areas, yet be an effective fence by modifying the momentum profiles in its lee and thereby forcing deposition of particulates, snow etc where desired.

A lot of the driving force taking this new subject forward now comes from outside the UK and from Japan in particular. This very meeting would not have happened without the success of our Japanese colleagues in Nagoya who developed an entire research programme on the topic, secured a very substantial Japanese research grant to support it and also obtained a travel grant to allow interactions with us in Europe. This meeting also shows that activity is growing in continental Europe too, beyond the fog in the English channel. Indeed, beyond this fog, a substantial German research grant was given to Oldenburg last year for research on fractal-generated turbulence; and it is only because of the initiative and help of Jean-Paul Bonnet and his colleagues in Poitiers that we were able to participate in the EU's OPENAIR programme, without which we would not have been able to demonstrate the acoustic and aerodynamic performance of fractal spoilers.

J.C. Vassilicos
Department of Aeronautics, Imperial College London, UK

MONDAY 28 MARCH 2011 I 9.15-9.50

Freeing turbulence from the tyranny of the past

W.K. George
Department of Aeronautics, Imperial College London, UK

There have been numerous studies over the past few decades about how scientists do research on difficult and intractable problems, both how we function as individuals and collectively. While we would like to think that as individuals we are purely objective, all evidence suggests that we are not, and our judgements are strongly influenced by intuition and past prejudices. In groups we tend to cluster around ‘group-think’, substituting consensus for critical analysis. Moreover there is a ‘herd’ instinct, meaning there is a tendency to flock to a new idea, often without a good reason for doing so.

Of course none of this behaviour has ever happened in turbulence. Nonetheless, by examining the problems those in other fields have had, we can learn how to guard against them in the future. Therefore the first part of this presentation will focus on the phenomena of how we function as turbulence researchers. And the second will try to identify potential problem areas where if we are not careful ideas we have long assumed to be true might be adopted as religious principles, even if they are false or only partially true.

Also in this talk we will try to distinguish between the mathematics of turbulence and the physics of turbulence. In mathematics, equations are precisely determined, and the laws of mathematics which must be applied to find solutions are well-defined Physicists, on the other hand, build mathematical models of the universe as we find it. Once we have built the model and defined the boundary conditions, however, there is nothing that is arbitrary: the laws of mathematics take over. The problem in turbulence (and other fields as well) is that often the consequences of the mathematics for our solutions are not consistent with what we observe in nature. So is the problem with our model, or is it with the boundary conditions we have assumed to be true? Since often we have had to assume these to be applied at infinity, we cannot be sure. Nonetheless, there are usually some criteria for evaluation we can agree upon. For example if our model is the Navier-Stokes equations, it should not generally be our first assumption that they are wrong, especially for the constant density flow of a Newtonian fluid. Nor should we throw away so quickly a theory developed for an infinite domain if our experiment is performed in a box. In fact it will probably be more productive to examine what the consequences are of the finite domain or our attempts to realize the solution in nature. Numerous examples will be used to illustrate these points [1,2,3,4,5].

MONDAY 28 MARCH 2011 I 9.50-10.25

Beyond mean flow scaling laws - how to obtain higher order moment scaling from new statistical symmetries

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[2] Center of Smart Interfaces, TU Darmstadt, GERMANY
[3] GS Computational Engineering, TU Darmstadt, GERMANY

We investigate the symmetry and invariance structure of the infinite set of multi-point correlation (MPC) equations for the velocity and pressure fluctuations *u(x, t)* and *p(x, t)*

$$\begin{aligned} S_{i_{\{n+1\}}} = \frac{\partial R_{i_{\{n+1\}}}}{\partial t} + \sum_{l=1}^{n} \Bigg[& \bar{U}_{k_{(l)}}(x_{(l)}) \frac{\partial R_{i_{\{n+1\}}}}{\partial x_{k_{(l)}}} - \nu \frac{\partial^2 R_{i_{\{n+1\}}}}{\partial x_{k_{(l)}} \partial x_{k_{(l)}}} + R_{i_{\{n+1\}}[i_{(l)} \to k_{(l)}]} \frac{\partial \bar{U}_{i_{(l)}}}{\partial x_{k_{(l)}}} \\ & - R_{i_{\{n\}}[i_{(l)} \to 0]} \frac{\partial \overline{u_{i_{(l)}} u_{k_{(l)}}}(x_{(l)})}{\partial x_{k_{(l)}}} + \frac{\partial P_{i_{\{n\}}[l]}}{\partial x_{i_{(l)}}} + \frac{\partial R_{i_{\{n+2\}}[i_{(n+1)} \to k_{(l)}]}[x_{(n+1)} \to x_{(l)}]}{\partial x_{k_{(l)}}} \Bigg], \end{aligned} \tag{1}$$

where n=1...∞. In (1) the MPC tensor is defined as $R_{i[n+1]} = \overline{u_{i(0)}(x_{(0)}) ... u_{i_{(n)}}(x_{(n)})}$ and with the four variations of it we have a complete statistical description of turbulence.

Equation (1) admits all symmetries of the Navier-Stokes equations where they originally emerged from in the first place. Nevertheless equation (1) possesses additional symmetries (see [6,7])

$$\begin{aligned} \mathbf{G_{sh}} &: \tilde{x} = x,\ \tilde{r}_{i_{(l)}} = r_{i_{(l)}},\ \tilde{\bar{U}}_i = e^{a_s} \bar{U}_i,\ \tilde{R}_{ij}(x,y) = e^{a_s} \left[(1 - e^{a_s}) \bar{U}_i(x) \bar{U}_j(y) - R_{ij}(x,y) \right], \cdots \\ \mathbf{G_{L(a)}} &: \tilde{x} = x,\ \tilde{r}_{i_{(l)}} = r_{i_{(l)}}, \tilde{\bar{U}}_i = \bar{U}_i + L_{(i)}, \\ & \quad \tilde{R}_{ij}(x,y) = R_{ij}(x,y) - L_{(i)} \bar{U}_j(y) - L_{(j)} \bar{U}_i(x) - L_{(i)} L_{(j)}, \cdots \\ \mathbf{G_{L(ab)}} &: \tilde{x} = x,\ \tilde{r}_{i_{(l)}} = r_{i_{(l)}},\ \tilde{\bar{U}}_i = \bar{U}_i,\ \tilde{R}_{ij}(x,y) = R_{ij}(x,y) + L_{(ij)}, \cdots \end{aligned} \tag{2}$$

The latter are purely statistical properties of the equations (1), while $\mathbf{G}_{\mathbf{sh}}$ can be identified as a statistical scaling group (SSG) and $\mathbf{G}_{\mathbf{L(a)}}$, $\mathbf{G}_{\mathbf{L(ab)}}$ as statistical translation groups (STG).

Assuming a plane parallel turbulent shear flow, the infinite set of equations (1) and the corresponding symmetries provide the invariant surface condition

$$\frac{\mathrm{d}x_2}{k_1 x_2 + k_x} = \frac{\mathrm{d}r_{(k)}}{k_1 r_{(k)}} = \frac{\mathrm{d}\bar{U}_1}{(k_1 - k_2 + k_a)\bar{U}_1 + l_1} = \frac{\mathrm{d}R_{(11)}(x,y)}{I(x,y)} = \cdots \tag{3}$$

with the group parameters k_1, k_2, k_x, k_a, l_1 and l_{11} descending from the groups (2) and the classical symmetry groups here written in infinitesimal forms.

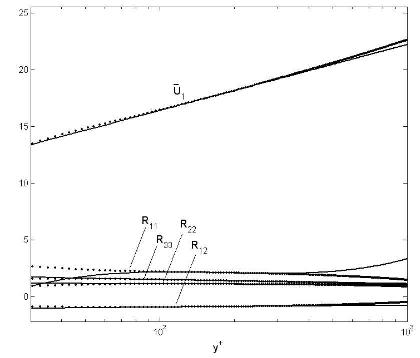

Figure 1. Comparison of the DNS data (dotted lines) with the scaling laws resulting from the new symmetries (solid lines)

The abbreviation $I(x, y)$ is defined as: $I(x, y) = [2k_1 - 2k_2 + k_a]R_{(11)}(x,y) + l_{11} - k_a \bar{U}_i(x) \bar{U}_j(y) - l_1(\bar{U}_i(x) + \bar{U}_j(y))$ and the indices in brackets denote no summation but instead each component is to be taken separately.

From (3) we may derive various new scaling laws for the MPC tensor. Presently, we invoke symmetries in the range of the validity of the logarithmic law of the wall i.e. $k_1 - k_2 + k_a = 0$ and compute the Reynolds stresses in the range or the logarithmic law of the wall. The parameters of the new equations describing the Reynolds stresses have been determined from the DNS-data of a boundary layer flow at $Re_\tau = 2003$ by Hoyas and Jimenez [8]. In figure 1, one can see that this provides an excellent match in the log region.

MONDAY 28 MARCH 2011 I 10.25-11.00

Multiscale self-similar coherent structures in developed turbulence

S. Goto
Department of Mechanical Engineering, Okayama University, JAPAN

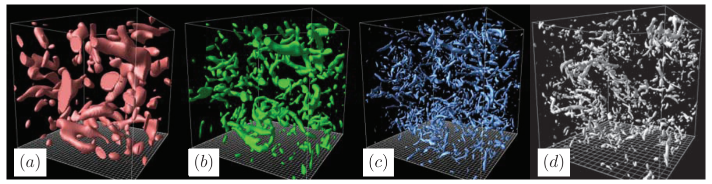

FIG 1: Iso-surfaces of the enstrophy coarse-grained at (a) 680η, (b) 340η (c) 170η and (d) 84η; where η is the Kolmogorov length scale. All of these scales are in the inertial range. The side of the shown cube is 5400η in (a,b,c), and 1700η in (d).

In order to reveal the coherent structures in fully developed turbulence and to understand their roles in the dynamics and statistics of turbulence, direct numerical simulations (DNS) of homogeneous isotropic turbulence in a periodic cube are conducted. By the DNS employing the Fourier spectral method with 2048^3 grid points, turbulence at the Taylor-length based Reynolds number equal to 580 is simulated. The multiscale coherent structures are then visualised by the iso-surfaces of the coarse-grained enstrophy, which is estimated by the low-pass filtering of the Fourier components of the vorticity field. Results are shown in the figure. It is clearly observed that thus visualised coherent vortical structures have mainly tubular shapes with radii of the order of the coarse-graining scale, whereas their length is as long as the integral length. This multiscale self-similar coherent structures play roles in the turbulence dynamics. For example, the fractal structure of preferentially concentrated heavy small particles in turbulence is well described in term of these multiscale coherent structures.

It is also important to describe, based on these coherent structures, one of the most important dynamics of turbulence, i.e. the energy cascade. To investigate this process in detail, we introduce [9] scale-dependent energy and its transfer. It is then numerically verified that the energy at a scale (ℓ, say) is confined in the coherent vortex tubes at ℓ, whereas the energy at scale ℓ transfers (probably to smaller scales) the regions surrounding the vortex tubes at ℓ, where the strain rate at the scale ℓ is high. This result implies that the energy cascade is caused by the creation of the thinner vortex tubes by the vortex stretching in larger-scale strain field around fatter vortex tubes. Indeed, we can easily find the invents which support this scenario of the energy cascade.

Two problems arise from this conclusion, however. First one is on the universality of turbulence statistics, since the above mechanism of the energy cascade implies that coherent structures at the Taylor microscale can be directly created by the large-scale structures at the integral length. Secondly, to my knowledge, the relation between the Kolmogorov energy spectrum and this mechanics of turbulent energy cascade is still open; where is the spiral structure, for example?

MONDAY 28 MARCH 2011 I 11.30-12.05

Successful attempts of large scale-turbulence realization by a Makita-Type turbulence generator and a buoyant jet in a cross wind

N. Sekishta and H. Makita
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Atmospheric boundary layers were simulated in a laboratory wind tunnel by regulating parameters of a turbulent shear flow generator. The generator has a shear flow device and an active grid with agitator wings driven by 40 stepping motors. The generator could control turbulence characteristics; mean velocity $U=0\sim8m/s$, turbulence intensity $u'/U_\infty=1\sim13\%$ and integral scale $L_{ux}=0.02\sim1.9m$. Reynolds stress distributions were also intensified throughout the thick boundary layer by the present setup. The maximum turbulence Reynolds number, R_λ, reached about 650 at U_∞=8m/s and the spectrum had a wide inertial sub range comparable to those in natural atmospheric boundary layers.

Coherent structures were investigated in a round jet of heated air with temperature difference, 0, 20, 40 and 60K. The present jet was vertically ejected in a cross flow field. Three kinds of flow pattern in the jet with smoke were observed by flow visualization in the cross flow generated with or without a turbulence grid. In the case of mode I, hairpin-type vortices occurred in the jet. Two vortex tubes with and without strong mutual interaction (bifurcation) were generated for mode II and III, respectively. Vortex behaviour, the convection velocity of the coherent vortices, the Strouhal number, etc., was investigated from the results of motion pictures taken by a high speed camera (1000frame/s). The convection velocity of the coherent structures decreased with increasing the temperature difference. These vortex shedding frequencies and the Strouhal numbers decreased with increasing the temperature difference.

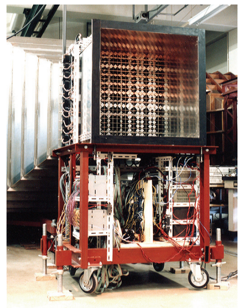

Fig. 1. Turbulent Shear flow generator.

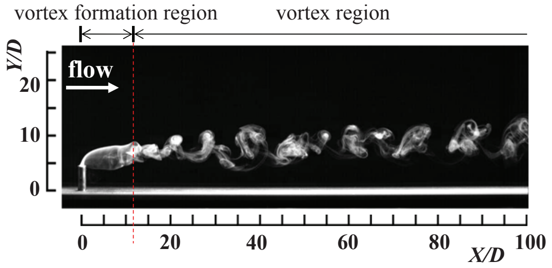

Fig. 2 Vortex formation region and vortex region.

MONDAY 28 MARCH 2011 I 12.05-12.40

Mean flow development of wake behind the Sierpinski tetrahedron

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This work is motivated by two physical facts: firstly fractal dimension of foliage distribution of crown tree is in the range between 2 and 2.4. Secondly, wind drag exerted on the tree is proportional to wind speed despite large Reynolds number based on the wind speed and square root of the projected area of trees. The latter suggests that the crown tree structure is optimal to the wind resistance and this feature can be relevant to the fractal geometry of the tree. Direct application can be artificial windbreakers during the development of forestation.

The Sierpinski tetrahedron has the fractal dimension of 2, which is the same as that of foliage distribution, and can cover the projected area efficiently. We used this three dimensional fractal structure as a model of tree to understand the turbulence generated in the natural environment.

In this preliminary report, the mean flow development of the wake behind the Sierpinski tetrahedron was investigated. The Sierpinski tetrahedron is installed at the upstream end of a small scale wind tunnel, which has 130mm by 130mm cross section and 2000mm in length. Development of the mean and r.m.s. velocities in the streamwise direction is measured at single experimental condition (4.9 ms^{-1} at the bulk velocity) by both Pitot tube and hot wire anemometry.

The mean velocity distribution in the cross section is quite inhomogeneous. Near the Sierpinski object, the local mean velocity varies by ±40 percent of the mean velocity over the cross section of the section and it remains strongly inhomogeneous far downstream. Inhomogeneity is a source of turbulence energy and produces relatively large fluctuations. Turbulence intensities decrease from 20 to 10 percent during the test section. Turbulence energy obeys the linear decay law. Reynolds number based on Taylor micro scale is around 150.

Our findings suggest that use of fractal objects can reduce the size of turbulent mixers, which is practical in the situation where a turbulent jet is not suitable for mixing.

MONDAY 28 MARCH 2011 I 14.15-14.50

Re-examination of fractal-generated turbulence using a smaller wind tunnel

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We reexamined the multiscale/fractal generated turbulence by Hurst & Vassilicos [4], Seoud & Vassilicos [5] and Mazellier & Vassilicos [10] using a smaller wind tunnel. The test section of the wind tunnel is $0.3\mathrm{x}0.3\mathrm{x}4.0\mathrm{m}^3$. The square-type fractal grid (blockage ratio $\sigma = 0.25$, thickness ratio $t_r = 13.0$, fractal dimension $D_f = 2$, $L_0 = 163.8$ mm, $L_1 = 78.9$ mm, $L_2 = 38.1$ mm, $L_3 = 18.3$ mm, $t_0 = 11.7$ mm, $t_1 = 4.9$ mm, $t_2 = 2.1$ mm, $t_3 = 0.9$ mm, where L_i are the successive bar length and ti are the successive bar thickness: see [4] and [5] for detail) was installed at 0.15m downstream of the entrance of the test section. The Reynolds numbers Re_0 based on t_0 and mean flow velocity upstream of the grid are 6,000 and 11,400. The instantaneous streamwise velocities are measured using the hot-wire anemometry with a self-made I-probe. The diameter and length of the sensor are d = 5 µm and l = 1 mm, respectively. The results are compared with those by [10] who used the larger wind tunnel. Figure 1 shows the normalised profiles of rms velocities. Here, x is the streamwise distance from the grid, x* is the wake-interaction length scale (see [10]), x_{peak} is the streamwise location where turbulence intensities exhibit the peak value and subscript c denotes the value on the centre line. Our results using a smaller wind tunnel agree well with that by [10]. Other statistics, for example skewness and flatness factors, also agree well with those of [10].

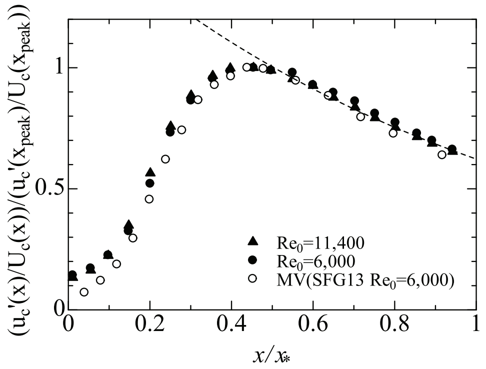

Figure 1 Streamwise evolution of turbulence intensities normalized by their values at x = x_{peak}

MONDAY 28 MARCH 2011 I 14.50-15.25

The decay of homogeneous turbulence generated by multiscale grids

P.C. Valente, J.C. Vassilicos
Department of Aeronautics, Imperial College London, UK

A new experimental investigation of freely decaying homogeneous, quasi-isotropic turbulence generated by a low-blockage space-filling fractal square grid is presented. We find good agreement with previous works by Seoud & Vassilicos [5] and Mazellier & Vassilicos [10] but also extend the length of the assessed decay region and consolidate the results by repeating the experiments with different anemometry systems and probes of increased spatial resolution. It is confirmed that this moderately high Reynolds number Re_λ turbulence does not follow the classical high Reynolds number scaling of the dissipation rate $\varepsilon \sim u'3/L$ which is in fact a direct reflection of the proportionality between the Taylor-based Reynolds number, Re_λ, and the ratio of integral scale L and the Taylor micro-scale λ. Instead we observe a proportionality between, L, and, λ, during decay. Alternative reasons for this non-classical behaviour are discussed, including various ways in which the turbulence may fall into a self-preserving, single-length-scale state induced by the initial conditions of this particular flow.

It is shown that the measured 1D spectra can be reasonably collapsed using a single length-scale over the entire decay region even though the Reynolds number is high enough for conventional decaying turbulence to display 1D spectra with two-scale (inner and outer) Kolmogorov scaling. We propose a correction for the weak anisotropy of the flow by computing the 3D spectrum function from two component velocity signals leading to further improved single-scale non-Kolmogorov collapse. Detailed checks on homogeneity and isotropy are also presented indicating that the single-length scale behaviour can not be an artifice of the hardly present inhomogeneity.

MONDAY 28 MARCH 2011 I 15.25-16.00

Fractal generated turbulence in isothermal and reacting opposed jet flows

R.P. Lindstedt, P. Geipel and K.H.H. Goh
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The opposed jet configuration presents a canonical geometry suitable for the evaluation of calculation methods seeking to reproduce the impact of strain and re-distribution on turbulent transport in reacting and non-reacting flows. The geometry has the advantage of good optical access and, in principle, an absence of complex boundary conditions. Disadvantages include low frequency flow motion at high nozzle separations and comparatively low turbulence levels causing bulk strain to exceed the turbulent contribution at small nozzle separations. In the current work, fractal generated turbulence has been used to increase the turbulent strain and velocity measurements for isothermal and reacting flows are reported with an emphasis on the axis, stagnation plane and the distribution of mean and instantaneous strain rates. Energy spectra were also determined and it showed that fractal grids increase the turbulent Reynolds number range from 48–125 to 109–220 for bulk velocities from 4 to 8 m/s as compared to conventional perforated plate turbulence generators. The applied instrumentation comprised hotwire anemometry, particle image velocimetry and a multi-step adaptive algorithm was developed and used to determine conditional statistics for reacting cases. Examples are given with respect to velocity and scalar statistics, the motion of the stagnation plane and with probability density functions for the instantaneous inclination of the flame sheet also determined. Finally, a proper orthogonal decomposition technique was adopted in order to examine the eigenmodes resulting from an analysis of the instantaneous vector fields and the dominant structures identified. The work shows that the application of fractal-generated turbulence holds significant advantages in the context of the opposed jet geometry.

MONDAY 28 MARCH 2011 I 16.30-17.05

A new class of turbulence - insights from the perspective of n-point statistics

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We apply a method based on the theory of Markov processes to fractal-generated turbulence and obtain joint probabilities of velocity increments at several scales. From experimental data we extract a Fokker-Planck equation which describes the interscale dynamics of the turbulence. In stark contrast to all documented boundary-free turbulent flows, the multiscale statistics of velocity increments, the coefficients of the Fokker-Planck equation, and dissipation-range intermittency are all independent of Reynolds number. These properties define a qualitatively new class of turbulence. Furthermore we use the multiscale statistics of homogeneous isotropic turbulence which can described by a stochastic "cascade" process of the velocity increment from scale to scale by a Fokker-Planck equation. We show how this description can be extended to obtain the complete multi-point statistics of the velocity field, i.e. we achieve an explicit expression for the joint probability $p(u(x_1), u(x_2), ..., u(x_n))$, where $u(x_i)$ is the velocity at the spatial point x_i (spatial point are obtained along one line using Taylor's hypothesis of frozen turbulence). We extend the stochastic cascade description by conditioning on the velocity value itself and find that the corresponding process is also governed by a Fokker-Planck equation, which contains as a leading term a simple additional velocity-dependent coefficient in the drift function. Taking into account the velocity dependence of the Fokker-Planck equation, the multi-point statistics in real space can be expressed by the two-scale statistics of velocity increments, which are equivalent to the three-point statistics of the velocity field. Thus, we propose a stochastic three-point closure for the velocity field of homogeneous isotropic turbulence.

MONDAY 28 MARCH 2011 I 17.05-17.40

The wake structure, energy decay and intermittency behind a fractal fence

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This paper reports the results of experiments on the structure of the wake behind fences inserted in a boundary layer flow in a wind tunnel, which was undertaken in the Shinjo wind tunnel in Japan, with Kouichi Nishimura (University of Nagoya) and colleagues at the Nagaoka Institute for Snow and Ice Studies. The fences varied in their porosity and the spacing of struts but, in addition, two fences were deployed where the struts were organised in a fractal pattern. Hence, this study marks a departure from previous work that has focussed on the flow structure behind fractal fences away from boundaries.

In general our results indicate that the nature of the fence, such as its porosity, has a larger control on wake structure than the Reynolds number of the flow (flows had mean input velocities of either 6 ms^{-1} or 8 ms^{-1}). However, we also find cases where the multiscale nature of the forcing with the fractal fences results in differences in wake structure that are greater than those due to porosity or Reynolds number. In particular, we show that the proportion of dissipation taking place over the range of forced scales is greater for the fractal fences and given the slope of the spectrum in this region, the implication is that the scale-to-scale transfer over this region is not inertial in a strict sense. This result parallels that from other studies on multiscale forcing in recent years by Vassilicos and coworkers.

In order to study this effect in more detail, we also examine the properties of synthetic turbulence generated from the experimental time series and by a comparison to the forcings at individual scales, attempt to identify the manner in which the unique properties of the fractal-forced flows become manifest.

TUESDAY 29 MARCH 2011 I 9.15-9.50

Mixing of high-Schmidt number scalar in regular/fractal grid turbulence: Experiments by PIV and PLIF

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Turbulent mixing of high-Schmidt-number passive scalar in the regular and fractal grid turbulence is experimentally investigated using a water channel. A turbulence generating grid is installed at the entrance to the test section, which is 1.5 m in length and 0.1 m x 0.1 m in the cross section. Two types of grids are used: one is a regular grid of the square-mesh and biplane construction, and another is a square type fractal grid, which was first investigated by Hurst & Vassilicos [4] and Seoud & Vassilicos [5]. Both grids have the same solidity of 0.36. The Reynolds number based on the mesh size, $Re_M = U_0 M_{eff}/v$ is 2,500 in both flows, where U_0 is the cross-sectionally averaged mean velocity, M_{eff} is the effective mesh size and v is the kinematic viscosity. A fluorescent dye (Rhodamine B) is homogeneously premixed only in the lower half stream, and therefore, the scalar mixing layers with an initial step profile develop downstream of the grids. The Schmidt number of the dye is $O(10^3)$. The time-series particle image velocimetry (PIV) and the planar laser induced fluorescence (PLIF) technique are used to measure the velocity and concentration field. The results show that the turbulence intensity in the fractal grid turbulence is much larger than the one in the regular grid turbulence (See Fig.1), and the turbulent mixing in the fractal grid turbulence is strongly enhanced compared with in the regular grid turbulence at the same Re_M (See Fig.2). It is also found that the scalar dissipation takes place locally even in the far downstream region at $M_{eff} = 120$ in the fractal grid turbulence.

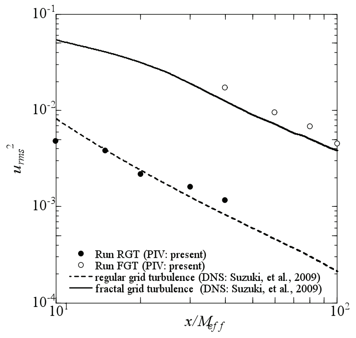

Figure 1 The streamwise evolutions of streamwise velocity fluctuation intensity normalized by U_0^2

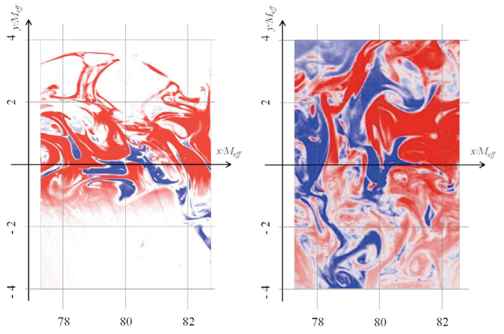

Figure 2 Instantaneous fluctuating concentration field at around $x/M_{eff} = 80$ by the regular grid (left side) and the fractal square grid (right side). Red: $c = 0.3$, Blue: $c = -0.3$.
Note: $M_{eff} = 10$ mm for the regular grid (left side),
$M_{eff} = 5.68$ mm for the fractal grid (right side)

TUESDAY 29 MARCH 2011 I 9.50-10.25

Aero-acoustic performance of fractal spoilers

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One of the major environmental problems facing the aviation industry is that of aircraft noise. The work presented here, done as part of the EU’s OPENAIR Project, looks at reducing spoiler noise whilst maintaining lift and drag characteristics through means of large-scale fractal porosity. It is hypothesised that the highly turbulent flow generated by fractal grids, which have multiple-length-scales, would reduce the impact of the re-circulation region and with it, the low frequency noise it generates. In its place, a higher frequency noise is introduced which is more susceptible to atmospheric attenuation and could be deemed less offensive to the human ear. A total of nine laboratory scaled spoilers were looked at, seven of which had a fractal design, one with a regular grid design and one solid for reference. The spoilers were inclined at an angle of 30°. Force, acoustic and flow visualisation experiments on a flat plate were carried out, where it was found that the present fractal spoilers reduce the low frequency noise by 2.5dB. Results show that it is possible to improve the acoustic performance by modifying a number of parameters defining the fractal spoiler, some of them very sensitively. From these experiments, two fractal spoilers were chosen for a detailed aero-acoustic study on a three-element wing system, where it was found that the fractal spoilers had a 1dB reduction in the sound pressure level and were also able to maintain the amount of lift and drag generated by the wing system.

TUESDAY 29 MARCH 2011 I 11.00-11.35

Turbulent premixed flames in fractal-grid-generated turbulence

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Reactions between fuel and oxidiser take place at the molecular level, so turbulent motion at the smallest scales has an immediate effect on the process. We are concerned here with premixed combustion, where the fuel and the oxidiser are homogeneously mixed before reacting; spark-ignition internal combustion engines are a notable example of premixed combustion in applications. In the flamelet description of turbulent premixed combustion, the thickness of a laminar flame with the same fuel-to-air ratio remains relatively unaffected by the turbulence. A main effect of turbulence is, through the stretch rate, to increase the surface area of the flamelets and, thus, increase the reaction rate.

The parameters used to describe a premixed flame are the normalised turbulent fluctuations u'/s_L where u' is the rms of the turbulent fluctuations and s_L is the laminar flame speed, and the ratio l/l_F where l is the integral length scale and l_F is the laminar flame thickness.

Turbulent premixed flames are established in a square burner, where a regular square mesh grid and a space-filling fractal square grid are used to generate turbulence at various distances upstream of the flame stabilisation position, so different values of u'/s_L and l/l_F are obtained; $0.76 < u'/s_L < 1.79$ and $7.1 < l/l_F < 11.8$. The measurement techniques include OH* chemiluminescence and OH Planar Laser Induced Fluorescence (PLIF) which are used to measure the turbulent flame speed, the flame width, the instantaneous flame front, the flame curvature and the flame surface density.

The main result of the present measurements is that, at the same level of normalised turbulent fluctuations and similar integral length scales, the flames show larger turbulent flame speeds when using the fractal grid than when using the square grid. An attempt to explain this difference relates to the different turbulence decay between normal- and fractal grid-generated turbulence.

TUESDAY 29 MARCH 2011 I 11.35-12.10

A parametric study about the effect of fractal-grid generated turbulence on the structure of premixed flames

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'Fractal' or multiscale turbulence-generating grids produce bespoke turbulent flows designed for the particular application at hand [4]. They allow more design and optimisation flexibility than conventional turbulence generators like perforated plates, for example, and generate high turbulence intensity at some distance away from the grid and over a long region downstream at a low pressure drop cost. This extended region of high turbulence intensity and the fact that it is possible to design where this region starts and its overall extent are of great interest for premixed combustion and may pave the way for future fractal combustors particularly adept at operating at the lean premixed combustion regime where NOx-emissions are the lowest. The high turbulence intensity, in particular, increases turbulent burning speed and leads to higher power densities of the flame. In previous work we observed a significant increase of turbulent flame speed when using a fractal instead of a regular grid [12].

In this work we further investigate the influence of fractal-grid generated turbulence on the structure of a premixed V-shaped methane-air flame. For a parametric study, a set of different space-filling fractal square grids is designed and several design parameters such as the blockage ratio and the ratio between the sizes of the largest and the smallest structures of the fractal grids are varied independently from each other. A regular square mesh grid with the same blockage ratio as two of the fractal grids acts as reference case. The velocity fields for the different grids are characterized based on hot wire measurements. The structure of the generated flames is investigated using the conditioned particle image velocimetry technique [13]. Quantities like the flame brush thickness, flame surface density and the turbulent burning velocity as well as the flow field characteristics are compared. Preliminary results show significantly higher corrugation of the flames and larger flame brush thicknesses for all fractal grids.

TUESDAY 29 MARCH 2011 | 13.30-14.05

Turbulence modulation through broad-band forcing

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The response of turbulent flow to forcing that is simultaneously imposed at a variety of length- scales is investigated numerically. This is a prime example of “modulated turbulence” in which a pre-specified departure from Kolmogorov turbulence is the target, e.g. to control mixing-rates or emphasize certain length-scales to stimulate embedded small scale chemical processes. We review the direct forcing approach and discuss the response to time-modulated forcing. Comparison is made with theoretical predictions. The occurrence of response maxima is presented and interpreted in terms of experimental observations reported in literature. A central remaining issue is the rigorous connection between the “modulating mechanism” and the associated broadband forcing. In case the modulation is derived from flow through complex gasket-structures, the possibility offered by immersed boundary methods to represent the flow and the geometry in all their details, is discussed. Some simulation results for turbulent pipe flow, tripped by flanges derived from fractal geometries, are presented.

TUESDAY 29 MARCH 2011 | 14.05-14.40

Direct Numerical Simulation of multiscale generated turbulence

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Multiscale (fractal) geometry is a concept in which a given pattern is repeated and split into parts, each of which being a reduced-copy of the whole. Multiscale (fractal) objects can be designed to be immersed in any fluid flow where there is a need to control the turbulence generated by the object. Experiments carried out at Imperial College London have shown that such objects can be used to control and manage the transition from laminar to turbulent flows. It was found that, unlike a regular object (where the turbulence is generated by only one scale), a slight modification of one of the object’s parameters can deeply modify the turbulence generated by the fluid’s impact on the object. Multiscale objects offer the opportunity to discover new complex flow effects/interactions that can help understand how to control and/or manage complex fluid flows. Furthermore, such multiscale objects can be designed as energy-efficient mixers, be designed to have a high sound transmission loss, be used around and/or inside buildings in order to reduce the cost of heating and/or cooling and therefore save energy (opening vents, louvres, etc.) or be used to force drifting of snow or sand to occur in a predictable place, rather than randomly.

The experiments from Imperial College were performed without time for optimisation and adaptation. Hence, possibilities for improvement are considerable with the potential to set new industrial standards. However, the development of such new flow solutions cannot be bring to fruition without a clear understanding of the unique properties of multiscale-generated flows. It is clear that carrying out experiments will help to tackle this ambitious task but will not be enough, even with advanced visualisation tools. It is absolutely necessary to undertake numerical simulations of such complex flows. In this work, these multiscale-generated flows will be investigated using High Performance Computing (HPC) resources [14,15]. It provides an opportunity to understand their highly unusual properties and it will be very useful to propose high-quality standards of new technologies.

TUESDAY 29 MARCH 2011 I 15.00-15.35

LES of opposed jet flows employing fractal turbulence-generating plates

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Generation of fully developed, isotropic turbulence is essential for the entire range of industrial combustors, as it promotes the mixing of reacting species and therefore improves efficiency in burning and reduces the emission of harmful waste products. However, such turbulence must typically be generated actively, which is often achieved by incorporating a swirl design. In laboratory experiments, blocking plates, grids or meshes, which are designed to encourage the transition from laminar to turbulent flow, are also used.

Opposed jet configurations are widely used for the investigation of laminar and turbulent premixed [16], partially-premixed [17] and non-premixed flames [18]. The compactness of the flow domain is of benefit to experimental and numerical studies alike, while good optical access to the stagnation plane and flame is permitted for the laser-based measurement techniques used to obtain two-dimensional velocity and scalar data. Through the use of a fractal turbulence-generating plate (Fig. 1) positioned downstream of the conventional perforated plate, Geipel et al. [19] report a significant increase in turbulent Reynolds numbers achieved for the configuration, while avoiding extinction of the flame due to excessive strain rates at the stagnation plane. The generated turbulence has been shown to be fully developed and isotropic near to the nozzle exit planes.

In the present work, LES is used to acquire a more complete understanding of the mechanisms that provide this level of turbulence, by allowing inspection of the flow field development within the nozzles of the opposed jets (Fig. 2). Statistical measures of first and second moments of flow velocity are obtained from simulations and compared to in-nozzle measurements. Entirely accurate representation of the complex plate geometry requires grid resolutions typical of a Direct Numerical Simulation. The study also aims to provide a deeper insight into the application of the theory upon which the fractal plate was designed, and may potentially suggest modifications or improvements that may be made to further improve the characteristics of the flow within the region of the flame.

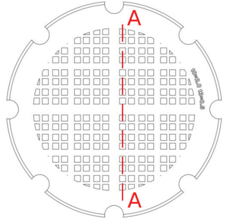

Figure 1: The fractal cross grid used in the present work.

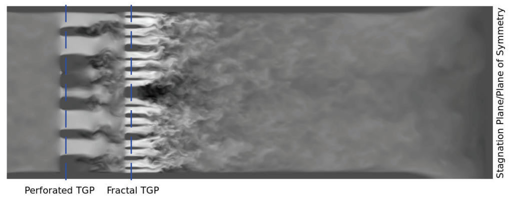

Figure 2: The resulting instantaneous axial velocity field within a single nozzle, corresponding to section ‘A-A’ in Fig. 1. Blue dashed lines indicate positions of the perforated TGP and fractal cross grid.

TUESDAY 29 MARCH 2011 I 15.35-16.10

DNS on spatially developing fractal generated turbulence with heat transfer

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In recent years, fundamental characteristics of fractal generated turbulence (FGT) [4] are investigated experimentally. The most noteworthy characteristic of FGT is a constancy of the integral length scale in the streamwise direction [5]. In this work, we focus on the heat transfer generated by the constant mean temperature gradient [20, 21] in the FGT by means of direct numerical simulation. It is known that the temperature variance generated by the mean temperature gradient exponentially increases in the streamwise direction [20]. This streamwise evolution corresponds to an exponential increase of the large scale [20]. Thus, it is worth investigating the streamwise evolution of the temperature fluctuation generated by the constant mean temperature gradient in the spatially developing FGT.

Direct numerical simulations based on the finite difference method is used for analysis of the heat transfer phenomena generated by constant mean temperature gradient in the spatially developing FGT. Our numerical techniques are based on the numerical scheme developed by Morinishi et al. [22], which enables us to perform DNS with analytically-expanded conservation of velocity and temperature fluctuations. In addition, higher order terms, i.e, viscous and diffusion terms, were discretized by the higher-order central compact schemes [23] and Fourier series expansion. Figure 1 shows the streamwise evolutions of temperature variance in the fractal and classical grid turbulence. The temperature variance in classical grid turbulence increases exponentially. In contrast, that in FGT monotonically decreases in downstream region, where turbulence is decaying.

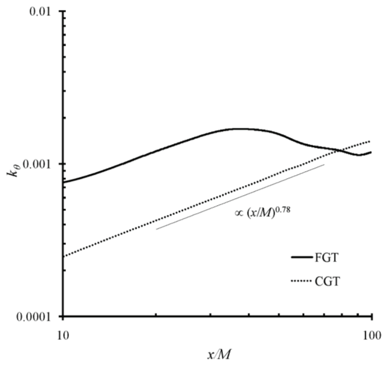

Figure 1 The streamwise evolutions of temperature variance in fractal (FGT) and classical (CGT) grid turbulence

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