

# Turbulent convection by thermoelectricity in a cooling-heating didactive device

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**Abstract.** Local Diffusion and the topological structure of vorticity and velocity fields is measured in the transition from a homogeneous linearly stratified fluid to a cellular or layered structure by means of convective cooling and/or heating. Patterns arise by setting up a convective flow generated by an array of Thermoelectric devices (Peltier/Seebeck cells) these are controlled generating a buoyant heat flux. The experiments described here investigate high Prandtl number mixing using brine and fresh water in order to form density interfaces and low Prandtl number mixing with temperature gradients. The set of dimensionless parameters define conditions of numeric and small scale laboratory modeling of environmental flows. Fields of velocity, density and their gradients were computed and visualized using the open software tools of DigiFlow. When convective heating and cooling takes place in the side wall of a stratified enclosed cell, the combination of internal waves and buoyancy driven turbulence is much more complicated if the Rayleigh and Reynolds numbers are high. Higher order moments calculations and intermittency are important in order to study mixing in complex flows Here some examples are shown using the Thermoelectric Convection Didactive Device (TCDD) built by BEROTZA, mainly in a symmetric two dimensional pattern, but many other combinations, using heating-cooling and angles with the vertical are possible in order to validate more complex numerical experiments.

**Keywords:** convection; thermoelectricity; peltier effect; experiments; numerical simulation; K-e Model; turbulence; digiFlow.

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## 1. Introduction

The combination of laboratory experiments and direct numerical simulations of the same experiments is an important source of information when studying the role of body forces in the turbulent cascade that takes place at large Reynolds numbers.

Richardson proposed fully developed turbulence as a hierarchy of eddies of different size. He assumed a cascade process of eddies breaking down. At eddies of size  $L$  energy is injected, then energy is transmitted to smaller and smaller eddies and finally it is dissipated in small eddies of scale  $\eta$  where viscosity plays a dominant role. A central role in this scheme is played by the mean rate of energy transfer per unit mass [1-3]. Rotation and Convection due to buoyancy are clear examples of the inverse cascade behavior [4,5]. We propose a combination of these effects in new experiments placing the device described below (Figures 1, 2) TC DD built by BEROTZA, further experiments using a rotating table will be reported elsewhere [6,7].

Here, we will describe the Thermoelectric, Thermal Convection Apparatus that may simulate easily Dirichlet and Neumann side and bottom heated or cooled wall boundary conditions. The Numerical validation of Environmental Turbulence programs with Laboratory Experiments as well as with field data and numerical models is fundamental to build student confidence. The possibilities of using the thermoelectric driven convective device in complex set-ups is also very interesting for didactive purposes, using student teams to model and validate different (but similar) configurations (varying the heat flux, its direction, the angle with gravity, using rotation,...) are very wide.

We first describe the Thermoelectric device and present some results obtained with DigiFlow [5] for 2D basic configurations, Then we introduce a RANS approach with K-e turbulence's model with side-wall heating-cooling and finally we discuss scaling in the 2D-3D transition leading to Buoyant-Convection, which is similar to the Rayleigh-Taylor flows multifractal scaling [8,9].

## 2. Thermoelectric control and experiments

The possibilities of heating and or cooling, are coupled with new methods of flow visualization exploited by DigiFlow [2, 5], and these new techniques allow us to map velocity and vorticity fields for these types of flows in the desired planes within the TCDD, both in 2D and 3D. We have modified existing methods based on techniques such as Laser Induced Fluorescence(LIF) or Correlation Image Velocimetry (CIV), Shadowgraph and Schlieren, in order to also allow comparisons of higher order descriptors of the turbulence and of the scale to scale transfer of (Scalar Tracers, Energy, Enstrophy, etc.). These methods involve the use of multi-fractal analysis as described in [9, 10].

The possibility of heating-cooling in the full side, by means of two Peltier cells acting on 5 cm x 5 cm inox steel plates as seen in figure 2 with a constant heat flux regulated by Voltage and Intensity from a versatile control, now allows to set the same conditions as in the numerical simulations. The simple flow used here is just heating in one lateral side and cooling in the opposite one with the same heat flux to avoid large changes in the temperature. An additional complication is to use brine in order to strongly stratify the flow and allow to propagate internal waves driven by the

convective flow. The asymmetry of the flow is reflected by the differences in vorticity between the bottom and top of the TCDD.

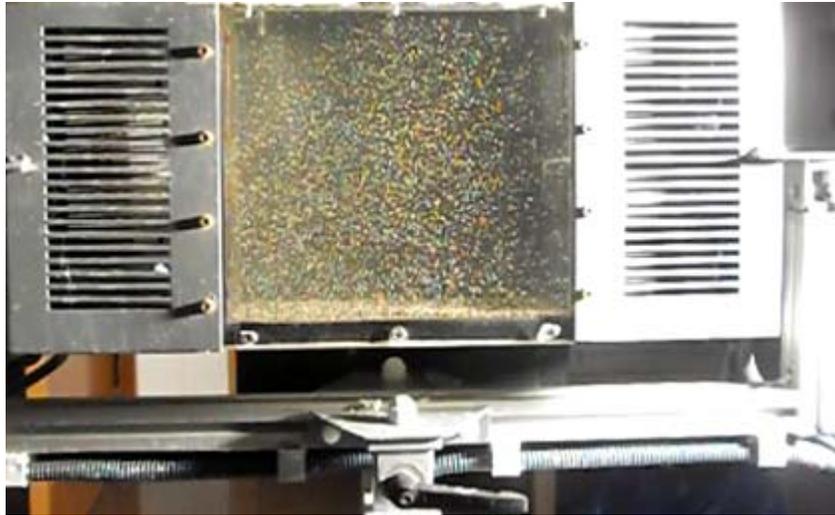


Fig. 1. Experimental Thermoelectric Driven Didactic Apparatus, used to generate cooling and heating at side or bottom boundary conditions. Here seeding for PIV is shown.

Convective mixing takes place, depending on the many possible boundary conditions regulating the cooling or heating fluxes with a transient phase, in most of the high thermal flux set-tings, the sides of the thermal elements produce fast ascending or descending plumes. It is very didactic to observe the different parts of the flow near regions of positive or negative divergence. Here, both the temperature (measured by probes) and velocity (measured by plane PIV [2, 5]) show different shapes of scalar spectra, the energy spectra, and the relationship between vorticity and stream functions, when only plane visualizations are available. These phenomena are similar in other flows where, the large coherent structures or Super-Cells, blobs or spikes [5, 8] are produced by an inverse cascade or by baroclinic effects that are very common in geophysical driven flows. To present the high resolution of the velocity and vorticity Lagrangian data, Figures 3 to 6 show aspects of the flow obtained by DigiFlow and ImaCalc software: (<http://www.winsite.com/Multimedia/Image-Editors/DigiFlow/>)

([https://www.academia.edu/420566/ImaCalc\\_Executable\\_Program](https://www.academia.edu/420566/ImaCalc_Executable_Program)).

The DigiFlow application was designed to provide a range of image processing features designed specifically for analyzing fluid flows. The package is designed to be easy to use, yet flexible and efficient, and includes a powerful yet flexible macro language. Whereas most image processing systems are intended for analyzing or processing single images, DigiFlow is designed from the start for dealing with

sequences or collections of images in a straightforward manner. Some key features of DigiFlow have been designed from the outset to provide a powerful yet efficient environment for acquiring and processing a broad range of experimental flows to obtain both accurate quantitative and qualitative output. Central to design philosophy is the idea that an image stream may be processed as simply as a single image. Image streams may consist of a sequence of images and efficiency is obtained through the use of advanced algorithms (many of them unique to DigiFlow/DigImage). Power and flexibility are obtained through an advanced fully integrated macro interpreter providing a similar level of functionality to standard applications such as MatLab. This interpreter is available to the user either to directly run macros, or as part of the various DigiFlow tools to allow more flexible and creative use. DigiFlow retains the potential to control a frame grabber, which greatly simplify the process of running experiments, acquiring images, processing them, extracting and plotting data, as it also enables real-time processing of particle streaks, PIV and synthetic schlieren, as shown in figures 3 to 7.

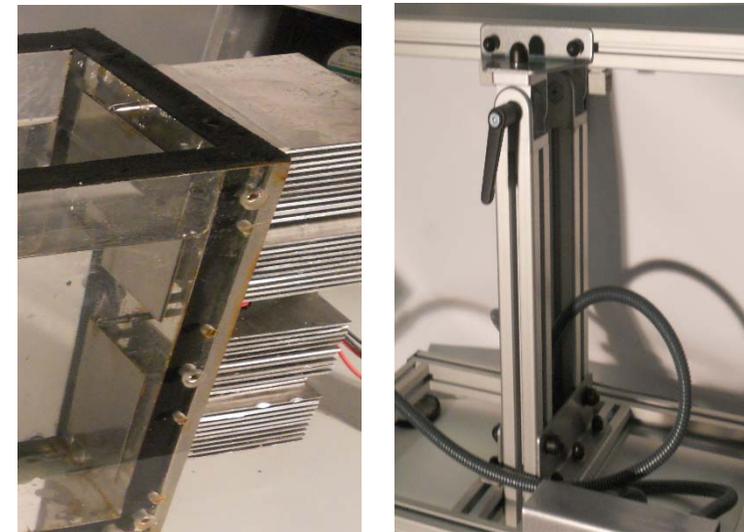


Fig. 2. Details of the Convective Thermoelectric Device produced by BEROTZA with details of the TECs dissipaters (left) and of the versatile position and angle holds [3, 9].

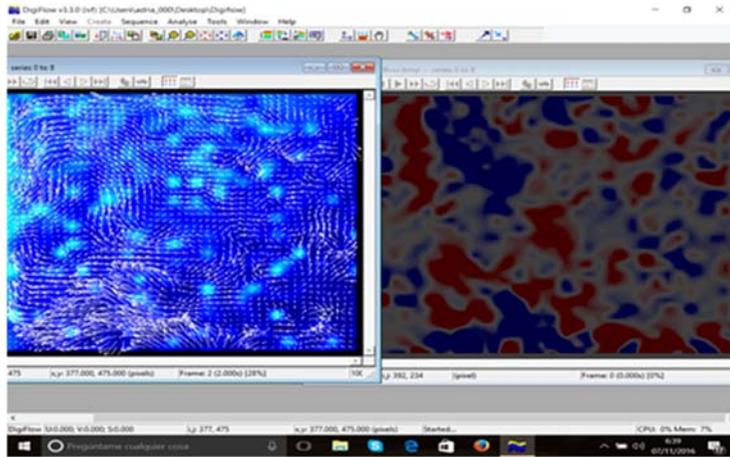


Fig. 3. Velocity and Vorticity patterns formed by sudden heating of a distributed TEC with uniform heat flux and non-homogeneous density [8, 10]. The DigiFlow Environment Program is shown, with some of the open software icons on top of the figure [5, 17]

Open Foam and some 2D RANS with K- $\epsilon$  turbulence's model simulations agree with the experiments in the very simple single convective cell situations of low Rayleigh numbers, but it is difficult to model the more complex 3D flows, what is not well understood is the role of the local mixing on the flows [11-16]. The combination of experiments and simulations is important when giving further insight on the different direct and inverse cascades processes that take place in the flow. New experiments, such as the one shown (Fig 3, 4, 5.) show the velocity and vorticity structure. By adding dye, the tracer structure and density spectra, may be studied. The vorticity spectra may control the complex structure evolution (Fig 4). which clearly shows a fractal structure in the appearance of connective local structures, when the TCDD is heated from below, even in a uniform (constant density experiment) There are few examples to compare between the experiment and the numerical simulation of even a simple theoretically model of the growth of the Benard-Taylor mixing layer in the limit of very high Reynolds number (Malkus regime, where the Nusselt number scales as one third of the Rayleigh number). The self-similar mixing layer in unstable flows is predicted to grow with a limit given by buoyancy (Ozmidov) scale so the Nusselt number depends on the Rayleigh number, these types of strong heating are difficult to realize in the laboratory [8, 9], as shown in figures 5 and 6. The presentation of such results as cascade slope or intermittency in wider parametric spaces (Akin to Poincare maps) [10-12] are expected to help in the understanding of turbulent mixing (Fig. 6).

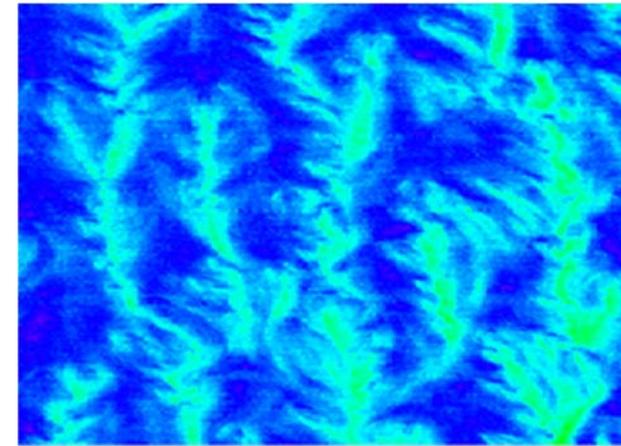


Fig. 4. Centers of Convective cells formed by sudden heating at the base of a distributed TEC with uniform heat flux [3, 9]

### 3. Numerical Model

Convective mixing takes place, mostly in the sides of ascending and descending plumes, different parts of the flow show shapes of the multi-fractal spectra, but most cases it is not easy to interpret, in some sense, it is similar in other flows where, the large coherent structures, i.e. blobs and spikes [7, 11].

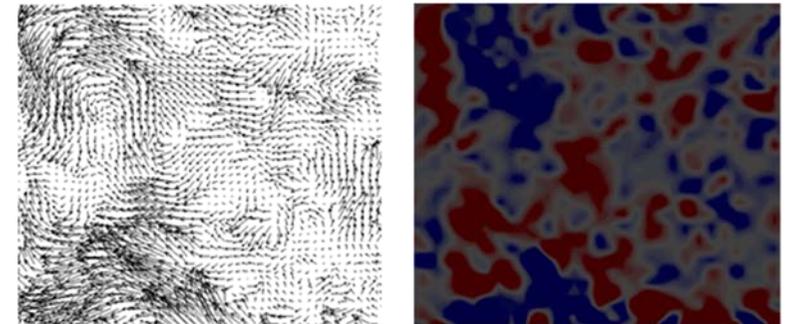


Fig. 5. Thermoelectric Convection induced flow Velocity (left), Vorticity (right) bottom Distribution of the corner driven vorticity complex 3D structure [13]

A key feature is that dominant flows of the CTDD take place in the center or symmetry plane (Figure 6). So far only flat, experiments, with no angle between gravity and the side walls have been performed, but a wide range of new configurations are possible [3, 6].

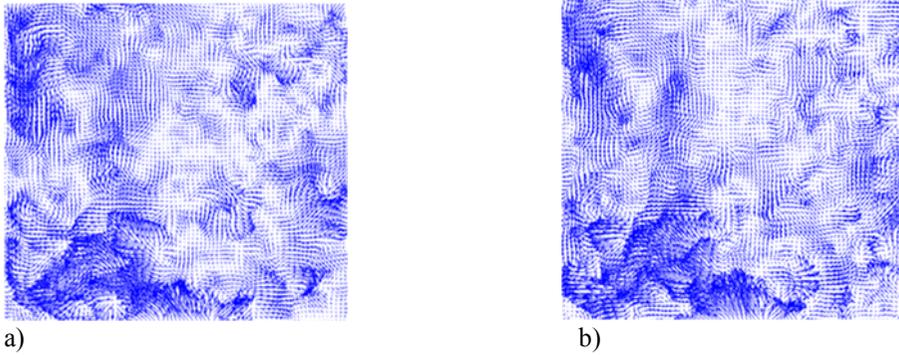


Fig. 6. Sequence of Convective induced flow Velocity (left). The corner driven flow is the most energetic creating a vorticity 3D structure [13,14]

A Reynolds-averaged Navier-Stokes (RANS) approach with a k-ε closure scheme was used to simulate the evolution of the rise of the thermoelectric driven convective structure. This is an interesting problem to investigate the mixing process, The model solves the Boussinesq equations in a two dimensional grid and is based in Cantalapiedra and Redondo [15], Versteegh [16] with updrafts and downdrafts clearly separated. Here 1:1 aspect ratio cells heated at the side walls were compared with the experiments, but other configurations were used, with a significant interest in the maximum growth flow at 2.7:1 ratio. At aspect ratios of 8:1 a complex convective pattern develops showing some asymmetry as in the experiments .

The present study is confined to the analysis of aspect ratio convection of 1:1 in an incompressible fluid using a Reynolds-averaged approach. The governing equations for the conservation of mass and momentum as:

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0, \quad \frac{D\bar{u}_i}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \nu \frac{\partial \bar{u}_i}{\partial x_j} \right] - \frac{\partial \overline{u'_i u'_j}}{\partial x_j} \quad \text{with}$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \bar{u}_j \frac{\partial}{\partial x_j}$$

Here,  $p, \rho, \nu$  and  $\bar{u}_i$  denote the pressure, density, viscosity and the Reynolds-averaged velocity based on Cartesian tensor notation, respectively. A turbulence closure model for the unknown Reynolds stresses  $\overline{u'_i u'_j}$  is necessary to obtain a closed system of equations, the election of the method is linked to the degree of mixing in the process. DNS, LES, KS, RANS include closures featuring different degrees of complexity and predictive quality. Implicit second-moment closures utilize individual transport equations for each component of  $\overline{u'_i u'_j}$ , which is computationally demanding. Other applications use explicit Reynolds-stress closures, which consists

of two parts, a stress-strain relation and a background model. The stress-strain relation describes the Reynolds stresses as a function of the mean-velocity gradients and the considered unknown turbulent scalars. The background model comprises the transport equations for the considered, relevant turbulent parameters.

The most common approach is a two-equation model, based on two transport equations for the unknown scalars, i.e. the turbulence energy  $k = 0.5\overline{u'_i u'_i}$  and the energy-dissipation rate  $\varepsilon$ . Various alternative formulations exist, e.g.  $k - \omega$ ,  $k - l$ ,  $k - \tau$ , which might yield a change of the Reynolds-stress magnitudes but do not alter the structure of the stress tensor. The active components of the Reynolds-stress tensor – in particular the degree of stress anisotropy – are primarily governed by the employed stress-strain relation for a given strain field. The anisotropy tensor is – of course – also influenced by the background model since, it globally scales with the turbulent time scale. The latter is, however, only a scalar, which carries no structural or tensorial information and thus creates no anisotropy on its own. The present paper is thus confined to a specific RANS approach with low-Re  $k - \varepsilon$  turbulence's model that solves:

$$\frac{Dk}{Dt} - \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{\nu_t}{Pr_k} \right) \frac{\partial k}{\partial x_j} \right] = P - \varepsilon,$$

$$\frac{D\varepsilon}{Dt} - \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{\nu_t}{Pr_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] = \frac{\varepsilon}{k} (C_{\varepsilon 1} P - C_{\varepsilon 2} \varepsilon),$$

with

$$C_{\varepsilon 1} = 1.44 f_1, \quad C_{\varepsilon 2} = 1.92 f_2, \quad Pr_k = 1, \quad Pr_\varepsilon = 1.3,$$

$$R_t = \frac{k^2}{\nu \varepsilon}, \quad R_k = \frac{\sqrt{k} n}{\nu},$$

$$f_1 = 1 + \frac{P}{P^*}, \quad f_2 = 1 - 0.3e^{-R_t^2}, \quad \text{and} \quad f_\mu = \frac{1 - e^{-\alpha_\mu R_k}}{1 - e^{-\alpha_\varepsilon R_k}}, \quad P = -\overline{u'_i u'_j} S_{ij},$$

$$P^* = \frac{f_2 C_{\varepsilon 2} k^{1.5}}{C_{\varepsilon 1} L_\varepsilon} e^{-\alpha_d R_k^2}, \quad \text{with} \quad L_\varepsilon = \kappa c_\mu^{(-0.75)} n (1 - e^{-\alpha_\varepsilon R_k}) \quad \text{and}$$

$$c_\mu = 0.09, \quad \alpha_d = 0.0022, \quad \alpha_\varepsilon = 0.263, \quad \alpha_\mu = 0.016.$$

The most popular representative of an explicit Reynolds-stress closure is the well known linear Boussinesq-viscosity model where:  $b_{ij} = -c_\mu T_i S_{ij}$ .

In above equation,  $b_{ij} = \left( \overline{u_i u_j} - \frac{2}{3} k \delta_{ij} \right) / 2k$  is the Reynolds-stress anisotropy tensor,

$S_{ij} = \left( \partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i \right) / 2$  and  $T_i = k / \varepsilon$  denote the strain-rate tensor and the turbulent time scale respectively. The main reason for the popularity of this model is

the similarity to the definition of viscous stresses, which simplifies the numerical implementation [15-18].

Under the assumption of a steady 2D boundary layer flow (i.e.,  $u \gg v$ ,  $\partial/\partial y \gg \partial/\partial x$ ), the governing equations for the velocity and temperature, in forced convection, are:

Conservation of mass:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Conservation of momentum:

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\partial}{\partial y} \left( v \frac{\partial u}{\partial y} - \overline{u'v'} \right)$$

Conservation of energy:

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\partial}{\partial y} \left( \alpha \frac{\partial T}{\partial y} - \overline{vT'} \right)$$

As this system of equations contains more unknowns than equations, so it is an open system. Here the closure of averaged above equations is ensured by different low Reynolds number  $k-\varepsilon$  turbulence models. The mean turbulent kinetic energy and its dissipation rate may be written in the following form for Newman conditions [16,17]:

$$u \frac{\partial k}{\partial x} + v \frac{\partial k}{\partial y} = \frac{\partial}{\partial y} \left( \left( v + \frac{v_t}{\sigma_k} \right) \frac{\partial k}{\partial y} \right) + v_t \left( \frac{\partial u}{\partial y} \right)^2 - \tilde{\varepsilon} - D$$

$$u \frac{\partial \tilde{\varepsilon}}{\partial x} + v \frac{\partial \tilde{\varepsilon}}{\partial y} = \frac{\partial}{\partial y} \left( \left( v + \frac{v_t}{\sigma_\varepsilon} \right) \frac{\partial \tilde{\varepsilon}}{\partial y} \right) + C_{\varepsilon 1} f_1 \frac{\tilde{\varepsilon}}{k} v_t \left( \frac{\partial u}{\partial y} \right)^2 - C_{\varepsilon 2} f_2 \frac{\tilde{\varepsilon}^2}{k} + F$$

The Reynolds stress  $\overline{u'v'}$  and the heat flux  $\overline{vT'}$  appearing in the system of conservation of momentum and conservation of energy equations, may be expressed as:

$$\overline{u'v'} = -v_t \frac{\partial u}{\partial y}, \quad \overline{vT'} = -\frac{v_t}{Pr_t} \frac{\partial T}{\partial y}$$

The eddy viscosity  $V_t$  is related to  $k$  and  $\tilde{\varepsilon}$  through the Kolmogorov-Prandtl relations as:

$$v_t = C_\mu f_\mu \frac{k^2}{\tilde{\varepsilon}}$$

$\sigma_k, \sigma_\varepsilon, C_{\varepsilon 1}$  and  $C_{\varepsilon 2}$  are empirical constants and  $f_1, f_2$  and  $f_\mu$  are the turbulence model functions for the near wall formulation. For low Reynolds numbers and the simple side wall heated experiments, good qualitative average 2D flows were obtained, even showing the asymmetry of corner vortex formation as seen in the

experiments (figure 7) and in the numerical simulations (figure 8). The problem with these models is detected when higher order moments and intermittency is evaluated. Mixing evaluations are very poor.

#### 4. Discussion and Conclusions

The calibration of fluids dynamics (CFD) source codes such as (OpenFoam, Imcompact3D, DigiFlow) for numerical simulation of different experiments is important at different resolutions, here spectral and fractal measurements in large Reynold numbers water or wind tunnels or experiments like the ones performed in Multiflow and EU Hit [21-23] are fundamental to write new solvers for different problems in tensorial partial differential equation from [11, 12], but considering fractal aspects. A flow field may be solved by an adaptation of original turbulence solvers for incompressible fluid (simpleFoam, pisoFoam, pimpleFoam). The core of these solver is the finite volume discretization of the governing equations. Almost all kinds of differential operators possible in a partial differential equation, such as temporal derivative, divergence, Laplacian operator, vorticity, etc. Even in the case of stratified flow [13] DNS and LES codes allow to predict and calculate structure functions and local intermittency [4,10], but detailed calibrations are also needed, in [19] it was noted how the transition between 2D and 3D flows produced different scale to scale cascades which departed from Kolmogorov local processes. By the use of experimental benchmarks such as the TCDD described here, it is possible, thanks to advanced visualization software such as DigiFlow, ImaCalc [20-22] to have similar resolution in laboratory experiments and numerical simulations as seen in figures 8 and 9 [14, 15].

By using the dimensionless variables, most of the times in a very large and complex parametric space, the experiments and simulations fit. The challenge is not just to model the system of conservation of mass, conservation of momentum, conservation of energy and the mean flow and turbulent kinetic energy, but also model and measure the structure functions, the fractal aspects and the intermittency, as in [23] for wind generator wakes.

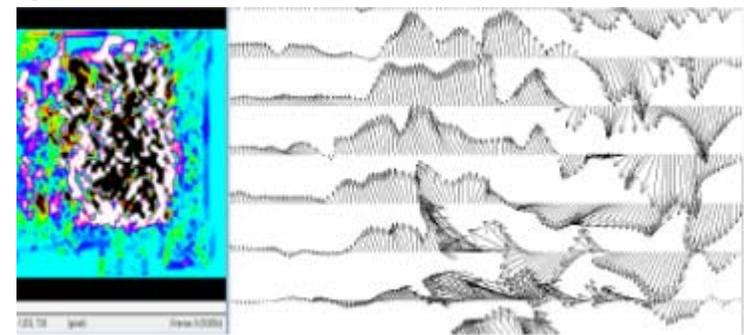


Fig 7. Dominant Vortical structure and Velocity fluxes(left), The Large scale structure is seen on the right, Structure functions and fractal structure may be calculated as in [10, 15]

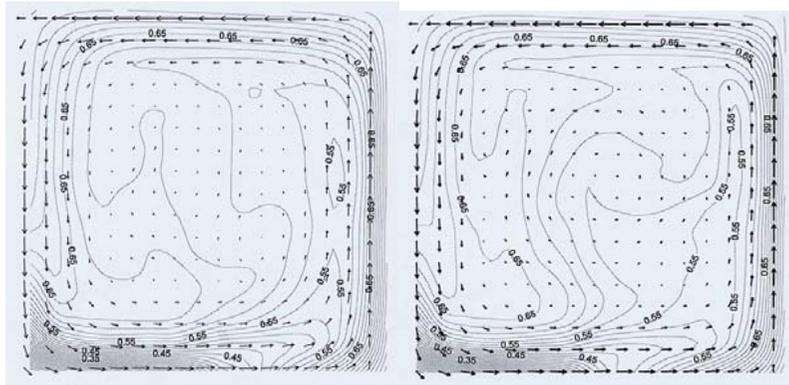


Fig 8. *K-e* model of a 2D convective cell in an 1:1 ratio enclosure. The recirculating average flow may be clearly seen [13]

Figures 7 and 8 show the global flow and the acceleration produced due to boundary layer induced buoyancy in an enclosed flow. When buoyancy acts on a density interface, Baroclinic vorticity is also generated internally and Rayleigh-Taylor flows advance in a non-linear fashion [8,9, 14], here only DNS models are able to predict mixing. But there is still a need to evaluate the multi-fractal and intermittent nature of the different forcing conditions. The detailed comparisons of experiments and numerical simulations, both in physical and spectral domains is necessary to understand the complex flows at high Reynolds numbers.

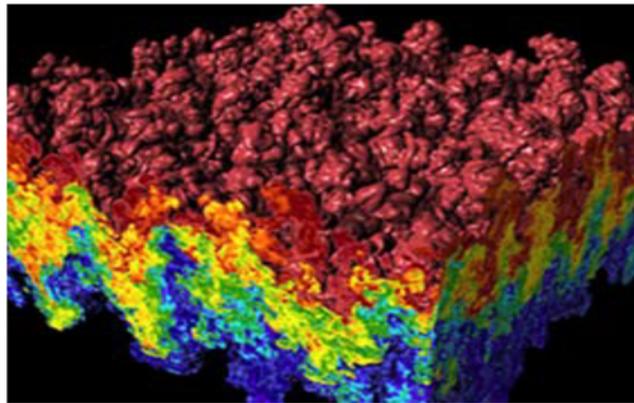


Fig 9. *DNS* of a Rayleigh-Taylor front where the filamentation may be seen [13]

Even considering intermittency in Kolmogorov's turbulent cascade, such complex flows are known to generate non-equilibrium turbulence, and probably also non-local turbulence. This produces different turbulence properties and modified mixing in strong convection as shown here with the TCDD. Also downstream of fractal grids (EU Hit proposal) the flow exhibits different mixing as compared with the classical

uniform grids. Applications to enhanced mixing and drag reduction are still being investigated [21, 22], even in other types of fractal fluxes. How do the turbulence and mixing properties change with Rayleigh and Reynolds numbers in different parameter spaces. In order to answer this, it seems necessary to investigate both numerically and experimentally the following properties: The turbulence intensity; the Reynolds stresses; The energy budget. The scalar gradients. The scalar fluctuations. The Skewness and the Kurtosis of flow velocity and vorticity, kinetic energy and enstrophy both for scalar tracer and flow. With the didactic apparatus and the software described above, we believe that the role of intermittency and of the structure functions may be compared and evaluated, which is very important in complex and environmental flows [23].

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## Турбулентная конвекция термоэлектричеством в охладительно-нагревательном устройстве

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**Аннотация.** Локальная диффузия и топологическая структура завихрения и поля скоростей измерены в переходном режиме от однородной линейно стратифицированной жидкости до ячеистой или многоуровневой структуры посредством конвективного охлаждения и/или нагревания. Подобные структуры возникают, создавая конвективный поток, при использовании массива термоэлектрических устройств (элементы Peltier/Seebeck), которые генерируют значительный тепловой поток. Описанные в статье

эксперименты направлены на изучение различных чисел Прандтля с использованием пластовой и пресной воды, чтобы сформировать градиенты плотности и низкие числа Прандтля для режимов смешения с градиентами температуры. Набор безразмерных параметров определяет условия численного и мелкомасштабного лабораторного моделирования для различных геофизических течений. Поля скорости, плотности и их градиенты были вычислены и визуализированы с использованием открытого программного пакета DigiFlow и численного моделирования на базе уравнений Рейнольдса с к-е моделью турбулентности. Когда конвективный нагрев и охлаждение происходят на стороне стратифицированной вложенной ячейки (комбинации внутренних волн и плавучести) управляемая турбулентность намного более сложна, если числа Релея и числа Рейнольдса велики. Вычисления моментов высшего порядка и перемежаемость важны для изучения процессов перемешивания в сложных течениях. В данной работе представлены некоторые примеры с использованием Thermoelectric Convection Didactive Device (TCDD), созданного в BEROTZA, главным образом в симметричного двумерного образца. Но существует много других технических вариантов устройства, например, с использованием охлаждения и нагревания, создания стенок под углом с вертикалью, позволяющих протестировать более сложные варианты с применением численных экспериментов.

**Ключевые слова:** конвекция; термоэлектричество; элементы Пелетье; эксперименты, к-е модель турбулентности; турбулентность; программа DigiFlow.

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