【RIMS 合宿型セミナー】

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② 題　目：乱流現象の多様性を貫く数理と物理

(英文名：Mathematics and physics across the diversity of turbulent phenomema　　)

③実施期間：　平成　21 年　　7 月　　9 日～平成　21 年　　7 月　　11 日(　3 日間)

④参加者数：　　19 名　（内、外国人　　3 名)

⑤講 演 数：　　19 コマ (内、英語で行なわれたもの　　19 コマ)

⑥研究集会の概要 (開催目的、成果など)：

乱れた流れは身のまわりにありふれており、古くから数理、物理科学の中心課題のひとつである。乱流が重要な役割を演ずる分野は、機械、土木、航空、化学工学など工学の様々な分野や農学はもちろん、地球科学、宇宙物理学まで多岐にわたる。各分野で乱流研究者は努力を続けてきたが、その多くは経験則に基づく個別論的なアプローチにとどまっている。そこで、これら様々な分野で個別的にではあるが極めて詳細に研究されてきた乱流現象の多様性を貫く数理的、物理的基礎描像の構築が求められている。こうした『乱流現象の統一的な基礎理解』の必要性を深く認識している若手および中堅研究者を国内外の各分野から集め、具体から抽象へむかう作業を丹念に行う合宿形式のセミナーを行った。各参加者が扱う個々の多様な問題例から、いかに統一的な数理的、物理的描像を浮びあがらせるべきかについて、また、逆に基礎描像から個々の問題へどのようなアプローチがありえるかについて毎日朝早くから夜遅くまで活発な議論がなされた。

研究成果の公表方法

⑦ 講究録を　　☐ 発行する　　☑ 発行しない
※発行する場合：原稿完成予定時期　　平成　　年　　月　　日頃

⑧ 講究録以外の方法で報告集を発行する場合：
タイトル:
出 版 社:　　　　出版予定時期：平成　　年　　月　　日頃

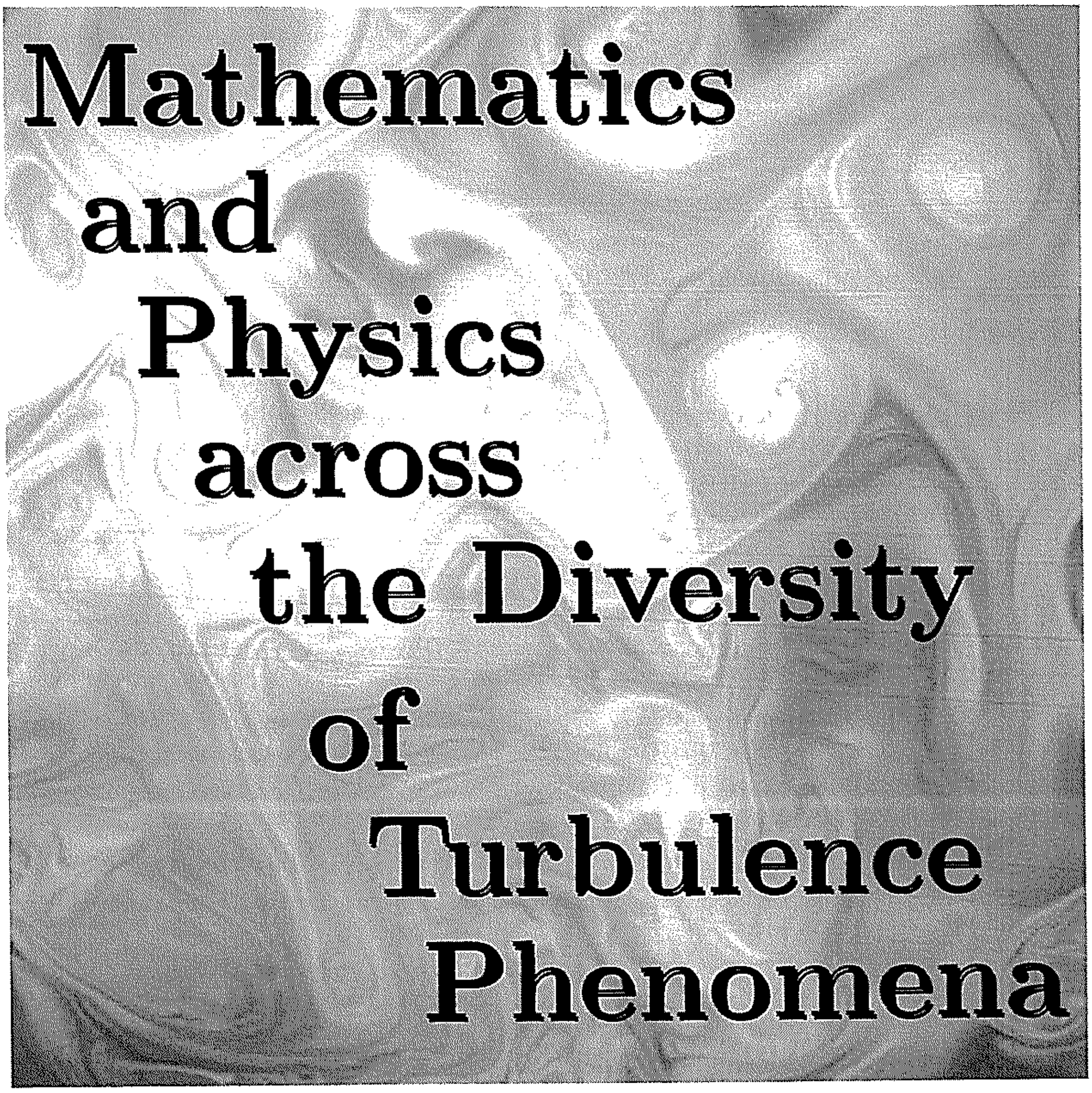
⑨ 専門誌等による場合：
主要な論文リスト (掲載予定、プレプリントを含む。準備中も可)

S. Goto and J.C. Vassilicos, “The dissipation rate coefficient of turbulence is not universal and depends on the internal stagnation point structure” Phys. Fluids 21 (2009) 035104.

A. Mizuta, T. Matsumoto and S. Toh, “Two-particle dispersion in 2D inverse energy cascade turbulence and a self-similar telegraph equation model” 準備中.

※２～３ページ目に研究集会実施 プログラム添付 (Ａ４版)

RIMS Workshop



9–11 July, 2009

@ the Kobe Institute

Programme

9th July, 2009

13:30 — 14:00 **Susumu Goto (Kyoto Univ.)**
Energy Cascade in Homogeneous Turbulence

I would like to discuss a possibility to explain the physical mechanism of the energy cascade in homogeneous turbulence in terms of coherent (vortical or some other) structures.

14:00 — 14:30 **Takeshi Matsumoto (Kyoto Univ.)**
Rayleigh-Taylor Turbulence and Scalar Turbulence

Similarity between the density field in Rayleigh-Taylor turbulence and the passive scalar field in homogeneous isotropic turbulence is discussed.

14:30 — 15:00 **Takashi Ishihara & Kazuki Takahashi (Nagoya Univ.)**
Computational Analysis of High Reynolds Number Turbulence Using Pressure Gradient Vector Field

Vortical structures in high Reynolds number turbulence are analyzed using the pressure gradient vector field obtained by high-resolution DNS data of box turbulence. It will be shown that a high-vorticity region can be characterized as a source of pressure gradient vector field. The analysis suggests that large-scale vortical structures in high Reynolds turbulence are well characterized by coarse graining pressure vector field.

15:00 — 15:30 Coffee

15:30 — 16:00 **Kaoru Iwamoto (Tokyo Univ. of Agriculture and Technology)**
Active Pump Control of Turbulent Flow for Drag Reduction

Direct numerical simulation and experiment of a pulsating turbulent flow have been carried out at a friction Reynolds number of 110. It is found that the optimal values of the cycle period and the mean pressure gradient in the acceleration phase exist for increasing the energy saving and drag reduction rates.

16:00 — 16:30 **Kiori Obuse (Kyoto Univ.)**
Large Time Asymptotic States of the Forced Two-dimensional Turbulence on a Rotating Sphere

We investigate large time asymptotic states of the forced two-dimensional turbulence of incompressible fluid on a rotating sphere, which is one of the most basic models for planetary atmospheres. In this system, a robust multiple zonal-band structure has been known to appear in course of time development. However, further numerical integration shows that the multiple zonal-band structure experiences a series of mergers/disappearances of its zonal jets, and the final flow field consists of only a few broad zonal jets dominating over the whole sphere. A weakly nonlinear theory of the interaction of zonal jets is also discuss ed to see the effect of a nonzonal flow behind the jets.

18:00 — 19:00 Dinner (Restaurant)

19:00 — Discussions (not-organized, at the Lounge)

10th July, 2009

08:00 — 09:00 Breakfast (Restaurant)

09:30 — 11:30 **J. Christos Vassilicos (Imperial College, London)**
The Turbulence Problem(s)

Abstract is available on pp. 5–7.

12:00 — 13:00 Lunch (Restaurant)

13:30 — 14:00 **Yoshiyuki Tsuji (Nagoya Univ.)**
On the Energy Dissipation Constant in High-Reynolds Number Turbulence

Analyzing the high-Reynolds number data in experiments, the constant defined by $C_\varepsilon = \varepsilon L/u_{rms}^3$, where L is integral scale and u_{rms} is root mean square of velocity fluctuation, is revisited. C_ε should not be universal as Taylor presented originally in 1935. Also recent reports support this tendency. A few comments are made on this topic, and suggest another understanding of C_ε.

14:00 — 14:30 **Atsushi Sekimoto (Osaka Univ.)**
Buoyancy Effects on Low-Reynolds-number Turbulent Flow in a Horizontal Square Duct

Direct numerical simulations of fully developed low-Reynolds-number turbulent flow in a horizontal square duct heated from below are performed at Richardson numbers $0 \leq Ri \leq 1.03$. We investigate the buoyancy effects on the coherent structures near the walls, i.e. streamwise vortices and associated streaks, and on turbulence-driven secondary flow of Prandtl's second kind.

14:30 — 15:00 **Masaki Shimizu (Doshisha Univ.)**
A Driving Mechanism of a Turbulent Puff in Pipe Flow

A turbulent equilibrium puff is numerically realized in a circular pipe. We propose self-sustenance cycle of the puff as below. Turbulence in the puff generates a number of low-speed streaks accompanied with streamwise vortices along the pipe wall. These low-speed streaks move upstream relative to the puff, across the trailing edge and create strong thin vortex layers together with the laminar flow coming from upstream. The vortex layers are unstable to roll up, through the Kelvin-Helmholtz instability, to induce velocity fluctuations which propagate downstream faster than the puff itself and enhance the turbulent activity in it.

15:00 — 15:30 Coffee

15:30 — 16:00 **Naoya Takahashi (Univ. Electro-Communications)**
The Influence of Turbulence on a Columnar Vortex with Axial Flow

The interaction between a columnar vortex and external turbulence is investigated numerically. A q-vortex is immersed in an initially isotropic homogeneous turbulence field. We analyze the formation of vortical structures of the flow field using visualization and statistical methods. In the marginally stable case, small thin spiral structures are formed inside the vortex core. In the linearly unstable case, the secondary instability causes the collapse of the columnar vortex and the sudden appearance of many fine scale vortices.

16:30 — 17:00 **Satoshi Yokojima (Shizuoka Univ.)**
Direct Simulation of Fully-developed Turbulent Flow Bounded by Perfectly-permeable Wall

The effect of wall imperviousness (wall-blocking effect) on the turbulent channel flows has been investigated. To this end, we numerically realize a new system, fully-developed turbulent flow bounded by a "perfectly-permeable" wall which is obtained by removing only the impermeable properties from a solid wall. It is shown that the perfectly-permeable wall has a drag two-order-of-magnitude higher than does the impermeable solid wall, indicating that permeable boundaries can be an efficient mixing device.

17:00 — 17:30 **Kyo Yoshida (Tsukuba Univ.)**
Spectra in Astrophysical Fluid Turbulences

We discuss the energy spectra in MHD turbulence which corresponds to the solar wind turbulence. Results from a closure theory and numerical simulations will be given. If possible, we will also discuss the spectra in a continuous model of the self-gravity system.

18:00 — 19:00 **Dinner (Restaurant)**

19:00 — **Discussions (not-organized, at the Lounge)**

11th July, 2009

08:00 — 09:00 **Breakfast (Restaurant)**

09:30 — 11:30 **Genta Kawahara (Osaka Univ.)**
Dynamical Description of Transition and Turbulence in terms of Unstable Periodic Orbits

Numerical methods are explained for computation of an unstable periodic solution to the incompressible Navier-Stokes equation, and then application of periodic solutions is discussed to dynamical description of transition to turbulence and developed low-Reynolds-number turbulence.

12:00 — 13:00 **Lunch**

13:30 — 14:00 **Lennaert van Veen (Concordia Univ.)**
On the Computation of Invariant Manifolds and their Role in Bursting Shear Flow

In many shear flows we observe a transition from laminar to intermittently turbulent behaviour for increasing Reynolds number. If this happens before the laminar flow becomes unstable, we call the transition subcritical. Recently, evidence has been found that saddle type periodic solutions play an important role in the transition. In the current work we use computational methods suitable for large, dissipative systems of ODEs to compute the unstable manifolds of periodic solutions. We aim to explain the dynamics of the transition in terms of such manifolds and demonstrate our ideas with results in plane Couette flow.

14:00 — 14:30 Kouji Nagata, Hiroki Suzuki, Yasuhiko Sakai, Ryota Ukai & Toshiyuki Hayase (Nagoya Univ.)

Experimental and Numerical Studies on Fractal-generated Turbulence with Scalar Transfer

Results of experiments using a water channel and direct numerical simulation will be presented. In the experiments, turbulent flow field and scalar field downstream of a fractal grid is measured using a PIV and PLIF. Rhodamine B (Sc$\sim$3000) is used as a scalar. In the DNS, turbulent flow field and scalar field (Pr=0.7) downstream of a fractal grids are examined. Effects of grid parameters on the flow field are also investigated.

14:30 — 15:00 Atsushi Mizuta (Kyoto Univ.)

The Effect of Coherent Structures on Two-particle Dispersion in 2D Turbulence

We investigate time evolutions of the distances of fluid particle pairs advected by 2D turbulent flows numerically. In the 2D Boussinesq convection turbulence, we observed that most of particle pairs elongated rapidly cluster in particular regions. On the other hand, in the 2D inverse cascade turbulence, such a clustering is not observed. This qualitative difference in the stretching process seems to stem from the difference of characteristics of coherent structures embedded in the two turbulences. We will discuss the relationship between the stretching mechanisms of particle pairs and the coherent structures.

15:00 — 15:30 Coffee

15:30 — 16:00 Stuart Coleman (Imperial College, London)

The Sweep-stick Mechanism of Particle Clustering in 2d and 3d Homogeneous Isotropic Turbulence

Our work focuses on the sweep-stick mechanism of particle clustering in turbulent flows introduced for 2D inverse cascading homogeneous,isotropic turbulence (HIT), whereby heavy particles cluster in a way which mimics the clustering of zero acceleration points. We extend this phenomenology to 3D HIT, where it was previously reported that zero acceleration points were extremely rare, which allows us to discard the modified sweep-stick mechanism of Goto and Vassilicos, PRL, 2008.

Having obtained a unified mechanism we quantify the Stokes number dependency of the probability of the heavy particles to be at zero acceleration points and show that in the inertial range of Stokes numbers the sweep-stick mechanism is dominant over the conventionally proposed mechanism of heavy particles being centrifuged from high vorticity regions to high strain regions.

16:00 — 16:30 Takahiro Tsukahara (Tokyo Univ. of Science)
Turbulence Stripe in Plane Channel Flow

A series of large-scale direct numerical simulations (DNS) and experiments were conducted in two types of plane channel flows, such as plane Poiseuille flow (PPF) and plane Couette flows (PCF) without/with system rotation, to investigate the subcritical-transition regime. Both flows give rise to co-existing laminar and turbulent equilibrium regions in the form of oblique bands, namely, turbulence stripe. The stripes are tilted by a certain angle with respect to the mean flow. In this context, the turbulence stripe can be seen as an intrinsic phenomenon in the reverse transition in a channel flow.

16:30 — 17:00 Takeshi Watanabe (Nagoya Institute of Technology)
Single Polymer Dynamics in Isotropic Turbulence

Statistical properties of the polymer stretching dynamics in isotropic turbulence are studied using Brownian dynamics simulations of polymer chain model with the direct numerical simulation of turbulent velocity field. It is found that although the polymer chain almost coiled state when the Weissenberg number $Wi_\eta \sim 1$, it remains stretched state for $Wi_\eta > 10$ during much longer time than the typical time scale of the velocity gradient fluctuation. Autocorrelation function of the end-to-end vector distance r_e of polymer chain has a maximum correlation time when $Wi_\eta = 3$, suggesting the existence of coil-stretch (CS) transition around $Wi_\eta = 3$. This feature does not depend on the number of bead N_b ($N_b = 20$ or $N_b = 2$) when using the parameter mapping proposed by Jin & Collins (2007). The Wi_η effect on the alignment of the end-to-end vector to the principal axes of the rate of strain tensor is examined, and we discuss the relationship between the polymer elongation and the local flow topology.

(cancelled) Rahul Pandit (Indian Institute of Science)
Statistical Studies of Fluid Turbulence: Dynamic Multiscaling; Polymer Additives; Thin Films.

We provide an overview of statistical studies of turbulence with special emphasis on our recent theoretical and numerical studies of (a) the dynamic multiscaling of time-dependent velocity structure functions, (b) the effects of polymer additives on homogeneous, isotropic turbulence, and (c) turbulence in quasi-two-dimensional, thin, fluid films.

This work has been done in collaboration with D. Mitra, S.S. Ray, and P. Perlekar.

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The Turbulence Problem(s)

J. C. Vassilicos (Imperial College London)

Arguably, the overarching aim of turbulence research is reduced order modelling of turbulent flows. This may be in the form of one-point, two-point (or even multi-point) closures such as $k - \epsilon$ and EDQNM, filtering closures such as LES or in terms of dynamical systems concepts such as state-space attractors. Arguably, too, such solution(s) to the turbulence problem(s) will not be fully satisfactory if they do not eventually impact industry and/or practical ocean/atmosphere prediction methods. This impact requirement is, however, only a necessary but not a sufficient condition as is clearly exemplified by the $k - \epsilon$ model which has had, and continuous to have, an enormous impact on industry even though it is not a solution to the turbulence problem(s). The reason why it is not a solution is directly linked to the issue of universality in the context of turbulent flows.

Reduced order models such as $k - \epsilon$ have been developed for and calibrated against a specific set of well-documented turbulent flows and can return useful results only when applied to conditions close to those particular turbulent flows. These models can fail by a wide margin when widely extrapolated beyond their comfort zone. They can therefore not be relied upon for predicting the behaviour of radically new turbulent flow concepts. Radically new flow concepts are urgently needed for the development of radically new industrial and environmental flow solutions which are to be part of the widespread technological step changes required to avert climate change projections and meet the dramatically evolving energy and environmental constraints. Industry cannot afford to remain within its well-documented comfort zones for long but may also not be able to step out of them significantly without some sort of universal reduced order modelling of turbulence which can be used to invent and investigate new turbulent flow concepts at will and at non-prohibitive cost.

The first question raised is whether universality classes of boundary conditions exist for which solutions of a given non-linear and non-local partial differential equation such as the incompressible Navier-Stokes equations have statistical properties which are independent of these boundary conditions, perhaps in some limit such as the high Reynolds number limit. Such properties may be statistical in terms of some averaging operation, for example over initial conditions or over time. The second question is whether sufficiently accurate and universal reduced order modelling is possible within these universality classes. Even if reduced order modelling is possible on a case-by-case basis, it may not be possible to develop a reduced order modelling approach which is the same for all the boundary conditions of the universality class. In fact, it might be expected that a negative answer to the first question implies a negative answer to the second. However, in the case where some kind of universal statistical properties of solutions of the incompressible Navier-Stokes equations do exist in some appropriate limit and within an appropriate universality class, the third question will then be to know how to use them to develop some kind of universal reduced order modelling approach to these equations.

These are very difficult questions which may sketch out, at best, broad goals for future generations of researchers. Indeed, it is instructive and also sobering to note that the textbook "Applied analysis of the Navier-Stokes equations" published in 1995 by C.R. Doering and J.D. Gibbon considers only periodic boundary conditions because of inherent technical difficulties with more realistic boundaries. Many turbulence researchers consider periodic boundary conditions but add a forcing term to the Navier-Stokes equations. It is therefore relevant to ask how such forcing approaches do or do not mimic the way that boundary conditions may drive turbulent flows in reality. In fact, this question is central to the Immersed Boundary Method which is currently making a very serious impact on DNS of turbulent flows with a variety of boundary conditions.

Which turbulence properties are our current best candidates for universality or, at least, for the definition of universal classes? The assumed independence of the turbulence kinetic energy dissipation rate ϵ on Reynolds number Re in the high Re limit is a cornerstone assumption on which Kolmogorov's phenomenology is built and on which one-point and two-point closures and LES rely, whether directly or indirectly. This cornerstone assumption is believed to hold universally (at least for weakly strained/sheared turbulent flows). It is also directly related to the universal tendency of turbulent flows to develop sharp velocity gradients, to the apparently universal geometrical statistics of these gradients, and to the apparently universal mix of vortex stretching and compression (described in some detail in the book "An informal introduction to turbulence" published in 2001 by A. Tsinober who introduced the expression "qualitative universality" to describe such ubiquitous qualitative properties). This universal assumption on turbulence dissipation and these apparently universal qualitative properties of turbulent velocity gradients are intimately linked to the mathematical search for Finite-time singularities and/or near-singularities of the Navier-Stokes equations.

Evidence against universality has been reported since the 1970s, if not earlier, in works led by Roshko, Lykoudis, Wygnanski and George (see for example the 2008 Freeman Award Lecture of W.K. George: "Is there an asymptotic effect of initial and upstream conditions on turbulence?") and has often been accounted for by the presence or absence of long-lived coherent structures. Coherent/persistent flow structure can actually appear at all scales and can be the carrier of long-range memory, thus implying long-range effects of boundary/inlet conditions. However, they can also be the reason for reduced order modelling as they introduce the possibilities for significant reductions in number of independent variables (see POD approaches introduced by Lumley). In these respects, it is noteworthy that the stagnation points of fluctuating velocities define persistence in the Eulerian frame (PRE 2005, 71, 015301) whereas low-acceleration regions define persistence in the Lagrangian frame (PRE 2009, 79, 015301), and both have a multiscale spatio-temporal structure. We refer to turbulence problem(s) for two reasons: (i) different universality classes or just boundary/inlet/upstream conditions may require different treatment and (ii) mixing/clustering of fluid/inertial particles in turbulent flows may require different reduced order approaches than the actual velocity field. Stagnation points and zero-acceleration points (different instances of critical points) are very useful in this last respect (see Phys Fluids 2009, 21, 015106; JFM 2006, 553, 143).

All these considerations suggest that kinetic energy dissipation, vortex stretching and compression, geometrical alignments, critical points and their universality or nonuniversality of each one of these properties are central to turbulent flows with an impact which ranges from fundamental mathematical aspects of the Navier Stokes equations all the way to engineering turbulence modelling and includes, of course, basic Kolmogorov phenomenology and scalings. Reduced order modelling may be too hard to attempt for the turbulent velocity field at the present and for some time to come, but research on the aforementioned properties are a clear prerequisite which can and must be carried out now. Given the current state of knowledge and technical possibilities, turbulence research can and must embark in a thorough experimental and computational investigation of the universality or non-universality of turbulence properties concerning dissipation, vortex stretching/compression, geometrical alignments and multiscale critical point spatio-temporal structure. Is it possible, for example, to tamper with these properties by systematic modifications of a flow's boundary and/or upstream conditions?

To investigate such questions, new classes of turbulent flows have recently been proposed which allow for systematic and well-controlled changes in multiscale boundary and/or upstream conditions. These classes of flows fall under the general banner of "fractal-generated turbulence" and have such unusual turbulence properties (see Phys Fluids 2007, 19, 035103; 2007, 19, 101518; 2009, 21, 025108) that they may directly serve as new flow concepts for new industrial flow solutions, for example conceptually new energy-efficient industrial mixers. Turbulence research does not need to come up with reduced order models valid over wide universality classes to impact industry if it can come up with new turbulent flow concepts which can directly offer possibilities for new industrial and/or environmental ow solutions. These same turbulent flow concepts in conjunction with conventional flows such as turbulent jets and regular grid turbulence are also being used for fundamental research into what determines the dissipation rate of turbulent flows and even to demonstrate the possibility of renormalising the dissipation constant so as to make it universal at finite, not only asymptotically infinite, Reynolds numbers (see Phys Fluids 2008, 20, 014102; 2009, 21, 035104). The dissipation rate constant depends on small-scale intermittency, on dissipation range broadening and on the large-scale internal stagnation point structure which itself depends on boundary and/or upstream conditions. In the case of at least one class of fractal-generated homogeneous turbulence, small-scale intermittency does not increase with Reynolds number and the dissipation constant is inversely proportional to it even though the energy spectrum is broad and power-law shaped.