Institute or Fundamental Technological Research
Polish Academy of Sciences

Synergy of Experiments and Computer Simulations in Research of Turbulent Convection

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Introduction

- Synergy in scientific research has long been recognized and practiced
- Yet, scientist tend more and more to specialize!
- Rapid developments of computers created a particular gap between experiments and computer simulations
- “Experiments will become obsolete and wind tunnels will be turned into storages of computer outputs”
- “Computer simulations? GiGo!” (“Garbage in, garbage out!”)
- Yet, tremendous advancements in both experimental and simulation/ modelling techniques and mutual feedback, synergic inspiration and incentives!

Examples of synergy in three research problems:

1. Thermal convection over horizontal and sloped surfaces in a broad range of conditions including the *extreme* ones
   - Experiments for $Ra=10^8-10^9$
   - DNS for $Ra=10^5-10^8$; LES for $Ra=10^6-10^9$
   - VLES/T-RANS for $Ra=10^6-2x10^{16}$

2. Impinging flows and heat transfer at *higher* Re numbers
   - Single impinging round jets
     - Experiments, RANS and LES, Re=20.000
   - Multiple impinging jets
     - Experiments and RANS
   - Single impinging round jet on a cube in cross-flow
     - Experiments, RANS and LES

1. Fluid magnetic dynamo: Hybrid DNS/RANS Computer simulations and interaction with experiments in Riga (Latvia) and Dresden (G)

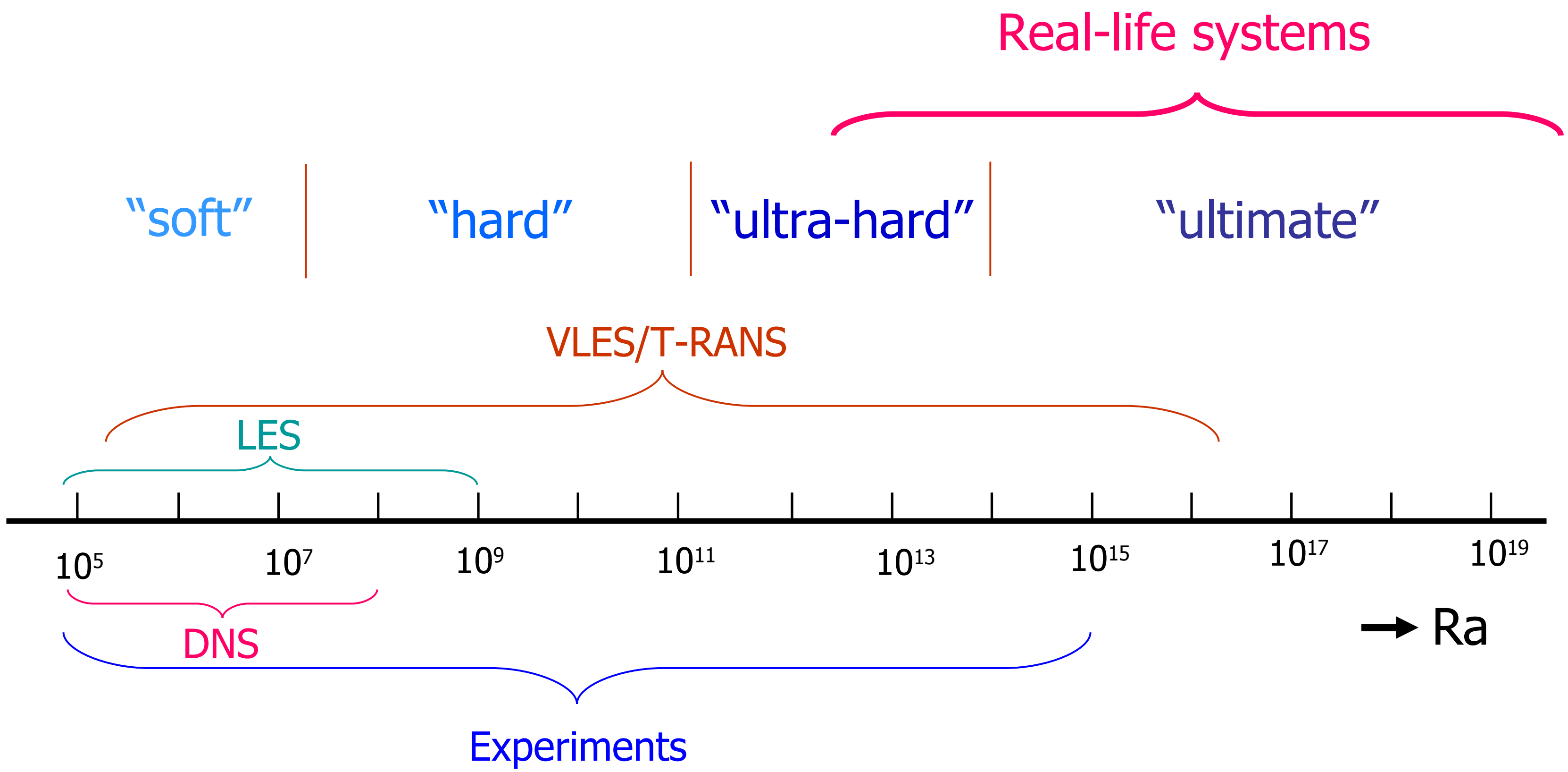
1. Thermal convection

Thermal convection from horizontal surfaces (Rayleigh-Bénard (R-B) and related problems

- R-B convection = a paradigm of thermal convection; contains most events, structures and features of real-large-scale situations in environmental, geo-, terrestrial and technological systems

- Despite long research, still burdened with controversies:
  - "soft", "hard", "ultra-hard" turbulence;
  - $Nu \propto Ra^n$, "n" from 2/7 (1/3?) ($10^7 < Ra < 10^{11}$) to 1/2 when $Ra \to \infty$
  - scaling of flow properties in various regions and regimes;
  - existence and definition of "wind", plumes, thermals,..
  - convective-cells and plume structure formation, ordering, ..
  - long-term oscillations, flow reversal, causes-consequences

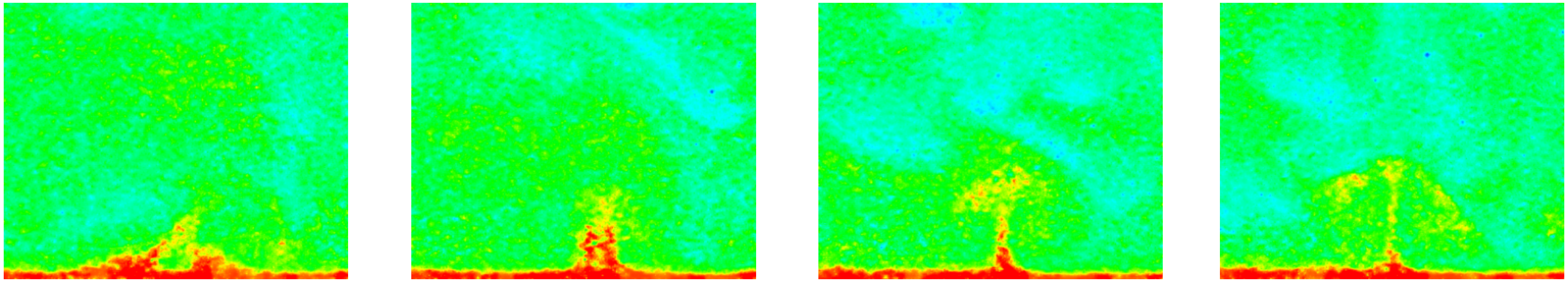
Thermal convection: problems and solutions



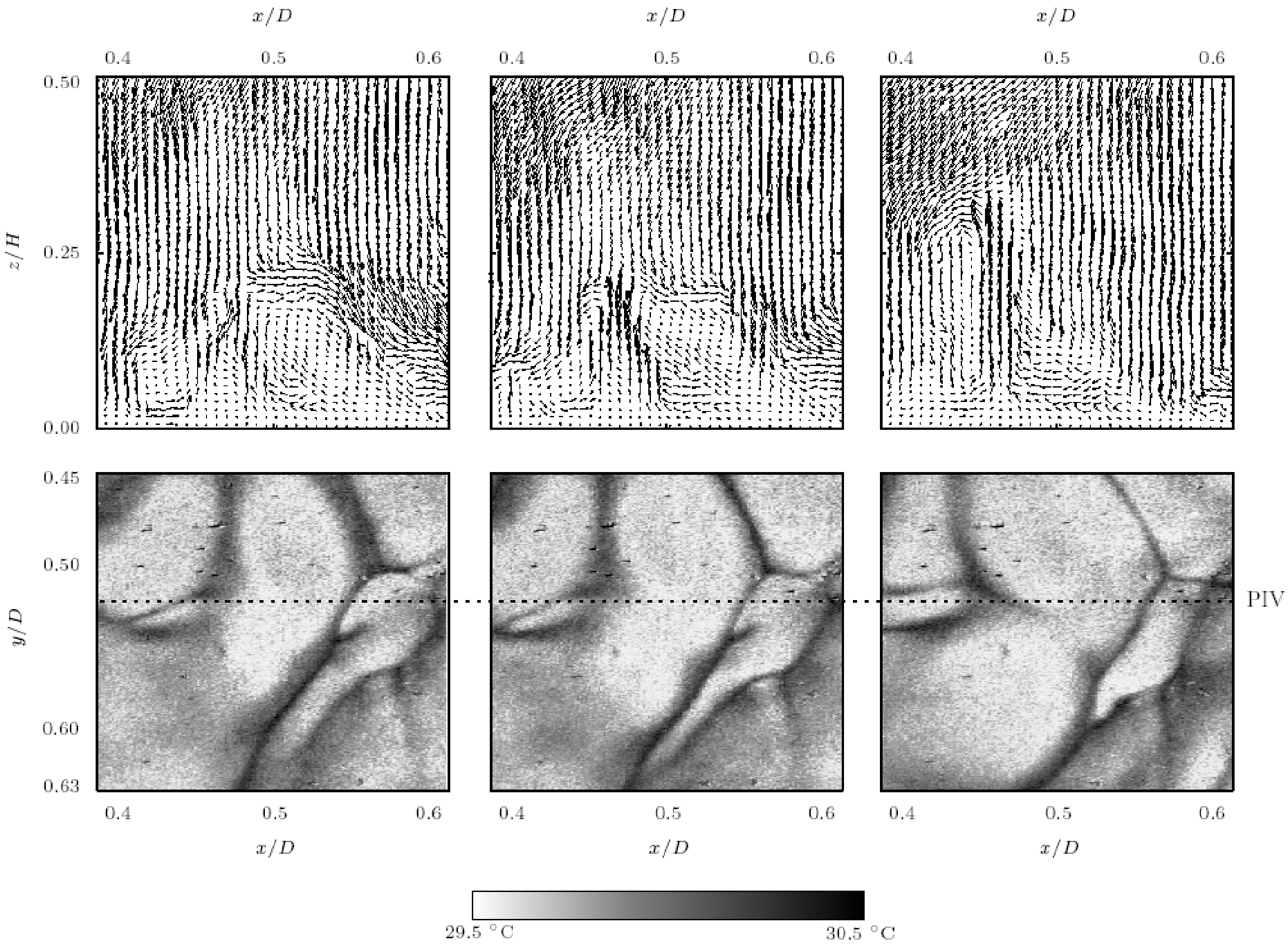
Achievements and limitations in R-B experiments

- Until recently, only point-measurements (especially at high Ra)
- PIV, PTF, LIF, LC brought much advancement, (almost all data) but still confined to one-plane, limited domains and single-fields
- 3-D instantaneous field essential for capturing structure and full dynamics: desirable simultaneous application of 3D PIV of PTV (holographic) with suspended LC, thermography and/or spectrometry
- Problems become more challenging with an increase in Ra!

Formation and evolution of thermal plume, suspended Liquid Crystals, Ra=10^8, Pr=7.0, 4:4:1 domain, (*Verdoold, Tummers, Hanjalic et al. 2004*)



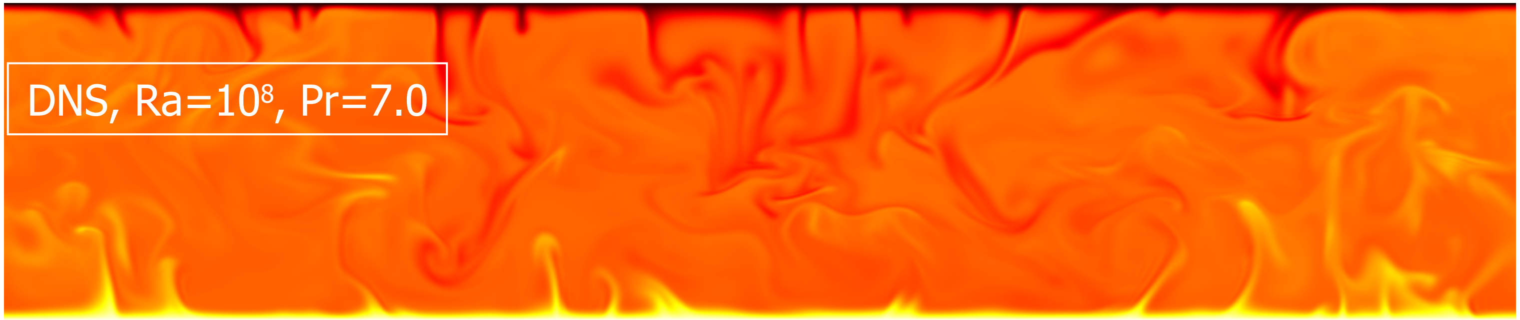
Synchronised snapshot of PIV in x-y and LCT in a near-wall x-z plane in R-B convection at 10 sec intervals (Ra=1.3x10^8, Pr=7.0) (*Verdoold et al. 2004)*

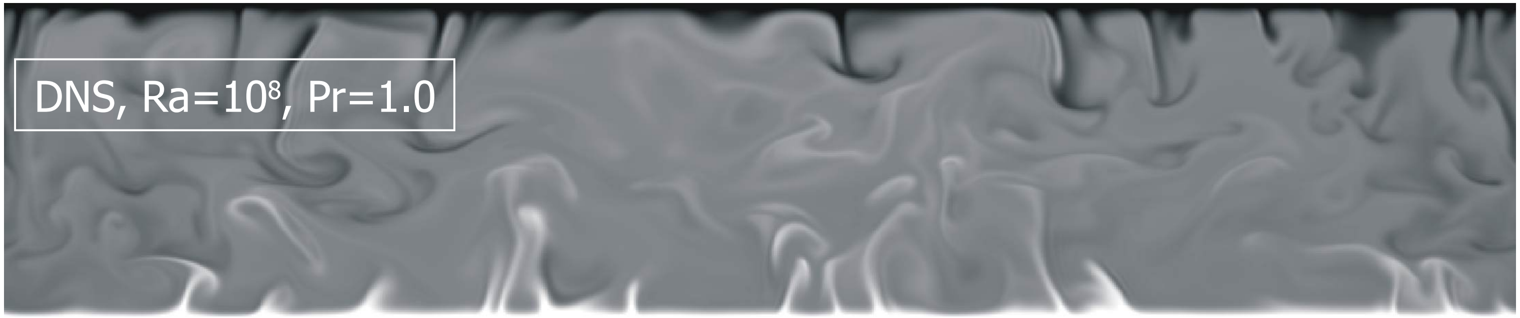


Achievements and limitations in DNS of R-B convection

- Computer simulations (DNS, LES): tremendous potential, make it possible to collect all information needed, (some are still inaccessible to experiments) , but only for low Ra's!

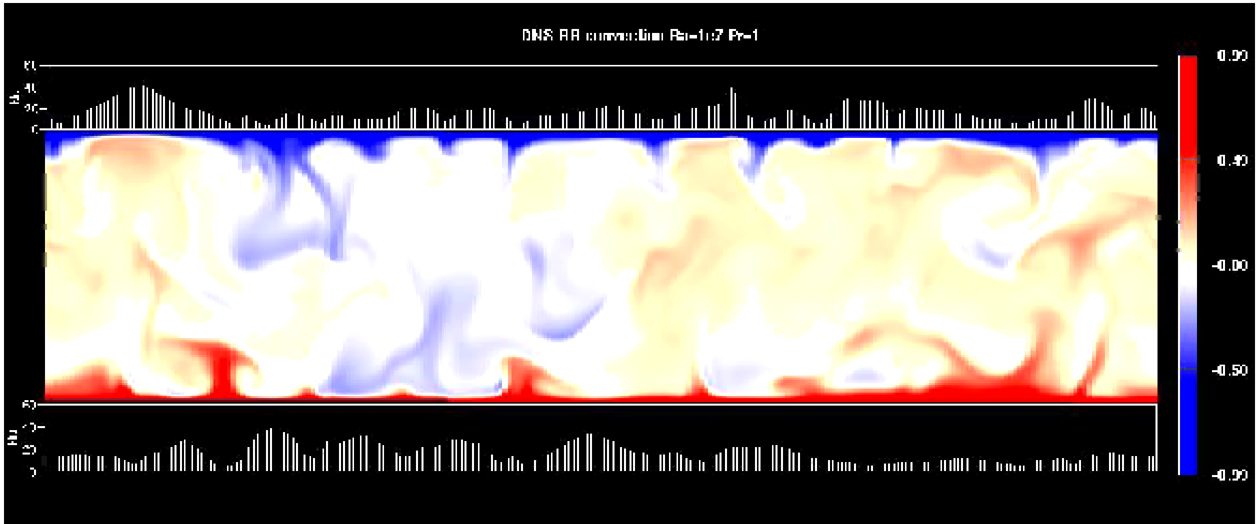
Recent: $Ra=1.1x10^8$, Pr=7, grid: 768x768x320 (~ 188 million!) on 192 processor of TERAS, (~ 22 hours per processor for **one turn-over time, ~55 sec real time**) *(Van Reeuwijk, Jonker, Hanjalic, 2005)*



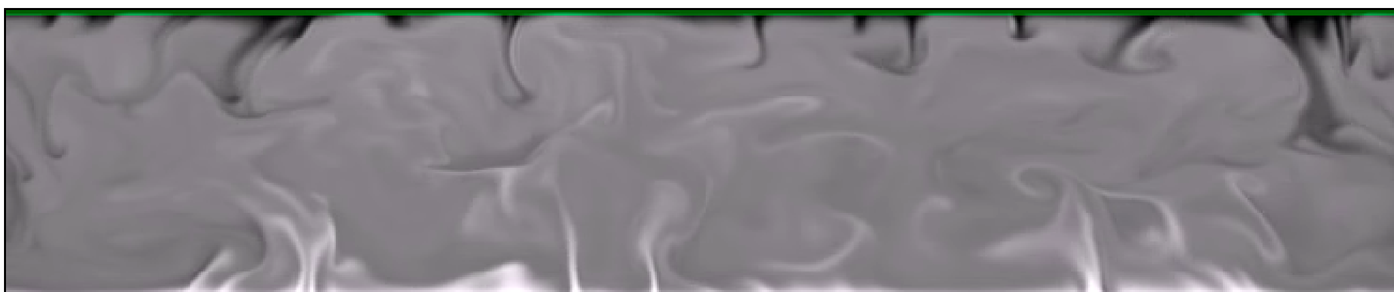


Recent achievements in DNS of R-B convection

Ra=1.1x10^8, Pr=7, grid: 768x768x320, Finite volume + spectral integration, grid clustered in near-wall regions, *(Van Reeuwijk, Jonker, Hanjalic, 2005)*



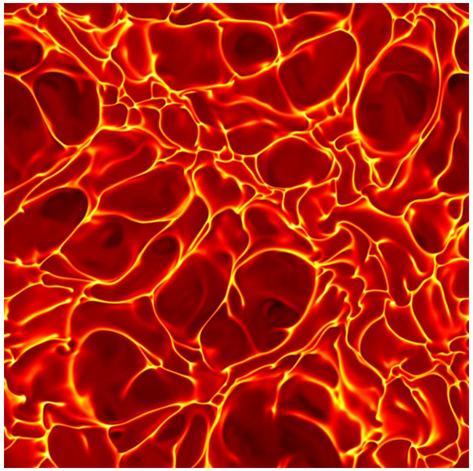
rb_v_TNu_Ra=1e7.avi

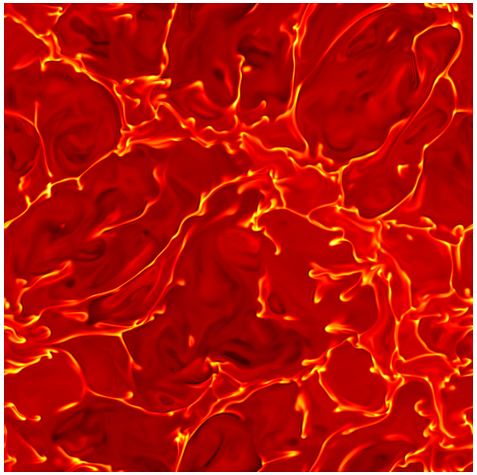


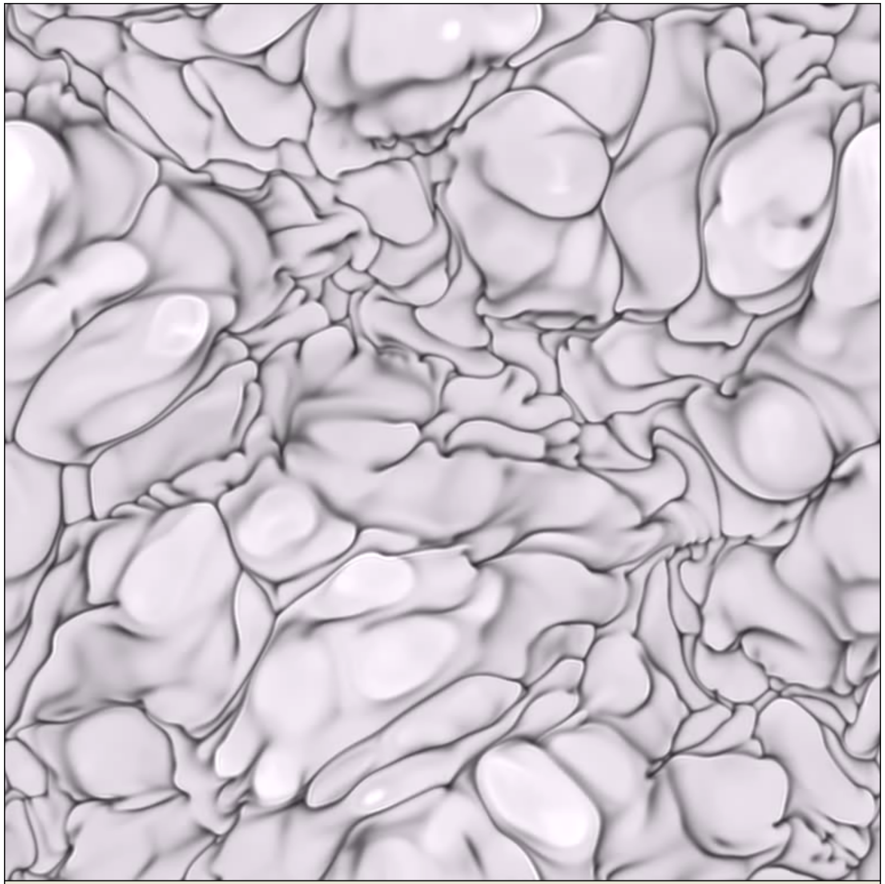
Ra1e8_Pr7_t01_xz.avi

Recent achievements in DNS of R-B convection

Ra=1.1x10^8, Pr=7, grid: 768x768x320, Finite volume + spectral integration, grid clustered in near-wall regions, *(Van Reeuwijk, Jonker, Hanjalic, 2005)*







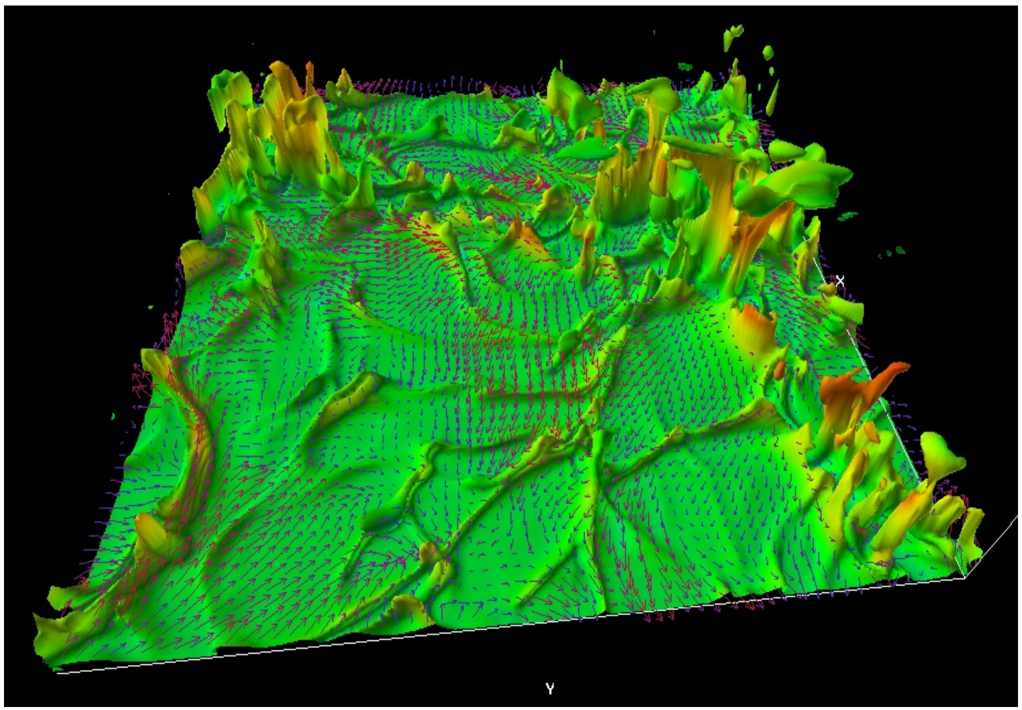
Ra1e8_Pr7_t01_xy_bl.avi

Some outcome of DNS: Identification of "Wind"

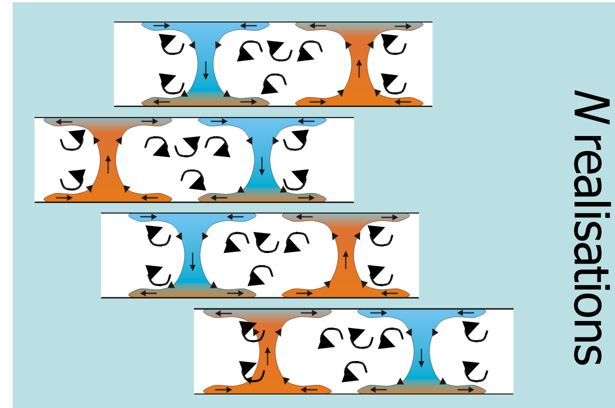
Triple decomposition:

Flow ='Wind'+ Plumes + Fluctuations

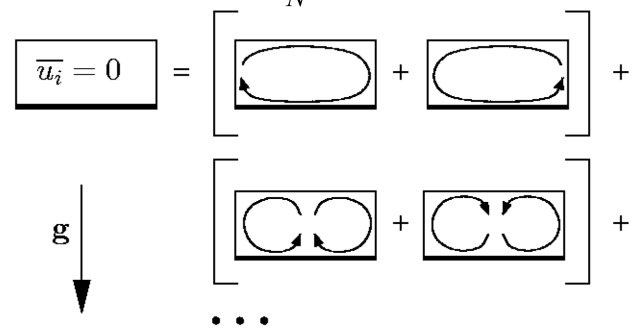
'Wind' + Plumes: Deterministic; Fluctuations: Stochastic



Classic ensemble averaging:



$$\overline{u}(\vec{\mathbf{x}}) = \frac{1}{N}\sum_{N} u_n(\vec{\mathbf{x}} - \vec{\mathbf{d}}_n)$$



'Wind': $\overline{u} = \overline{v} = \overline{w} = 0$

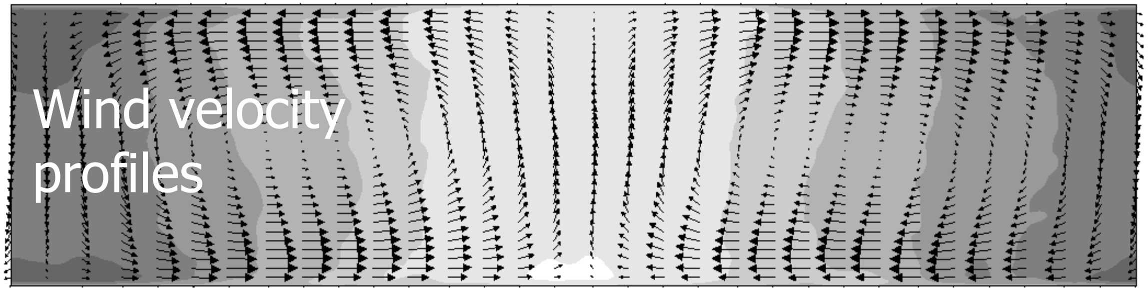
Symmetry-accounting ('conditional') ensemble averaging

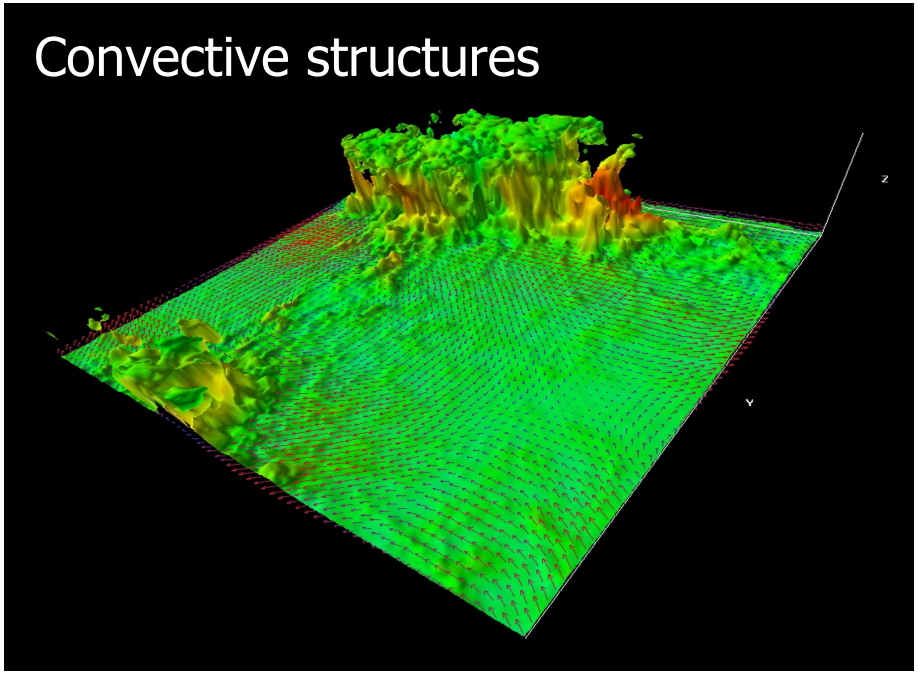
Using DNS data

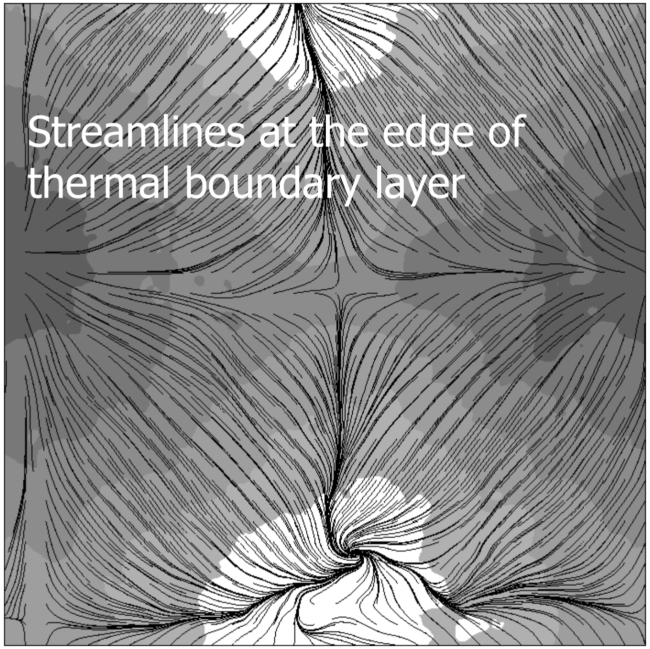
Van Reeuwijk, Jonker, Hanjalic, Phys.Fluids, 2005

$$\overline{u}(\vec{\mathbf{x}}) = \frac{1}{N}\sum_{N} u_n(\vec{\mathbf{x}} - \vec{\mathbf{d}}_n)\, \boxed{S^{(\alpha)}}$$

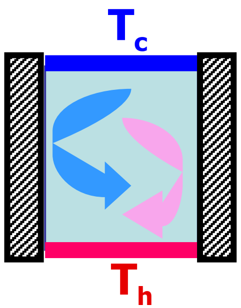
$S^{(\alpha)}$ = *symmetry operator*



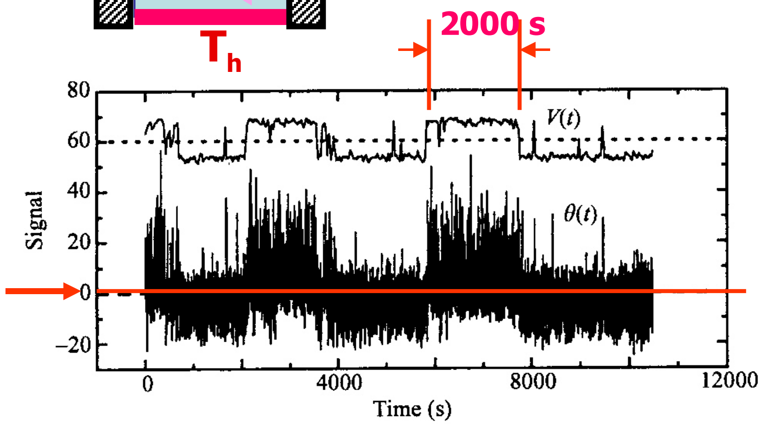




Some controversies related to long-term oscillations and sudden reversal of Wind direction

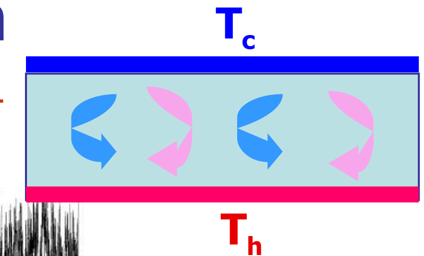


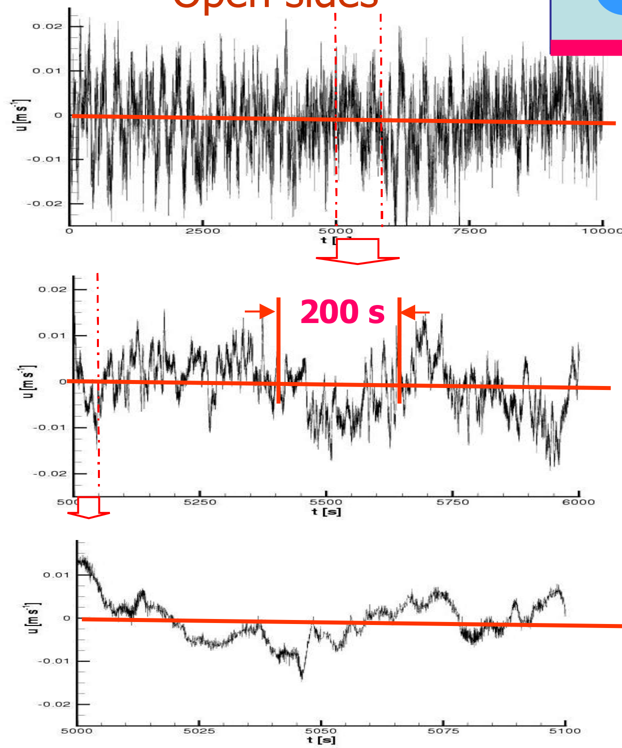
Low aspect ratio,
W:H~1, Closed sides



Wind velocity (smoothed) and temperature recordings in the experiment with cryogenic helium in a cylindrical enclosure 50×50 cm at Ra=1.5×10^{11} *(Niemela et al. 2001)*

High aspect ratio, W:H>>1
Open sides

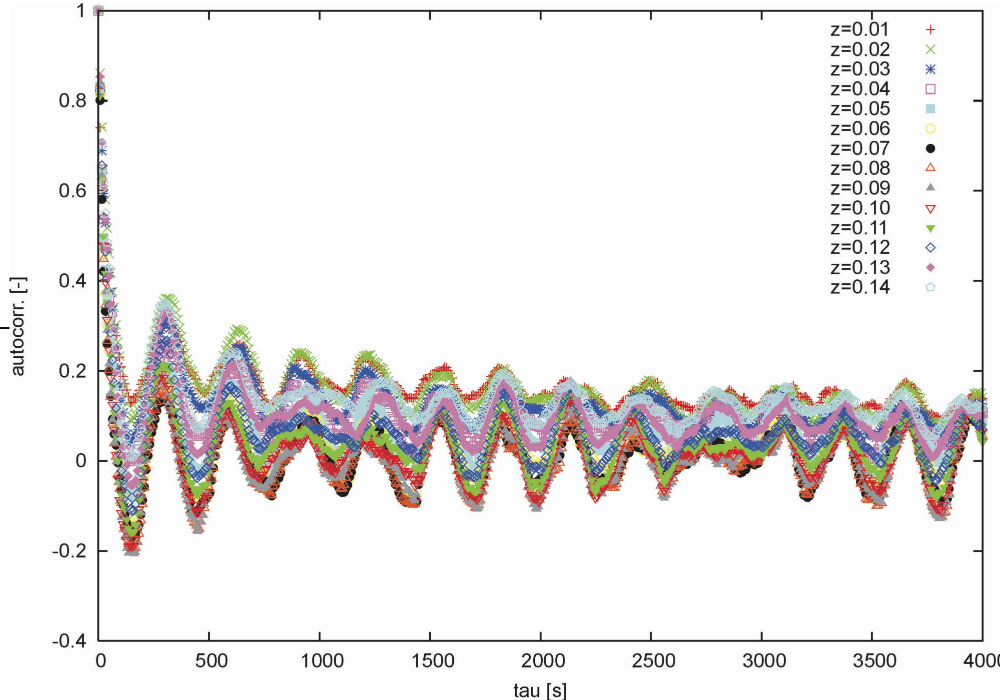


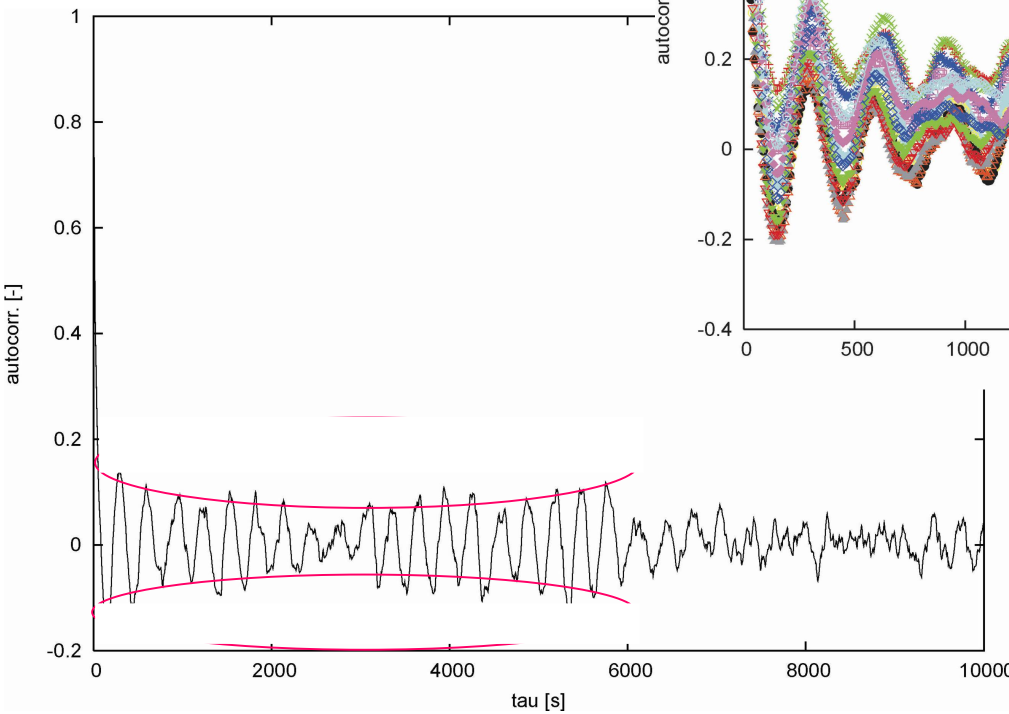


LDA long-term velocity recording at 33 mm from the bottom wall in the centre of a 60× 60×15,5 cm R-B experiment with water, Ra ≈10^9 (Verdoold et al. 2004/05)

Velocity autocorrelation in R-B convection

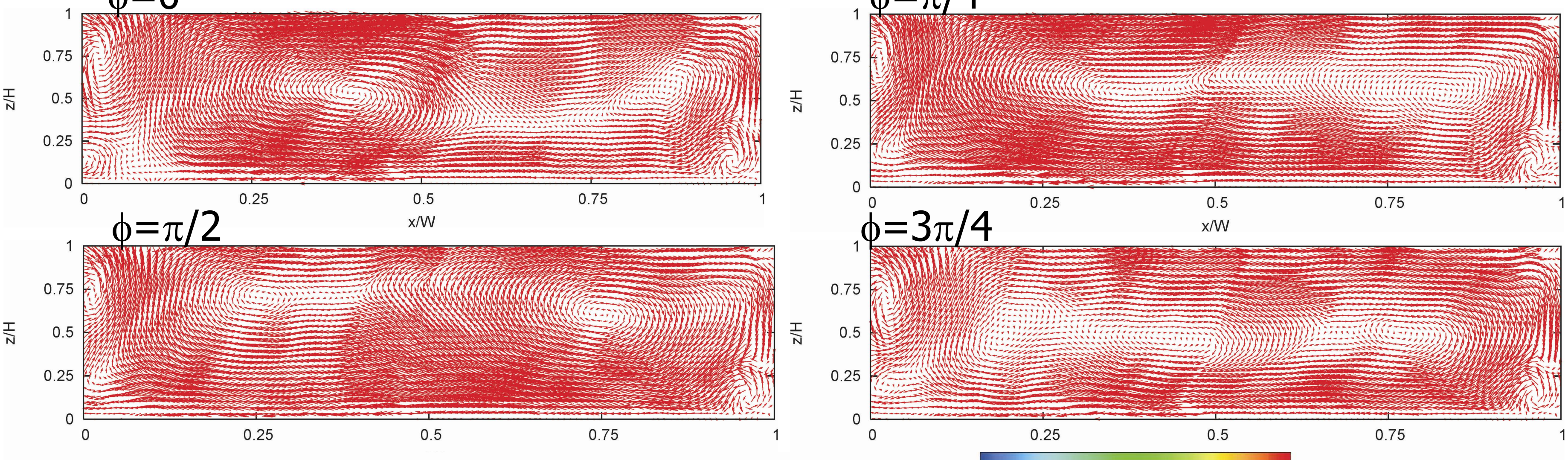
Measurements: Verdoold et al, 2005



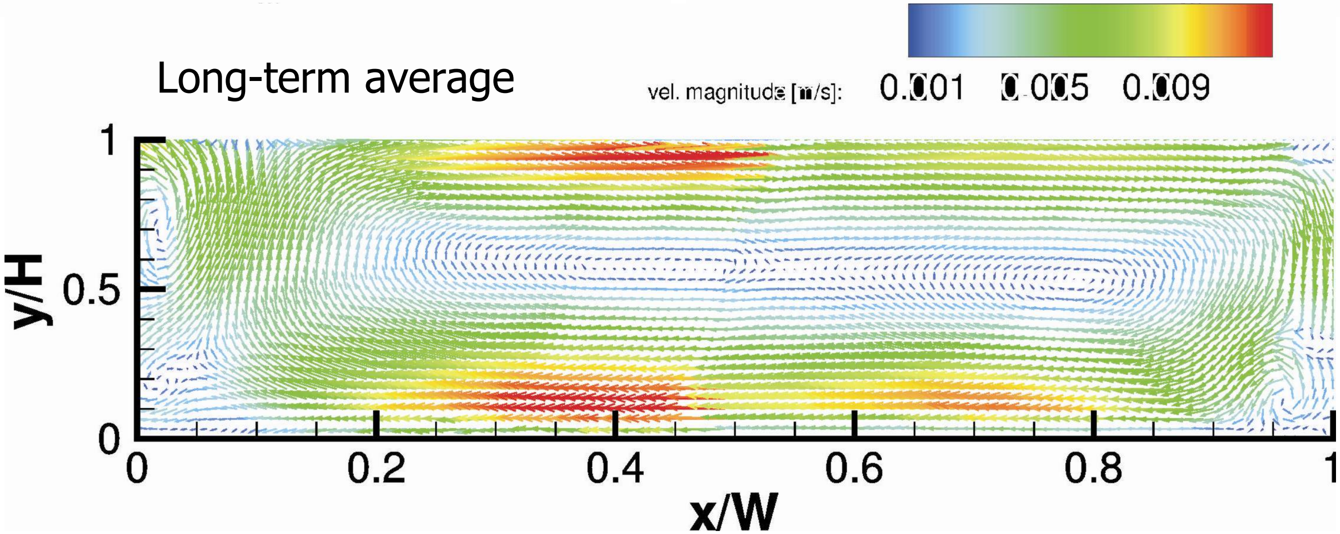


Convective patterns in R-B convection

Phase average



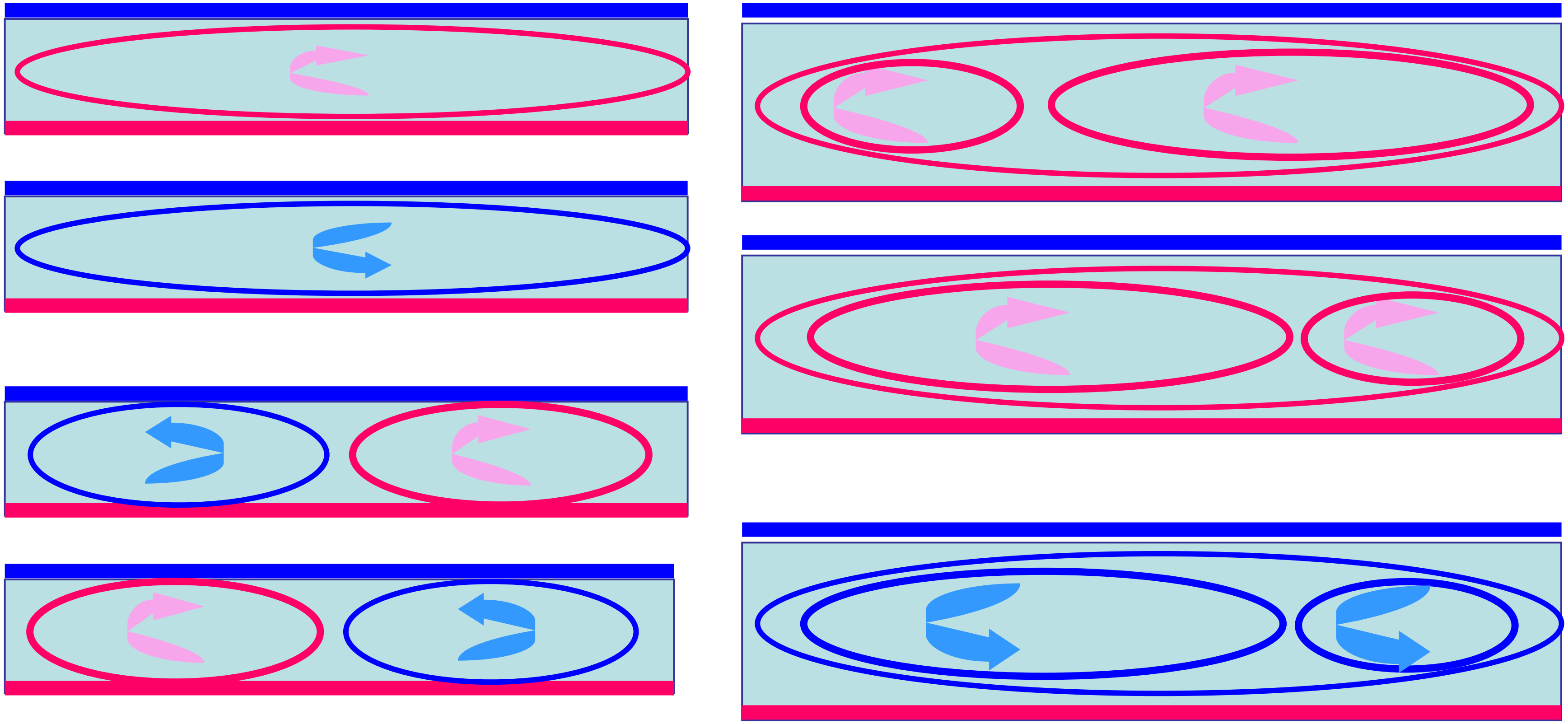
Long-term average



Convective patterns in R-B convection

Classic

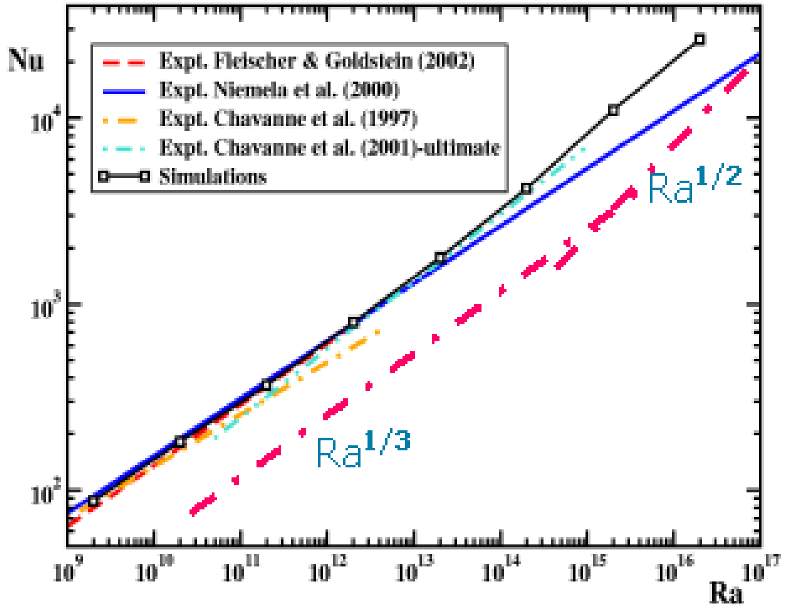
Possible long-term periodic scenario

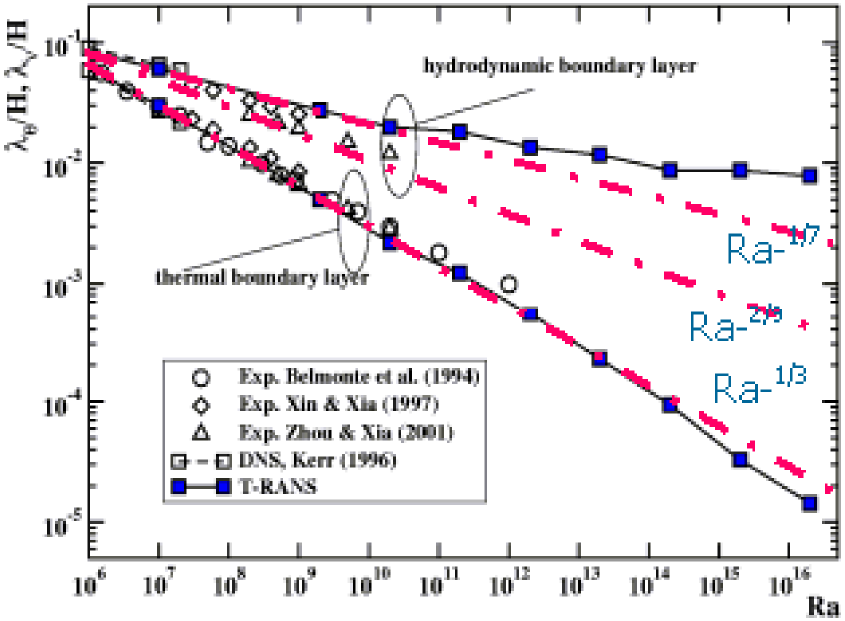


High Ra challenges in R-B convection: Transient RANS

(*Kenjeres & Hanjalic, Phys Rev. E, 2002*)

- $Nu \propto Ra^{1/3}$ for $Ra<10^{12}$ *(Pr $\mathcal{O}(1)$)*
- $Nu \propto Ra^{1/2}$ for $Ra \rightarrow \infty$





- $\lambda_v/H \propto Ra^{-1/7}$
- $\lambda_\theta/H \propto Ra^{-1/3}$

A priori test of different models in generic flows

The AFM of Kenjeres *et al* (2004) in conjunction with the $v2\text{-}f\text{-}\theta^2$ model reproduces best the heat flux components in both generic cases of natural convection: vertical and horizontal plane channels with $\nabla T \perp \vec{g}$ and $\nabla T \parallel \vec{g}$ respectively.

SGDH

$$\overline{\theta u_i} = -C_\theta \tau k \frac{\partial T}{\partial x_i}$$

GGDH

$$\overline{\theta u_i} = -C_\theta \tau \overline{u_i u_j} \frac{\partial T}{\partial x_j}$$

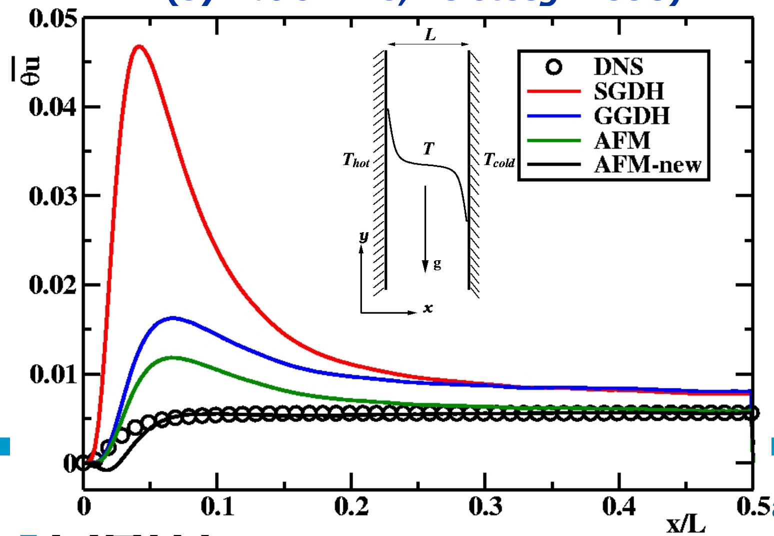
AFM

$$\overline{\theta u_i} = -C_\theta \tau \left[\overline{u_i u_j} \frac{\partial T}{\partial x_j} + \overline{\theta u_j} \frac{\partial U_i}{\partial x_j} + \beta g_i \overline{\theta^2} \right]$$

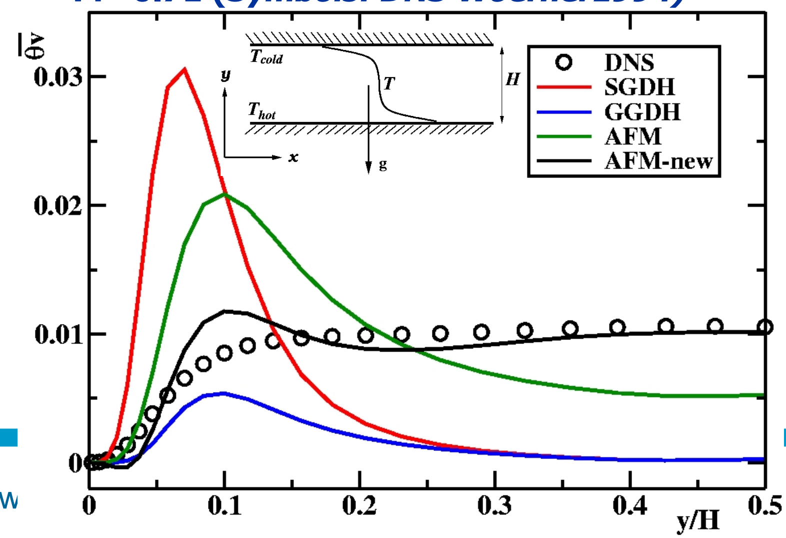
AFM-new

$$\overline{\theta u_i} = -C_\theta \tau \left[\overline{u_i u_j} \frac{\partial T}{\partial x_j} + \overline{\theta u_j} \frac{\partial U_i}{\partial x_j} + \beta g_i \overline{\theta^2} \right] + 1.5 a_{ij} \overline{\theta u_j} \qquad \tau = \max\left[\frac{k}{\varepsilon}, C_\mu \left(\frac{\nu}{\varepsilon} \right)^{1/2} \right]; \quad C_\theta = 0.3$$

Wall normal heat flux in a side heated vertical channel; Ra=5x10⁶, Pr=0.71 (*Symbols: DNS, Versteegh 1998*)



Wall normal heat flux in a heated-from-below horizontal channel (R-B-convection) Ra=6.3x10⁵, Pr=0.71 (*Symbols: DNS Woerner1994*)



T-RANS Equations and subscale models:

$$\frac{\partial\langle U_i\rangle}{\partial t}+\langle U_j\rangle\frac{\partial\langle U_i\rangle}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\nu\frac{\partial\langle U_i\rangle}{\partial x_j}-\tau_{ij}\right)-\frac{1}{\rho}\frac{\partial\left(\langle P\rangle-P_{ref}\right)}{\partial x_i}+\beta g_i\left(\langle T\rangle-T_{ref}\right)$$

$$\frac{\partial\langle T\rangle}{\partial t}+\langle U_j\rangle\frac{\partial\langle T\rangle}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\nu}{Pr}\frac{\partial\langle T\rangle}{\partial x_j}-\tau_{\theta j}\right)$$

$$\frac{\partial\langle C\rangle}{\partial t}+\langle U_j\rangle\frac{\partial\langle C\rangle}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\nu}{Sc}\frac{\partial\langle C\rangle}{\partial x_j}-\tau_{cj}\right)$$

assuming weak equilibrium

$$(D/Dt-\mathcal{D}iff)\overline{\varphi u_i}=0$$

Subscale ASM/AFM/ACM

$$\tau_{\theta i}=-C_\phi\frac{\langle k\rangle}{\langle\varepsilon\rangle}\left[\tau_{ij}\frac{\partial\langle T\rangle}{\partial x_j}+\xi\tau_{\theta j}\frac{\partial\langle U_i\rangle}{\partial x_j}+\eta\beta g_i\langle\theta^2\rangle\right]$$

$$\tau_{ci}=-C_\phi\frac{\langle k\rangle}{\langle\varepsilon\rangle}\left[\tau_{ij}\frac{\partial\langle C\rangle}{\partial x_j}+\xi\tau_{cj}\frac{\partial\langle U_i\rangle}{\partial x_j}\right]$$

$$\tau_{ij}=-\nu_t\left(\frac{\partial\langle U_i\rangle}{\partial x_j}+\frac{\partial\langle U_j\rangle}{\partial x_i}\right)+\frac{2}{3}\langle k\rangle\delta_{ij}+C\frac{k}{\varepsilon}\beta g_i\overline{\theta u_j}$$

+final closure: 3eqn. model

$$\frac{D\langle k\rangle}{Dt}=D_k+P_k+G_k-\langle\varepsilon\rangle$$

$$\frac{D\langle\varepsilon\rangle}{Dt}=D_\varepsilon+P_{\varepsilon 1}+P_{\varepsilon 2}+G_\varepsilon-Y$$

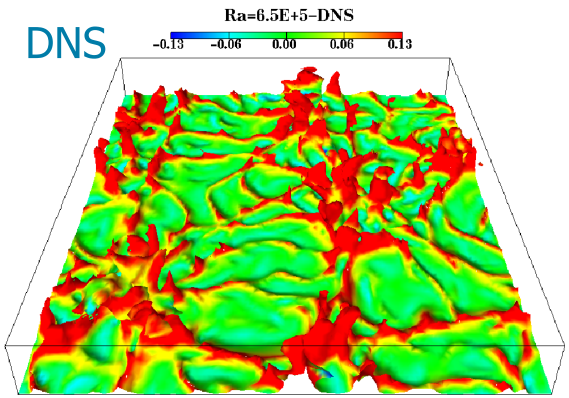
$$\frac{D\langle\theta^2\rangle}{Dt}=D_\theta+P_\theta-\langle\varepsilon_\theta\rangle$$

Meeting the high Ra challenges: Transient RANS

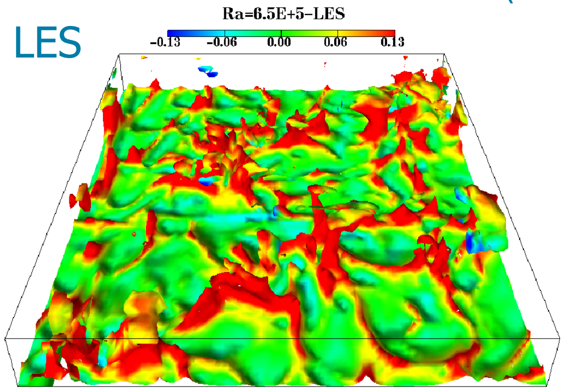
Comparison of DNS, LES and T-RANS for Ra=6x10^5 and T–RANS "extrapolation"

(*Kenjeres & Hanjalic, Phys Rev. E, 2002*)

DNS

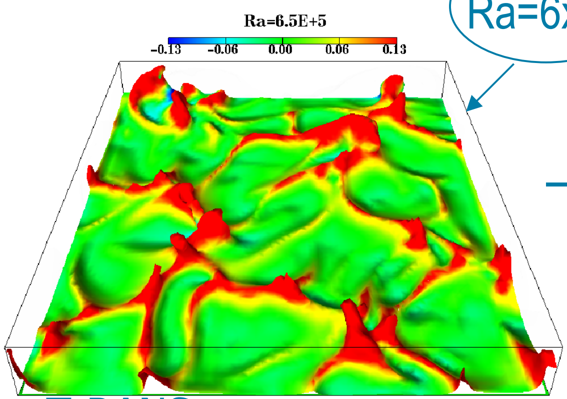


LES



Planform structures and finger-like plumes

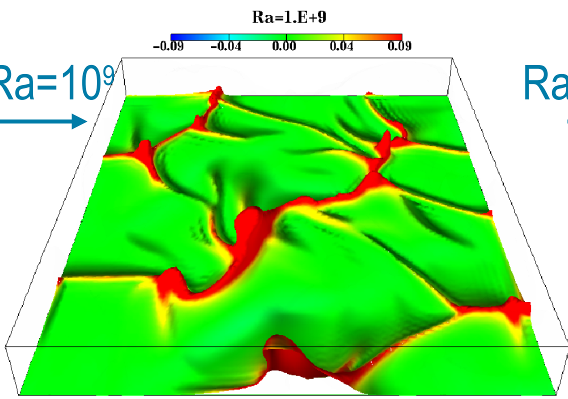
Ra=6x10^5



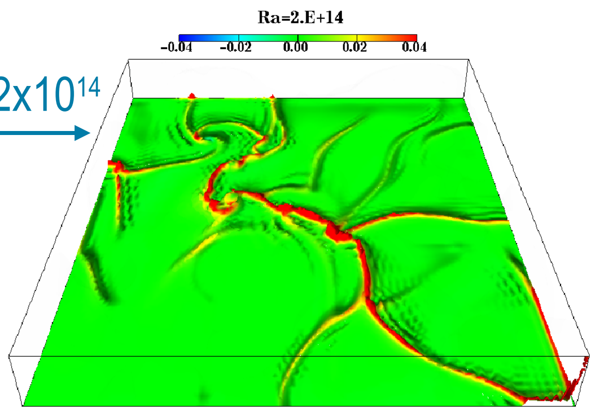
T-RANS

Capturing effects of Ra number

Ra=10^9

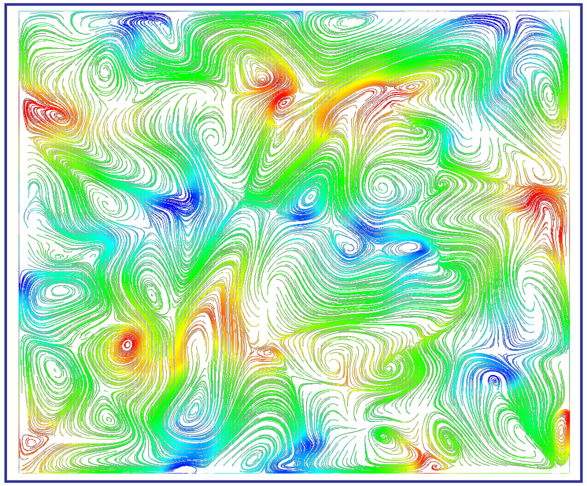


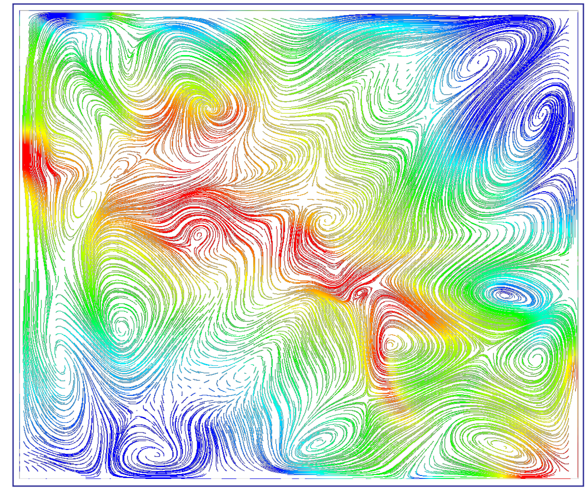
Ra=2x10^{14}



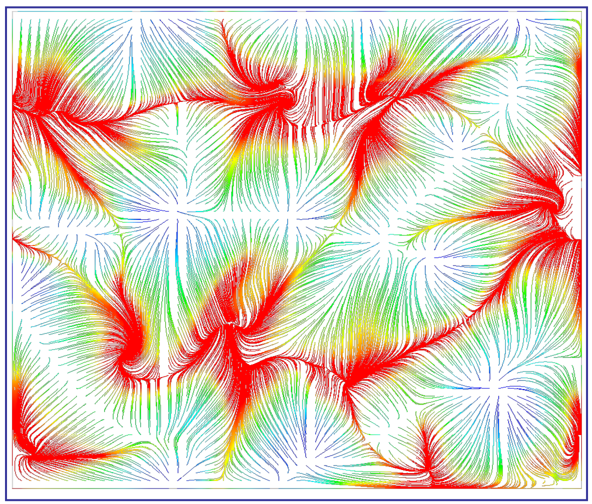
T-RANS of R-B: Temperature colored instantaneous trajectories

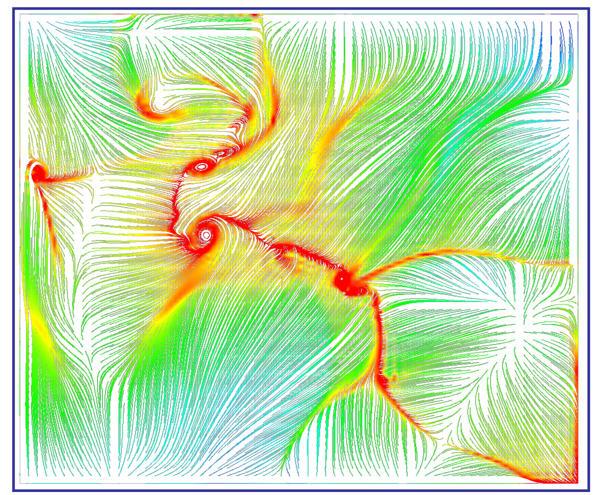
central horizontal plane (z/D=0.5)





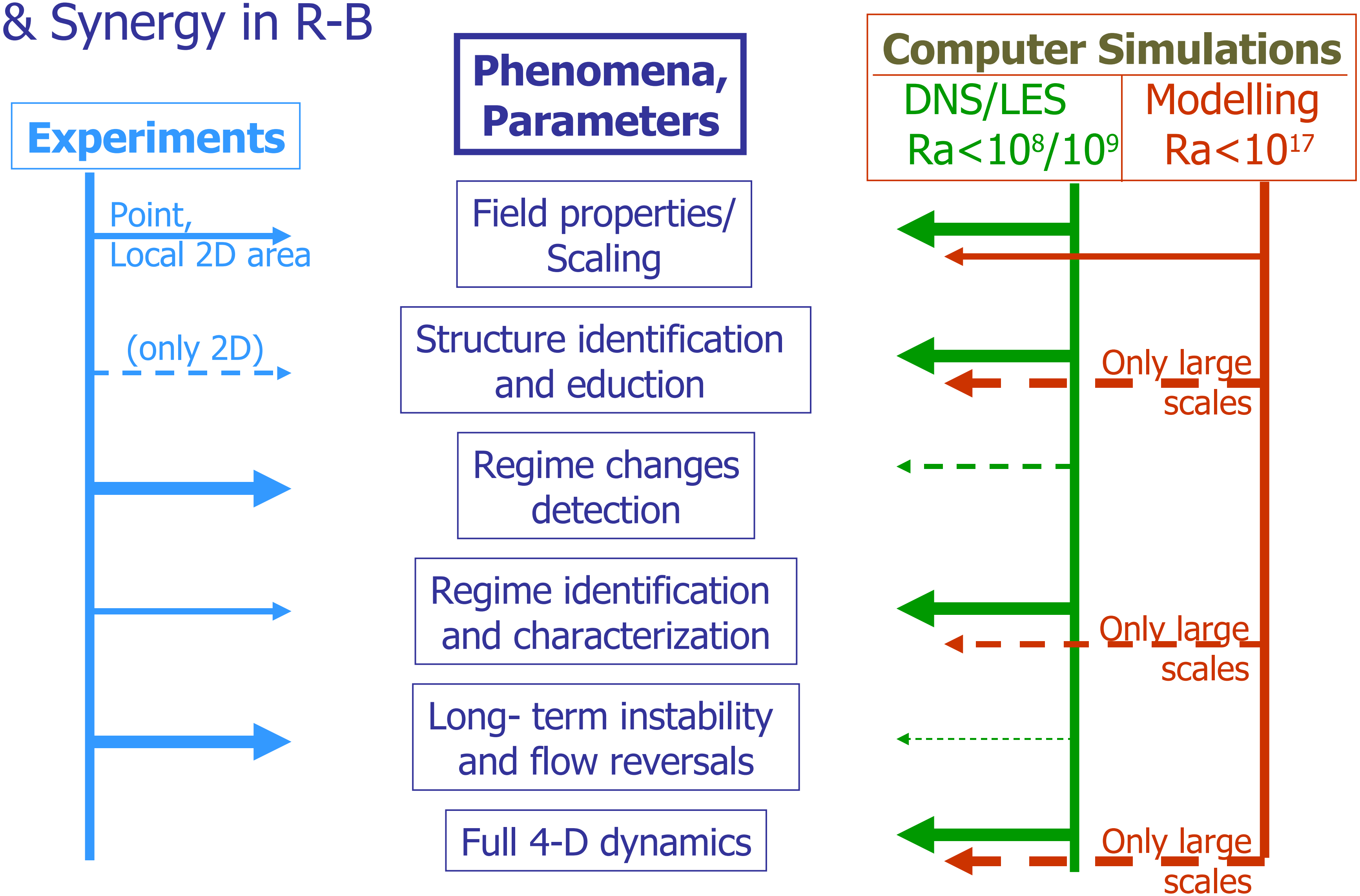
inside thermal boundary layer (z/D=0.05):





Ra=6.5x10^{5} Ra=2x10^{14}

Complementarity & Synergy in R-B

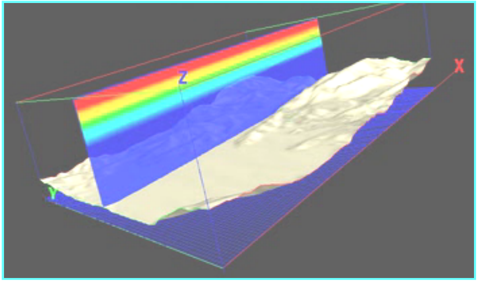


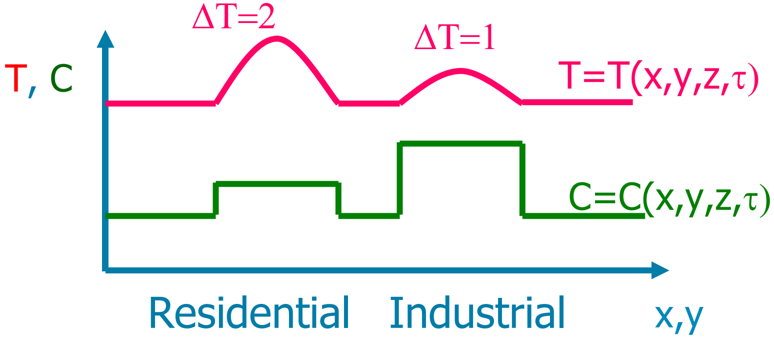
Synergy of experiments and simulations of R-B: A summary

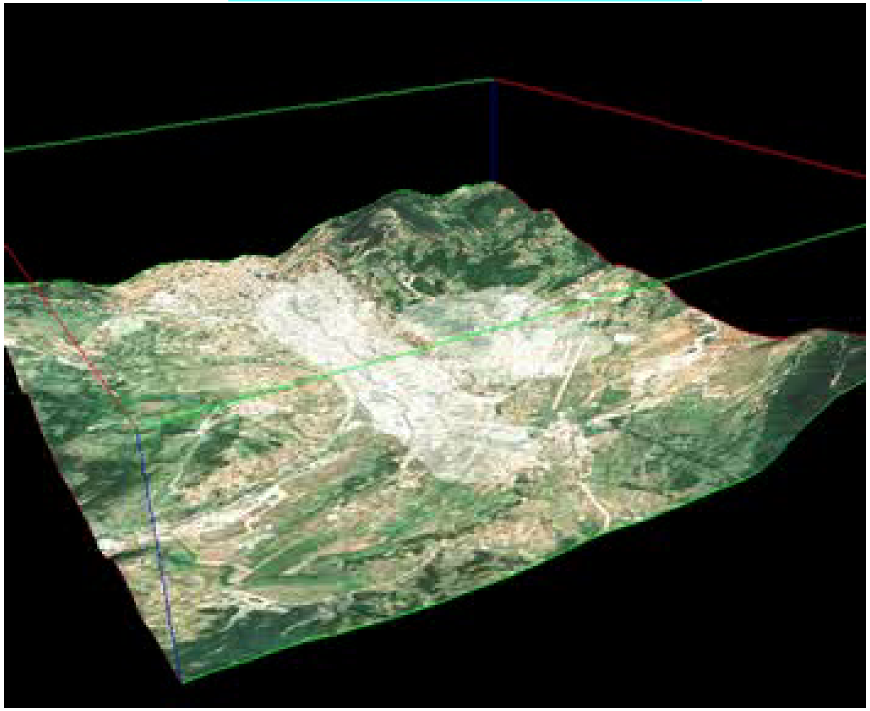
- Experiments proved invaluable in detecting some new physics, e.g.:
  - long-term oscillation and the phenomenon of sudden or gradual reversal of flow direction (τ=200-2000 sec);
  - detecting a change of regimes, etc., but
  - limited to point- or (local) plane measurements, and usually only a single field (velocity or temperature or..)!
- Computer simulations are uncontested in providing 3-D time dynamics (4D field) and subtle flow and structural details, but
  - DNS and LES very demanding on computational resources (only low Ra's and short real times!)
  - VLES/T-RANS (hybrid RANS/LES): the only viable tools for very high Ra's, but burdened with modelling approximations!
- "Together, we win!"

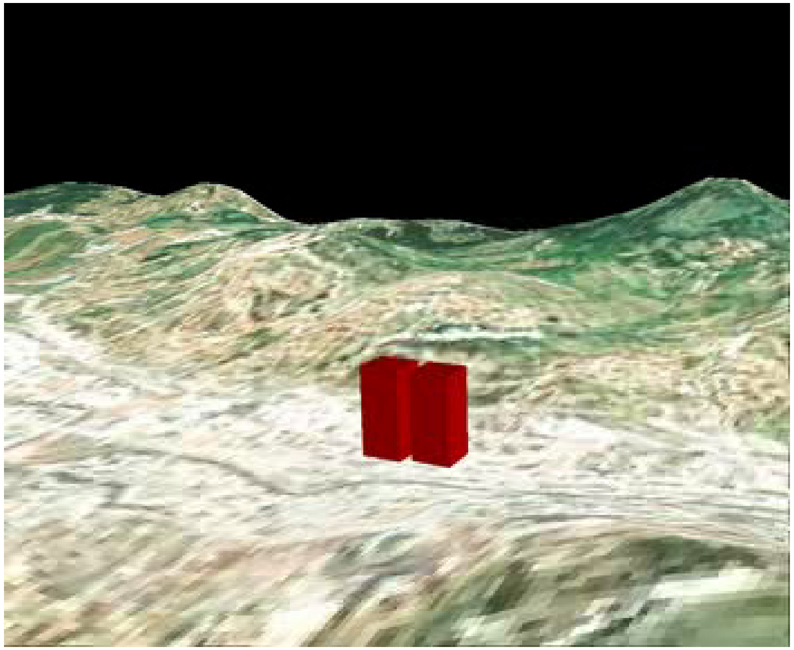
T-RANS of pollutant dispersion in a town valley

Diurnal cycles for a windless period capped by an inversion layer, with imposed ground temperature and emission scenarios





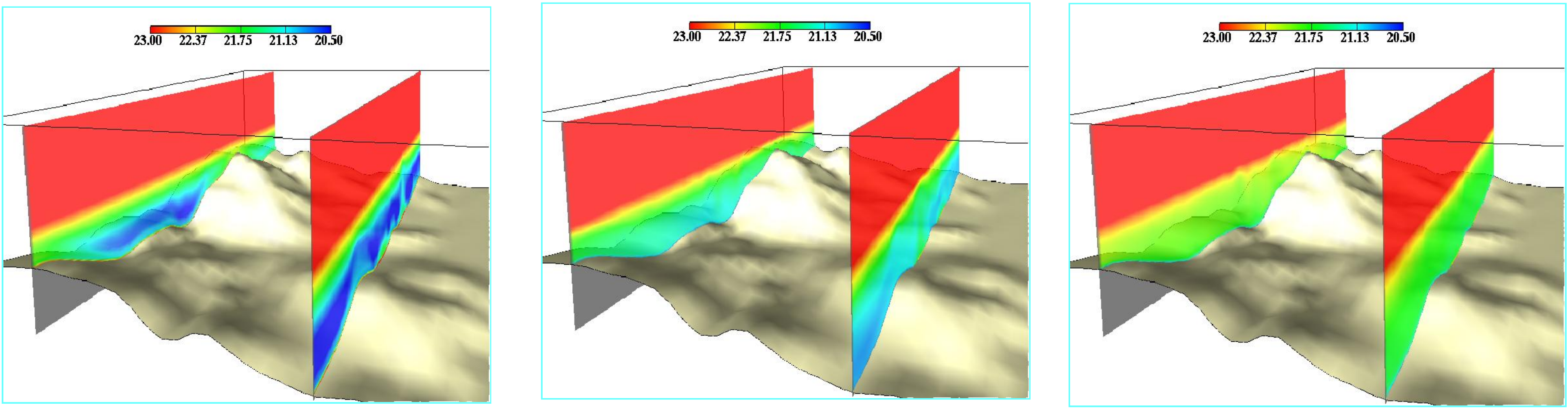




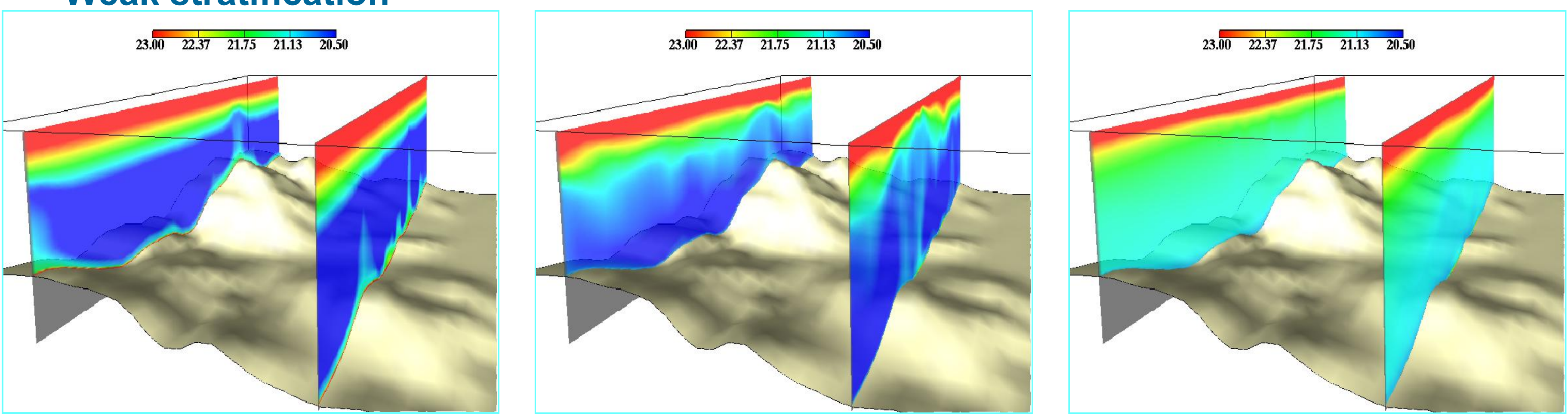
Time evolution of the potential temperature

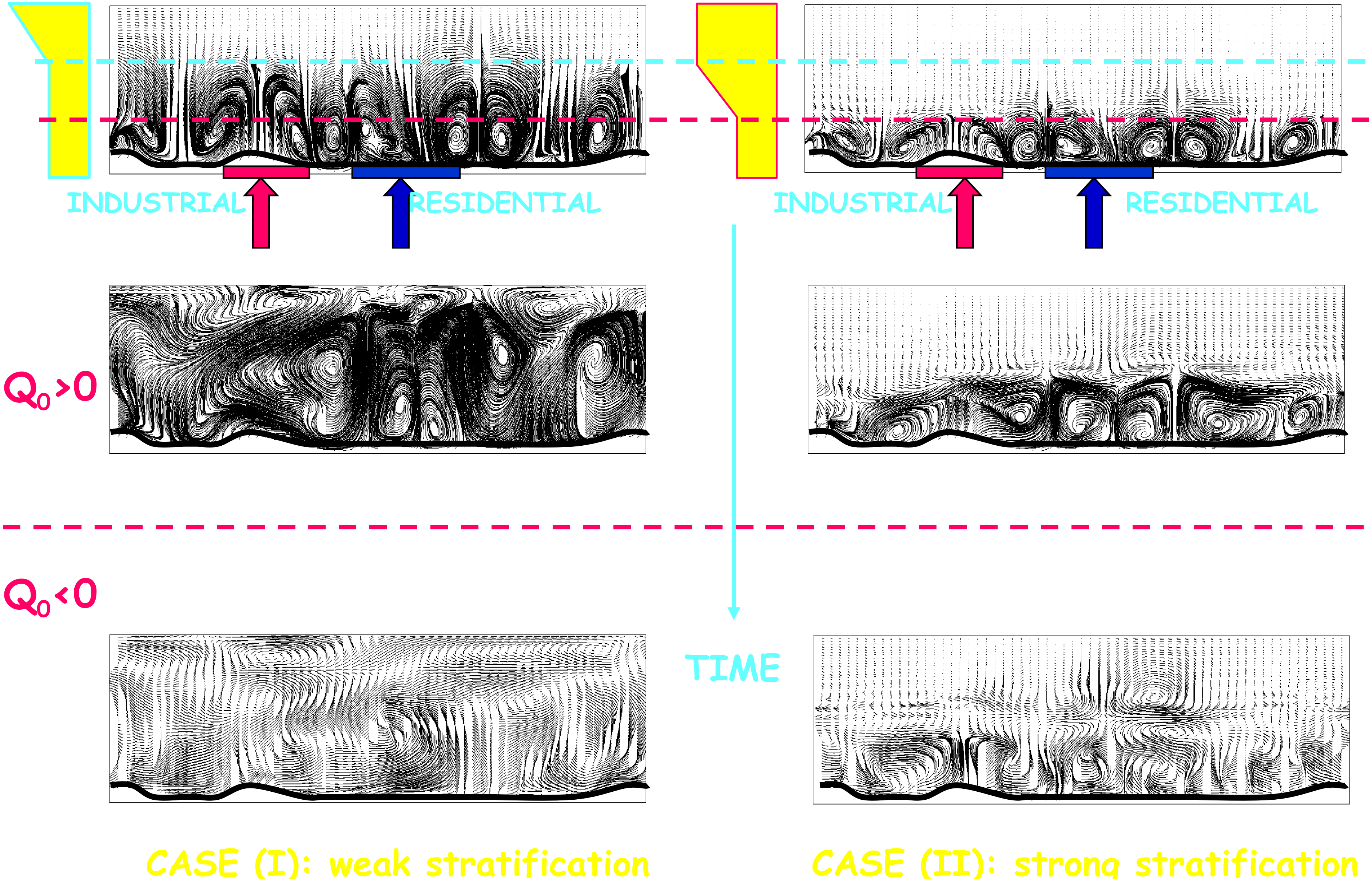
Time

Strong stratification

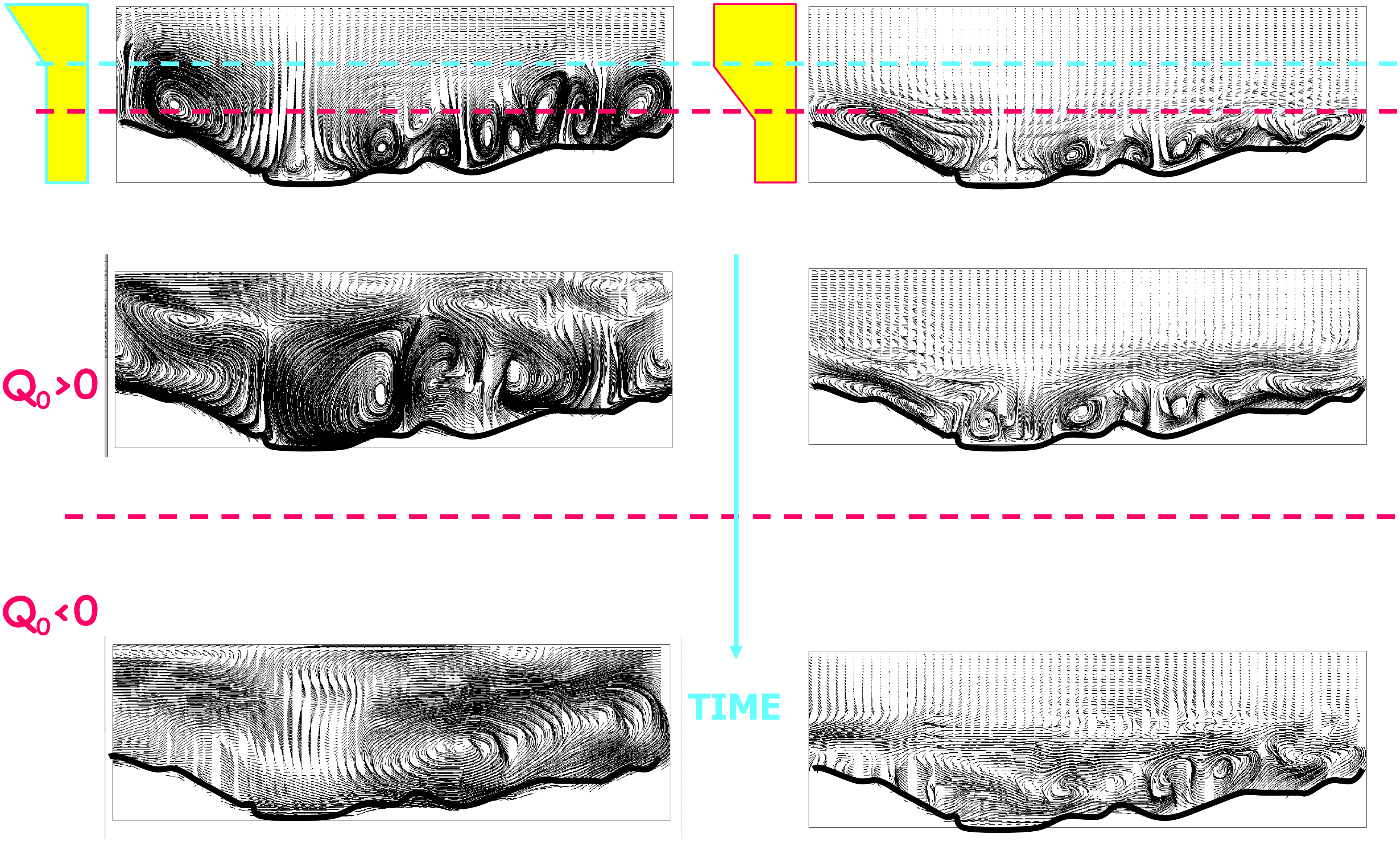


Weak stratification





Instantaneous trajectories in vertical plane over residential and industrial zones



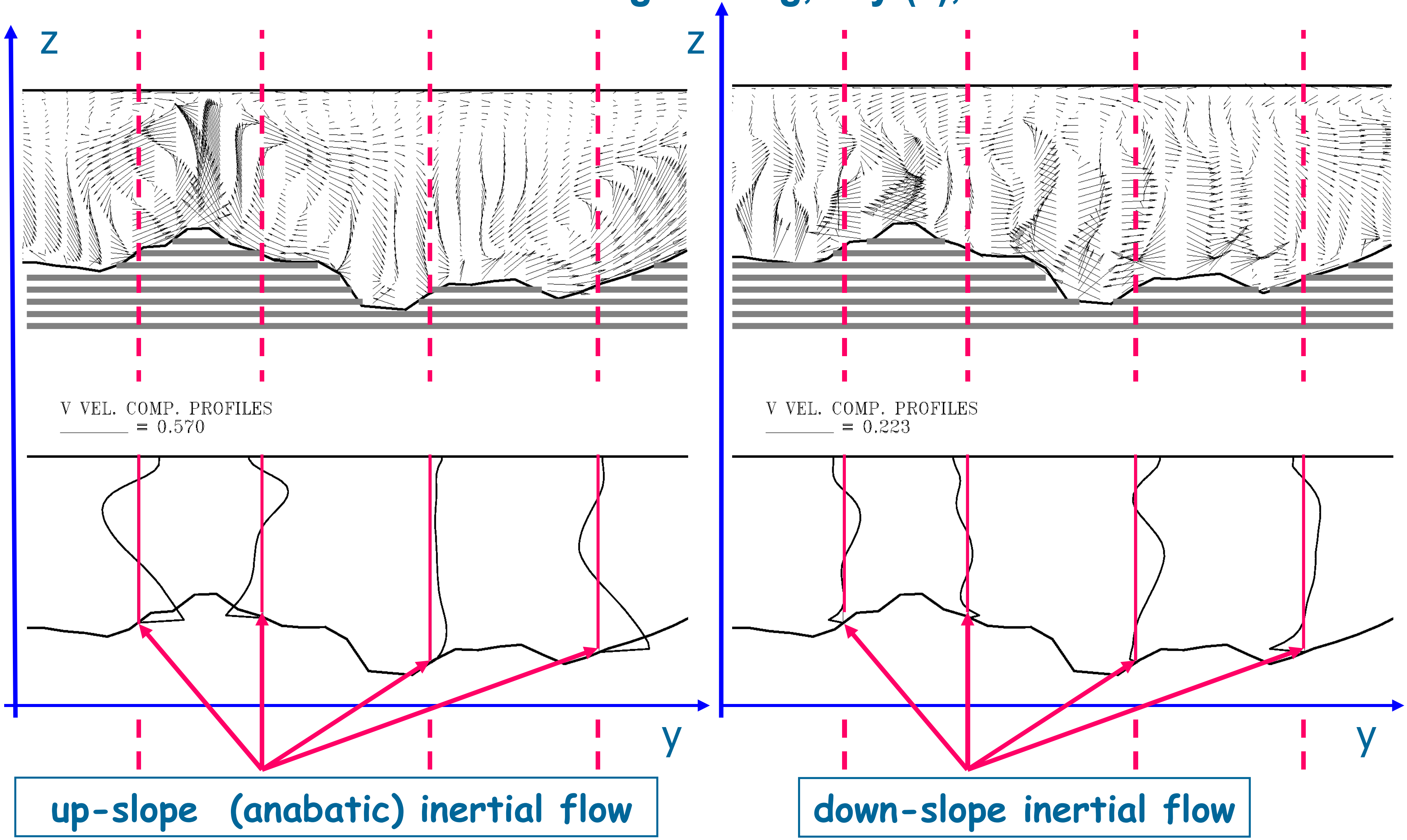
INITIAL STRATIFICATION

CASE (I): weak

CASE (II): strong

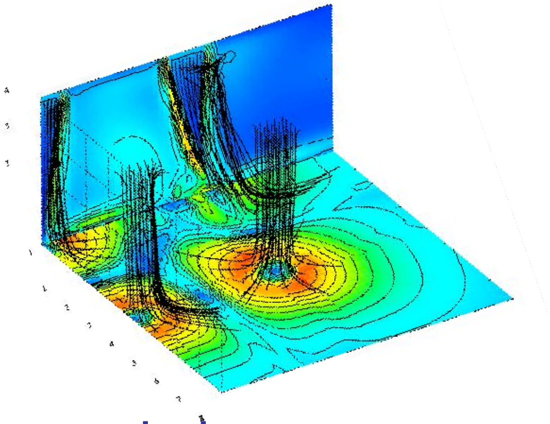
Instantaneous trajectories in vertical plane over hilly terrain

Velocity vectors and horizontal velocity component profiles 2hrs after onset of heating/cooling, day (II), weak stratification



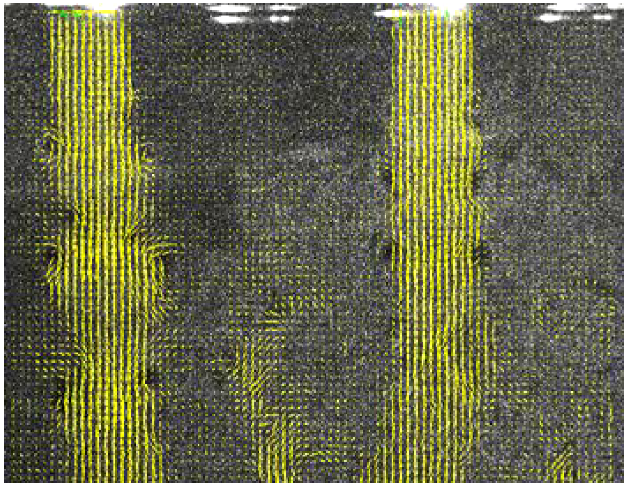
1. Impinging flows and heat transfer at *higher* Re numbers

Impinging flows and heat transfer



- Impinging jets: one of the most frequent configuration for efficient heating and cooling of solid surfaces
- Optimum performances depend on a number of parameters and no unique criteria exist
- In addition to technological interest, Impinging jets contain a number of interesting physical events and phenomena
- Challenges: identification of flow and turbulence structure, their interaction with heated surface (thermal imprints), heat transfer mechanism and its control
- Most studies confined to a single jet at relatively low Re numbers, but extra effects in multiple jets (jet-jet interaction, wall-jets collision, ejection fountains, embedded vortices, jets in cross-flows,…

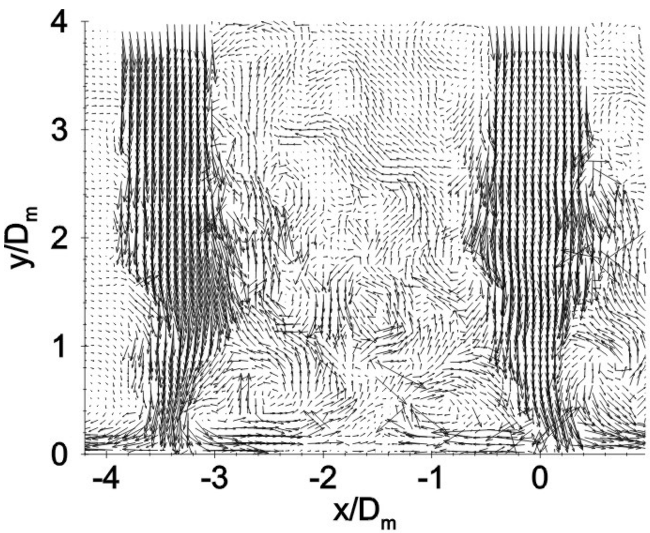
Impinging jets: potential and limitations of experiments

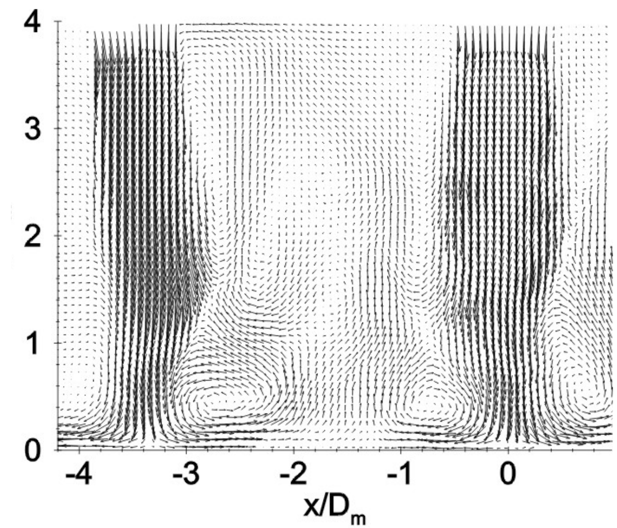


PIV of multiple round jets impinging on a flat surface

(Geers, Tummers, Hanjalic, Exp. Fluids, 2004)

Original (left) and POD filtered (left) snapshots.



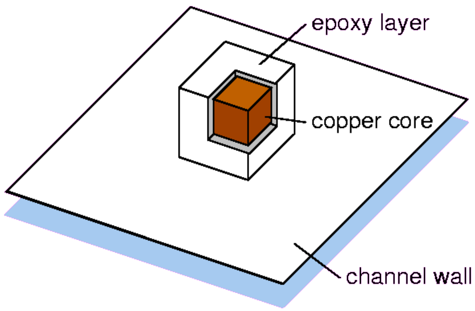


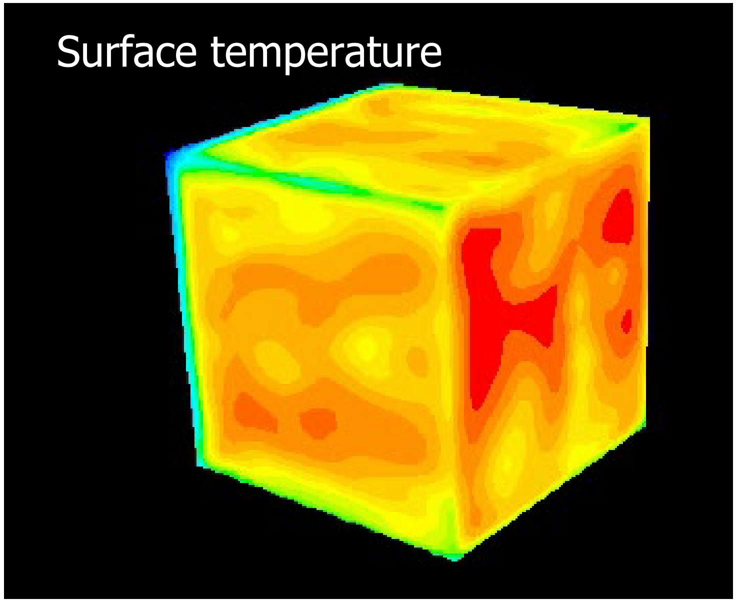
Computer simulations of Impinging Flows

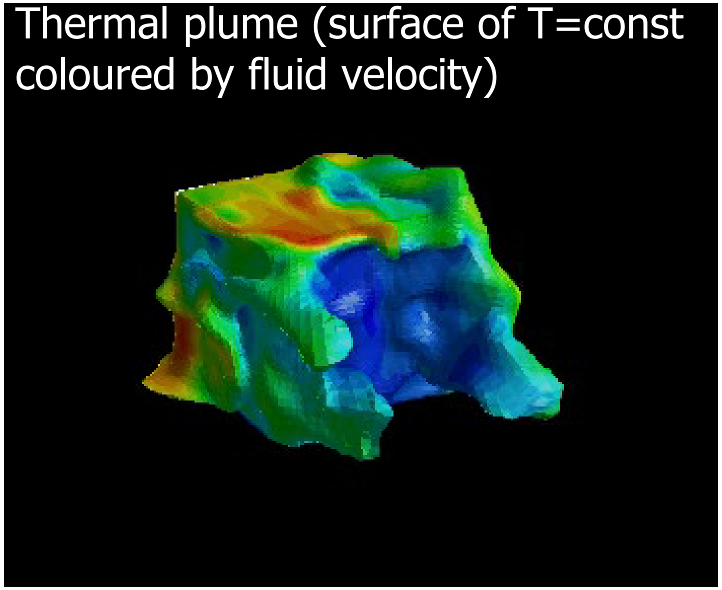
LES Niche: low Re's, separated flows (electronics cooling, gas turbine blades,..)

Heat transfer on a multi-layered wall-mounted cube in a matrix (Re~10^4)

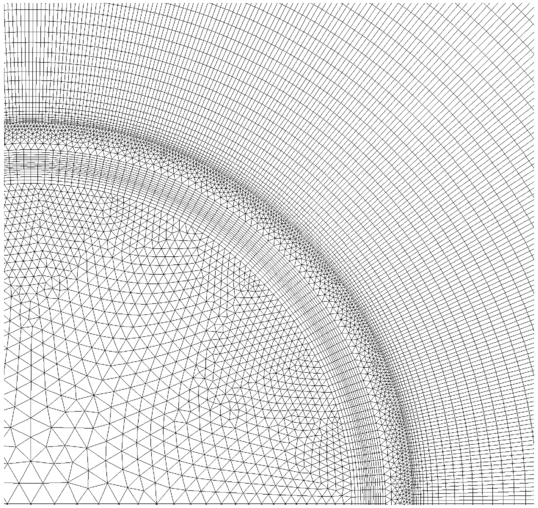
(*Ničeno and Hanjalić, 2001, 2002*)







Computer simulations of Impinging Flows

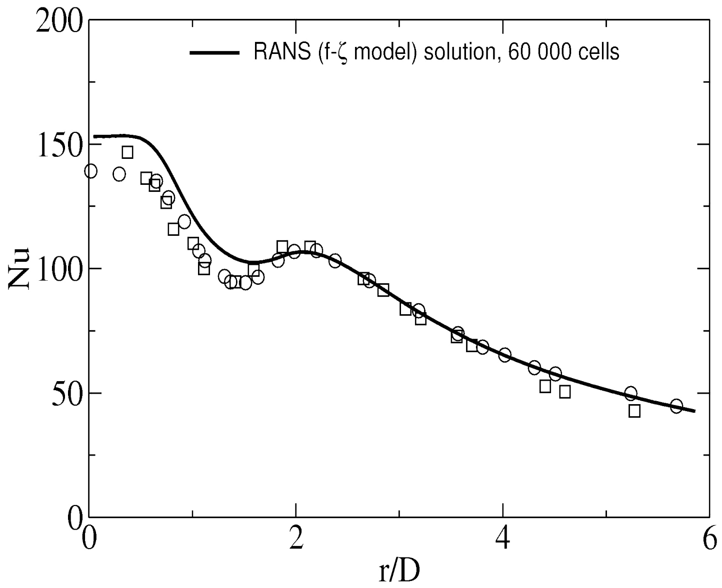


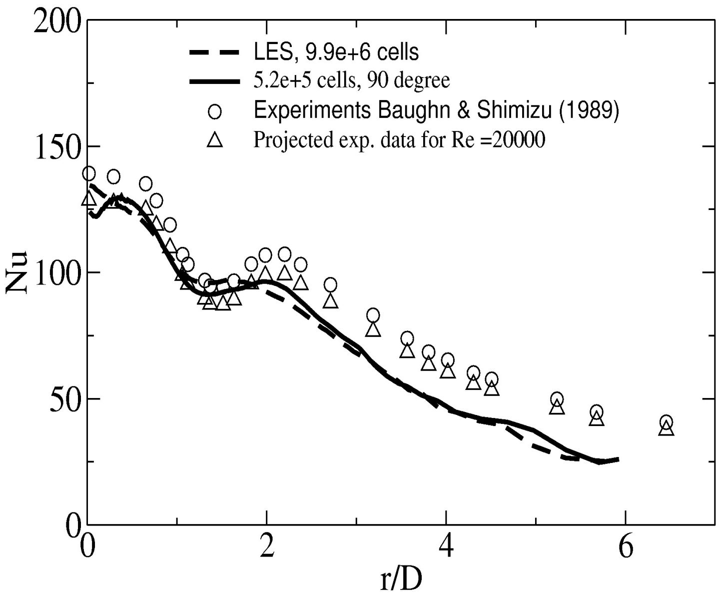
Real challenge: attached impinging flows

A single round impinging jet

Re=20.000, H/D=2 , unstructured grid

(*Hadziabdic and Hanjalić, 2004/05*)

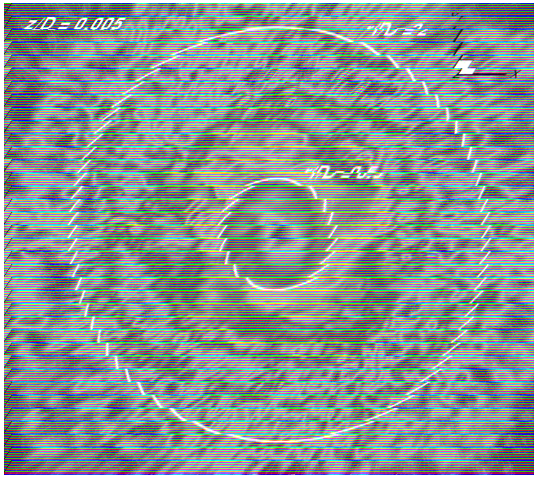




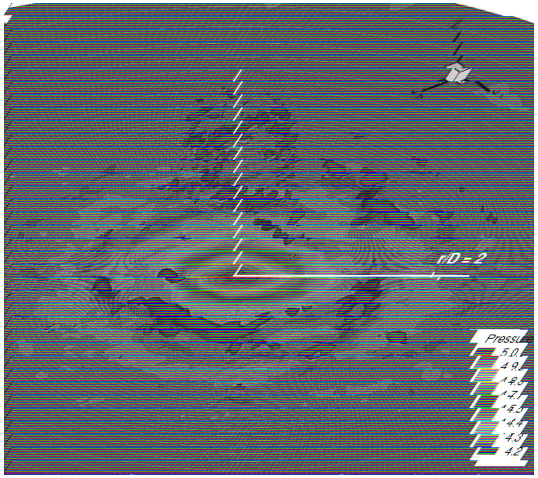
Computer simulations of Impinging Jets

Re=20.000, H/D=2 (*Hadziabdic and Hanjalić, 2004/5*)

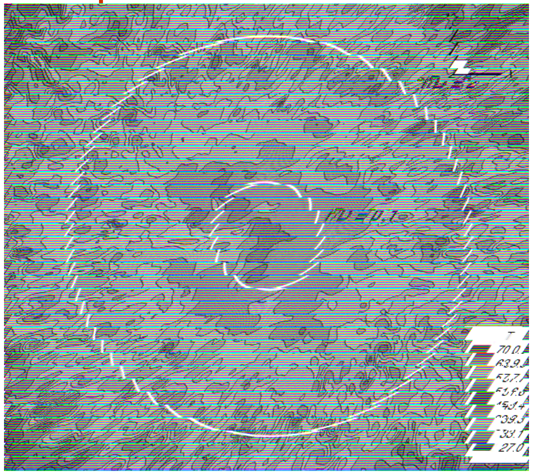
Pressure field: top view



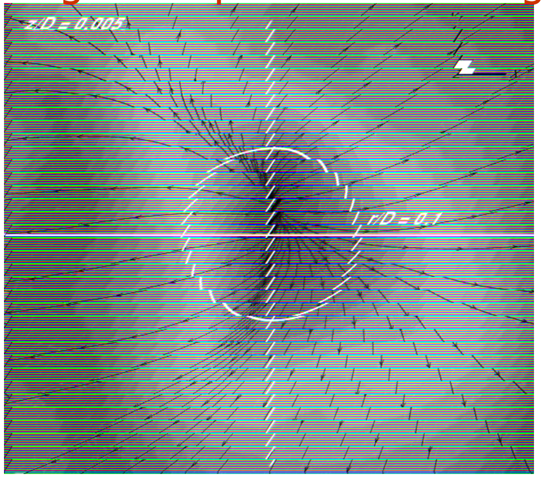
Pressure field: side view



Temperature field

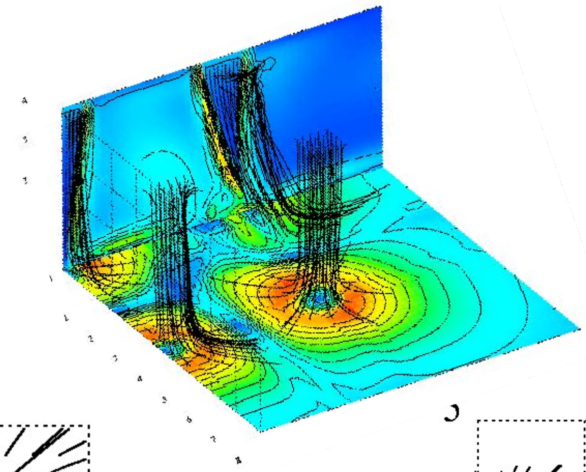


Stagnation point meandering

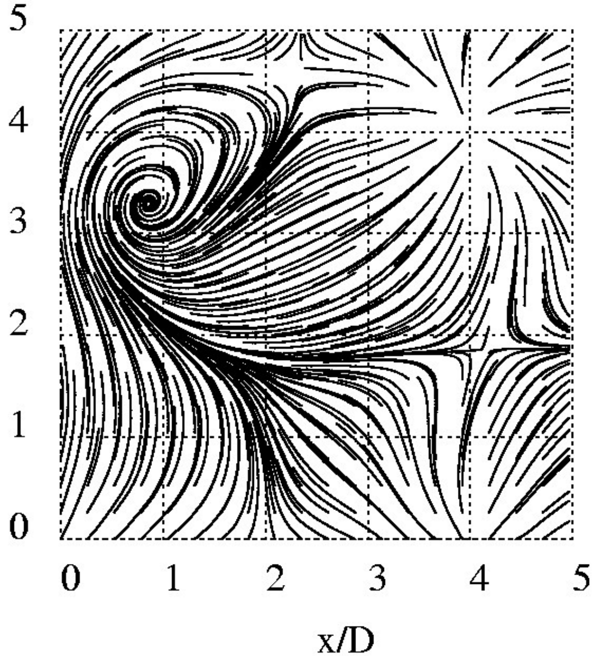


Some RANS-detected anomalies in multiple-impinging jest

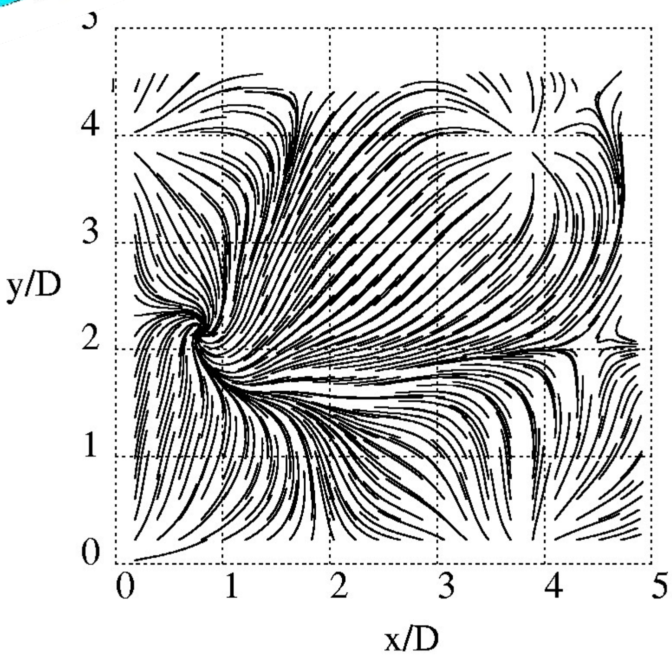
Inherent asymmetry, bifurcation, embedded vortices



RANS computations

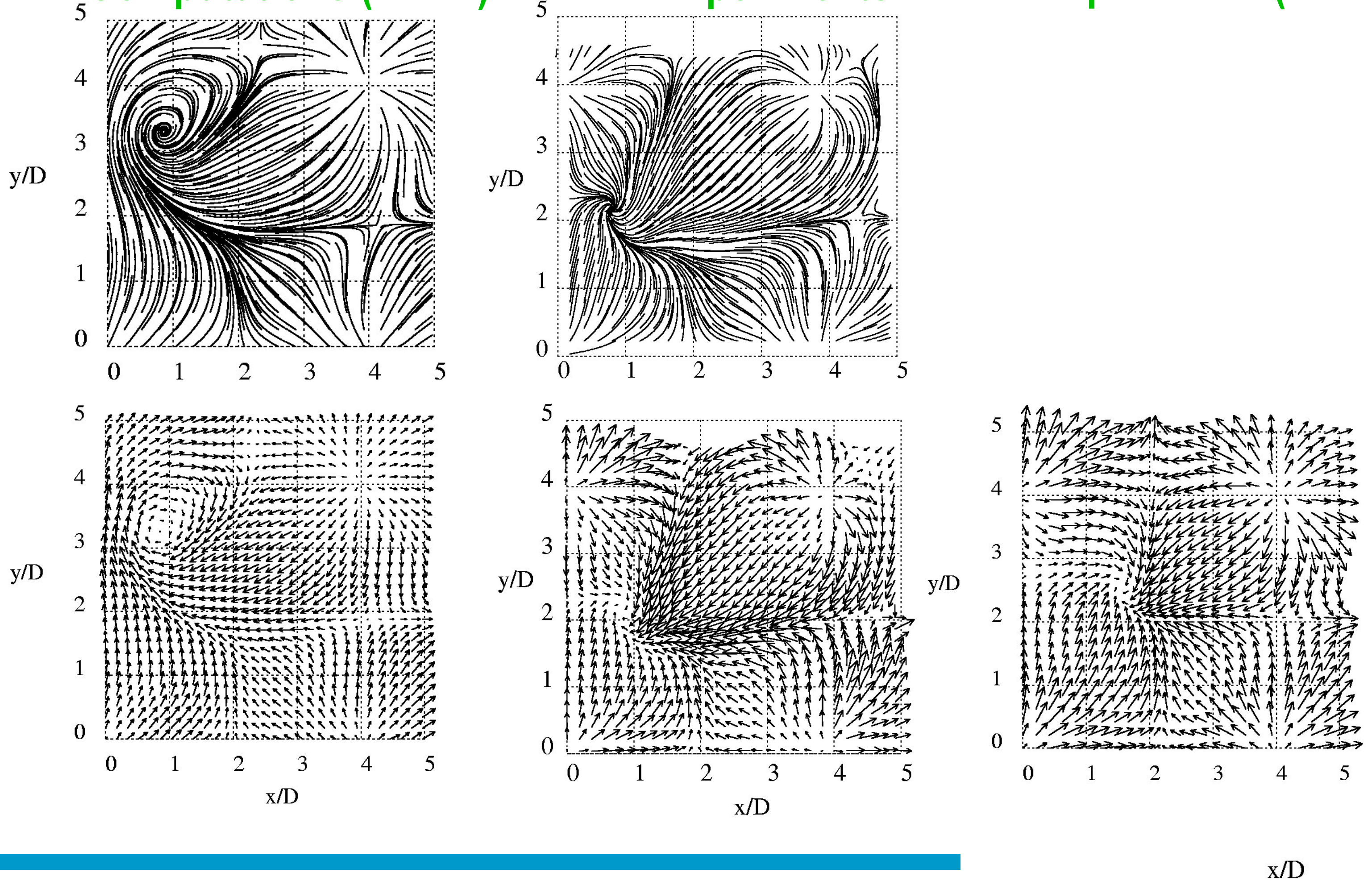


PIV measurements



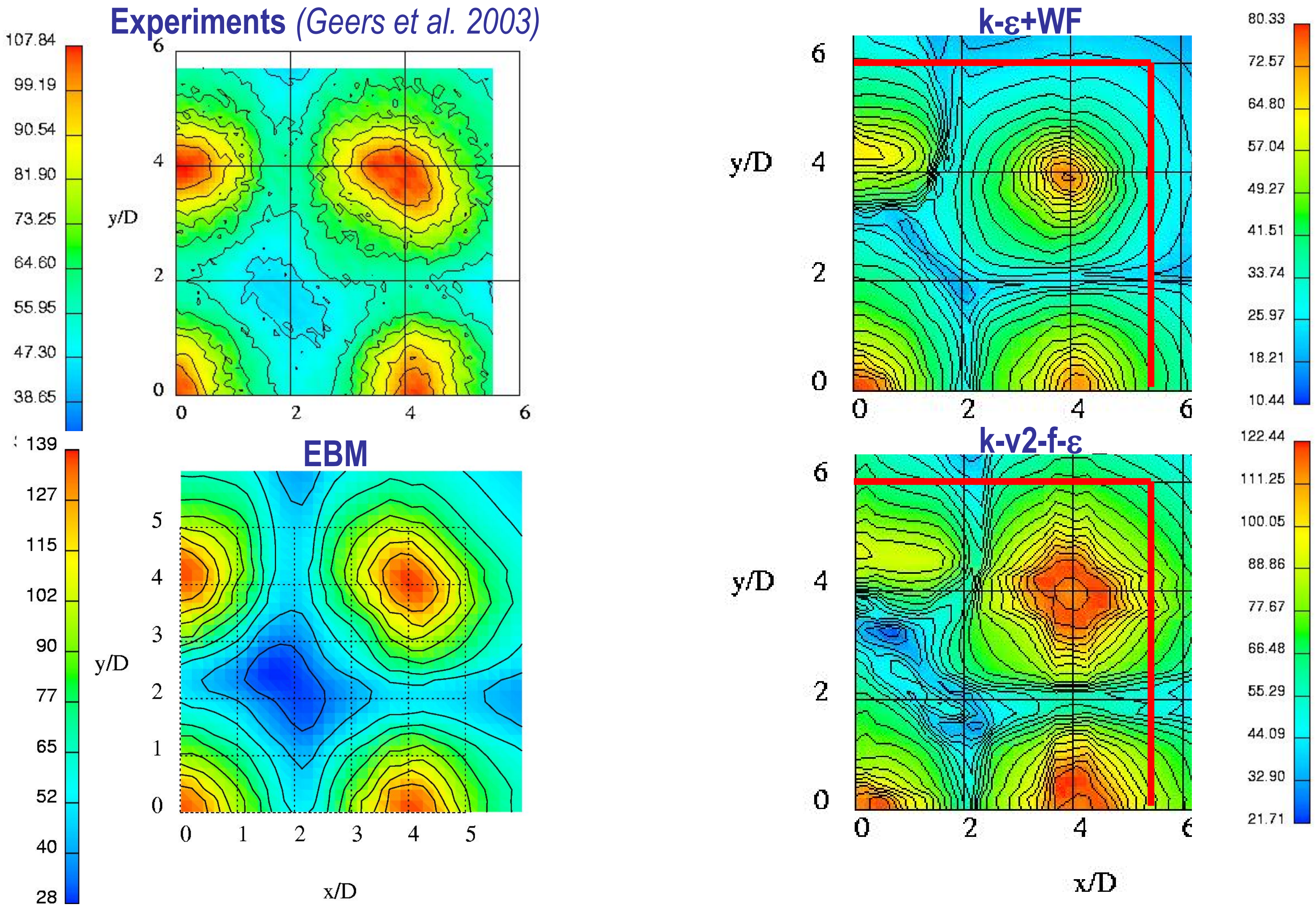
Averaged streamlines and velocity vectors for the square jet arrangement at y/D=0.54 above the plate *(Geers, Tummers , Hanjalic, Exp. Fluids, 2004; Thielen, Jonker & Hanjalic, IJHFF, 2003)*

Computations (k-v2-f) **PIV Experiments** **Computations (EBM)**

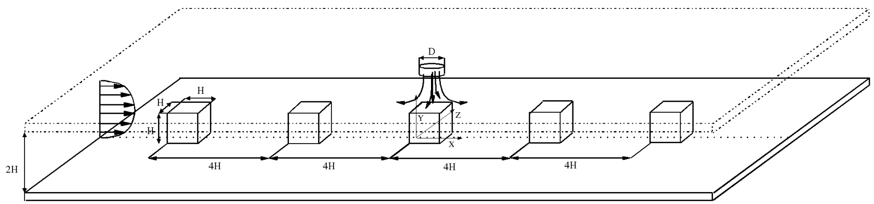


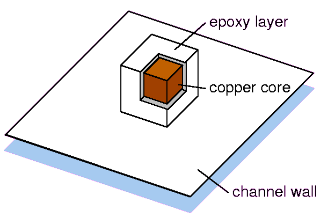
Computed Nusselt number for square jet arrangement

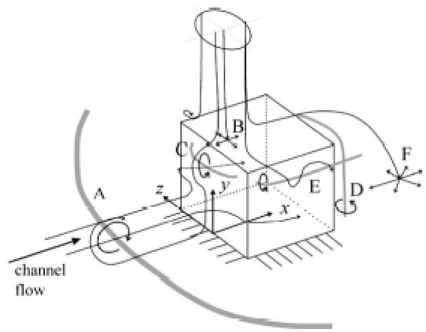
(Thielen, Hanjalic, Jonker, Manceau, IJHMT'03)

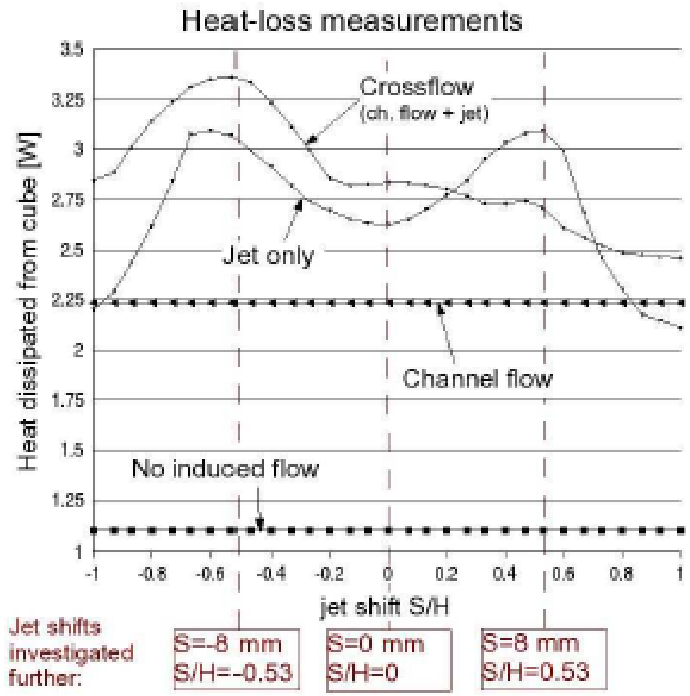


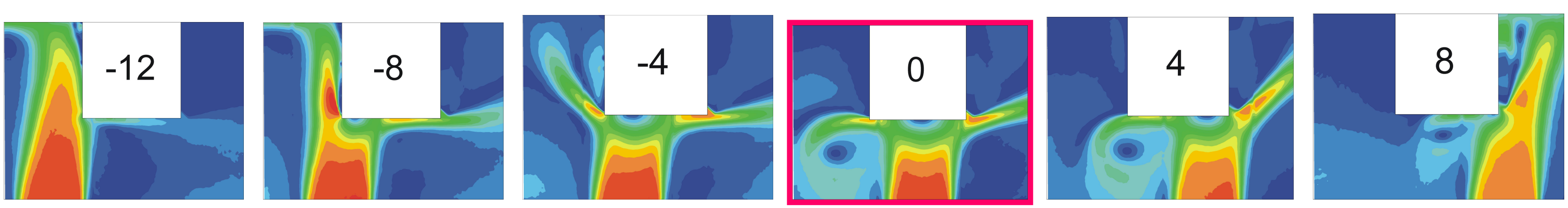
Impinged cube in a cross-flow
(Flikweert et al., 2005)





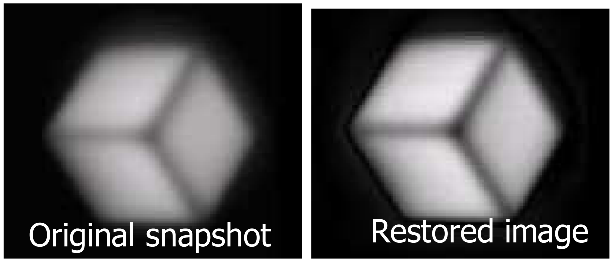


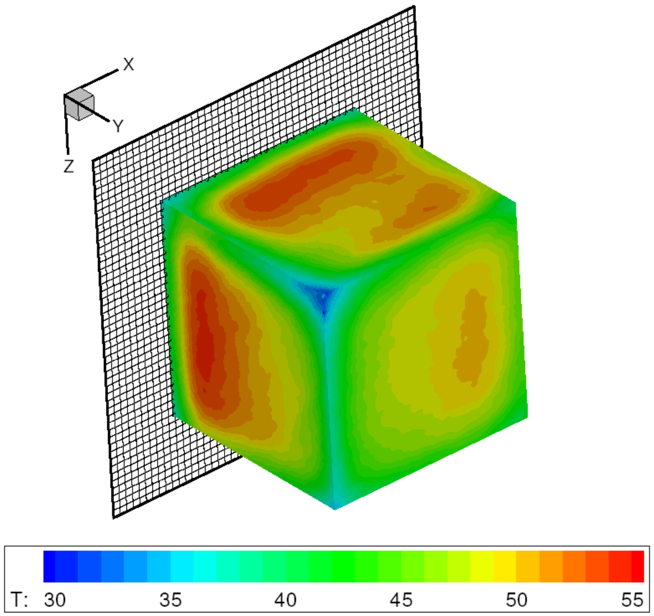




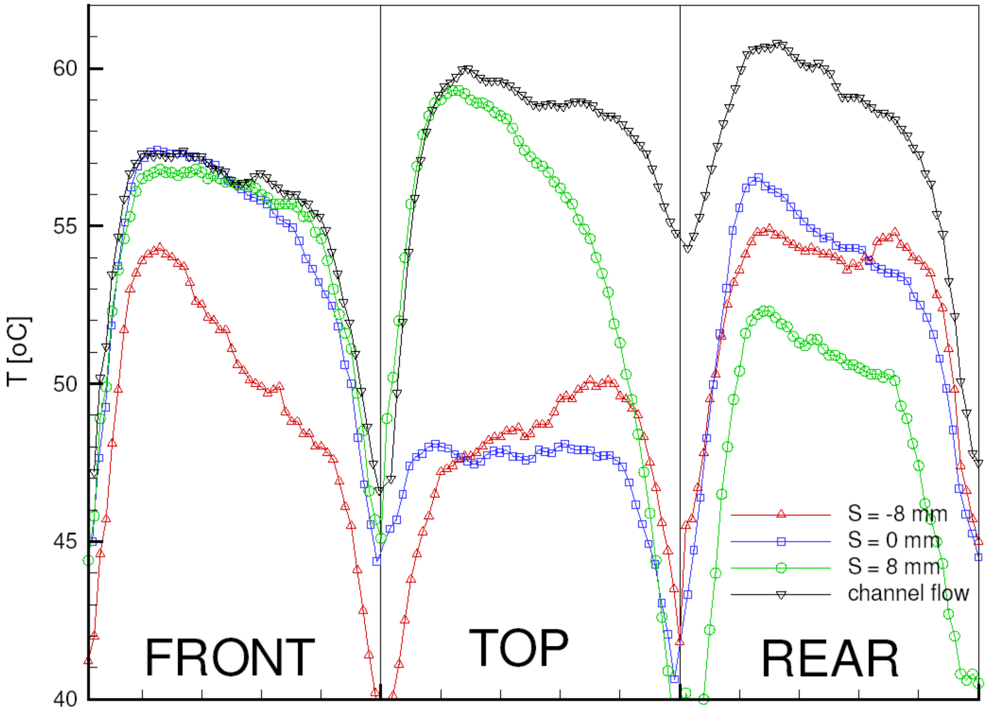
Impinged cube in a cross-flow: Surface temperature

Infrared Thermography (Flikweert et al., 2005)

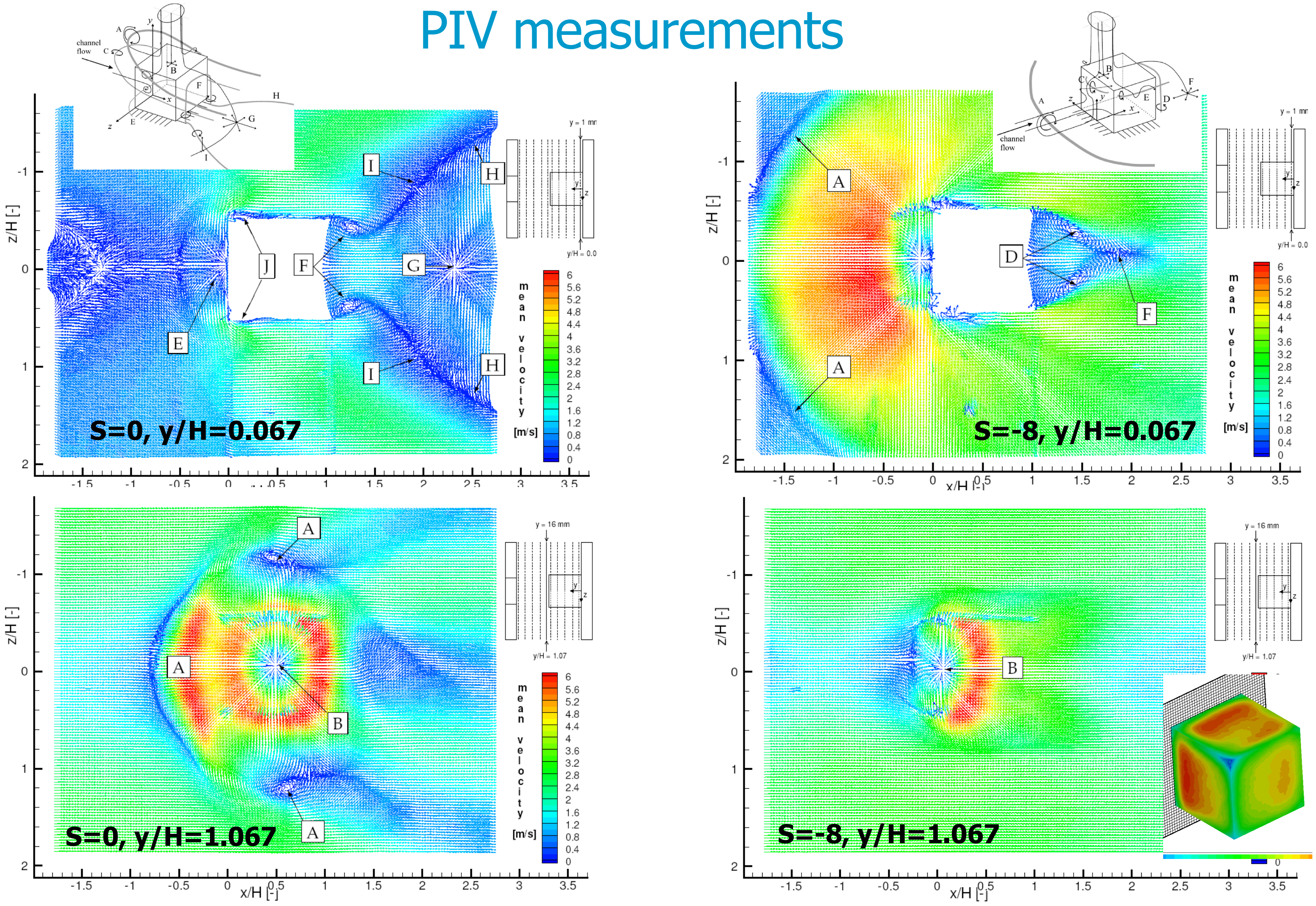




Challenges:
- optical accessibility
- image deformation and degradation
- low time resolution (only time average)

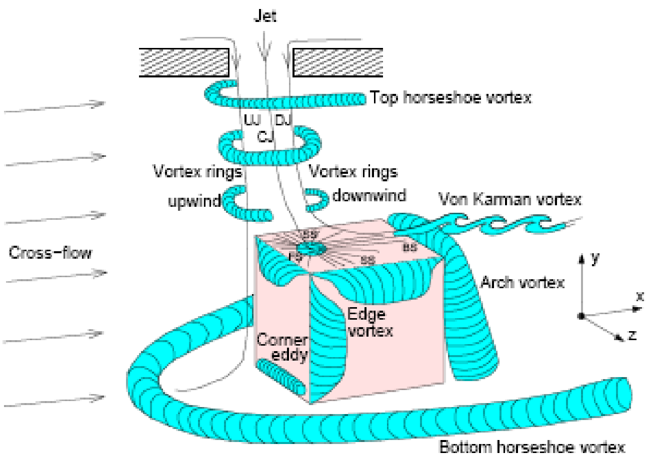


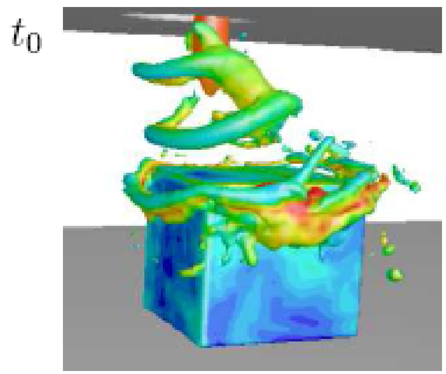
Impinged cube in a cross-flow
PIV measurements

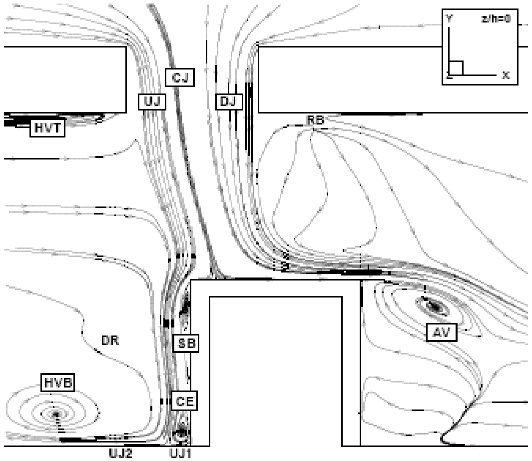


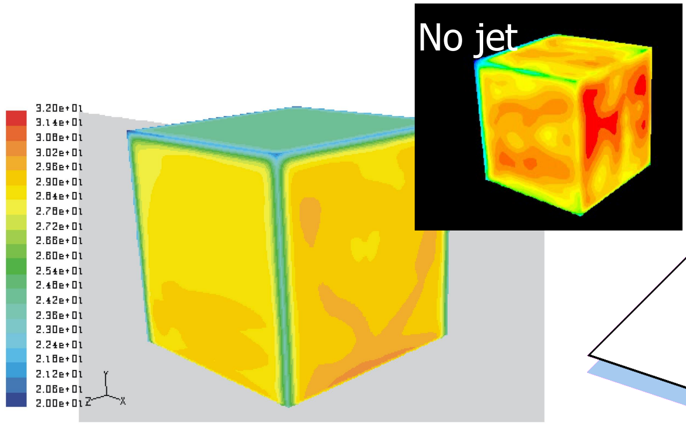
Impingement cooling of a wall-mounted cube in a cross-flow

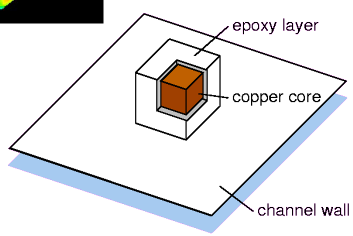
(Conjugate LES+heat conduction in surface coating, 4.6×10^6 grid cells

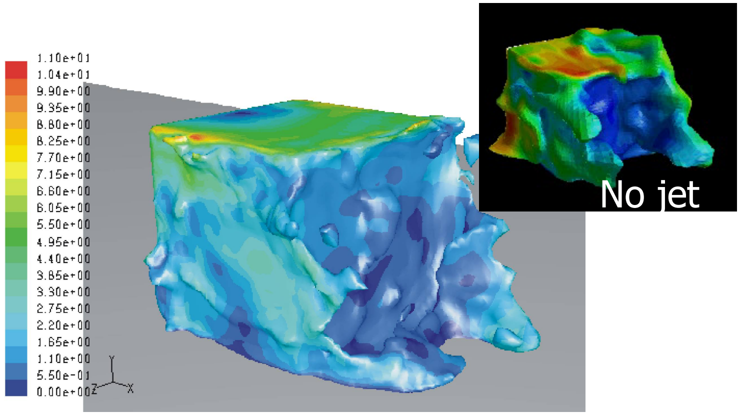










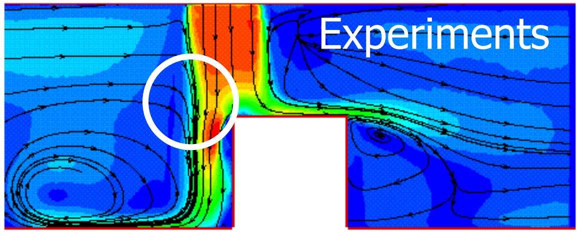


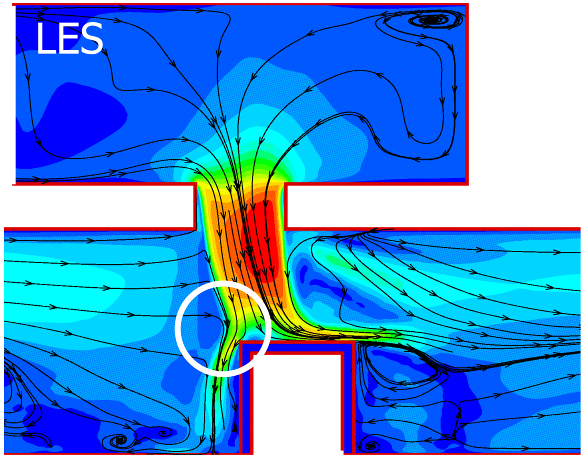
Popovac and Hanjalic 2006

Niceno and Hanjalic, 2001,2002

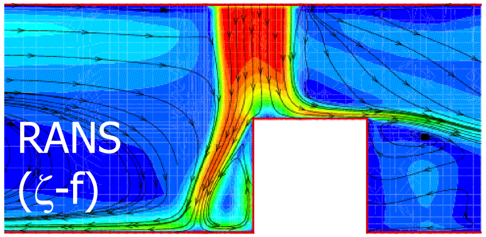
Impinged cube in a cross-flow
Challenges for modelling and simulations

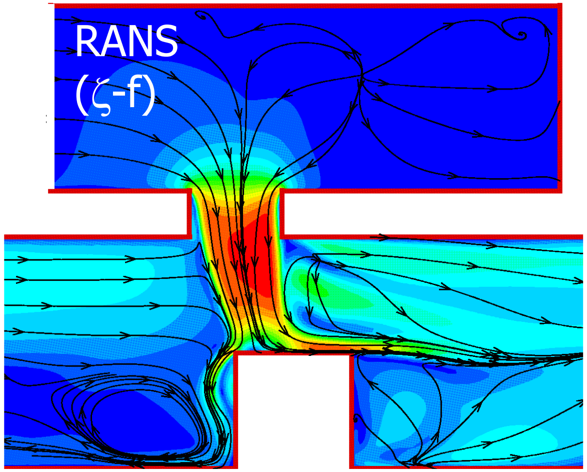
- Proper imitation of experimental inflow and boundary conditions
- Grid resolution and distribution





- Solution domain
- Appropriate RANS and sgs model

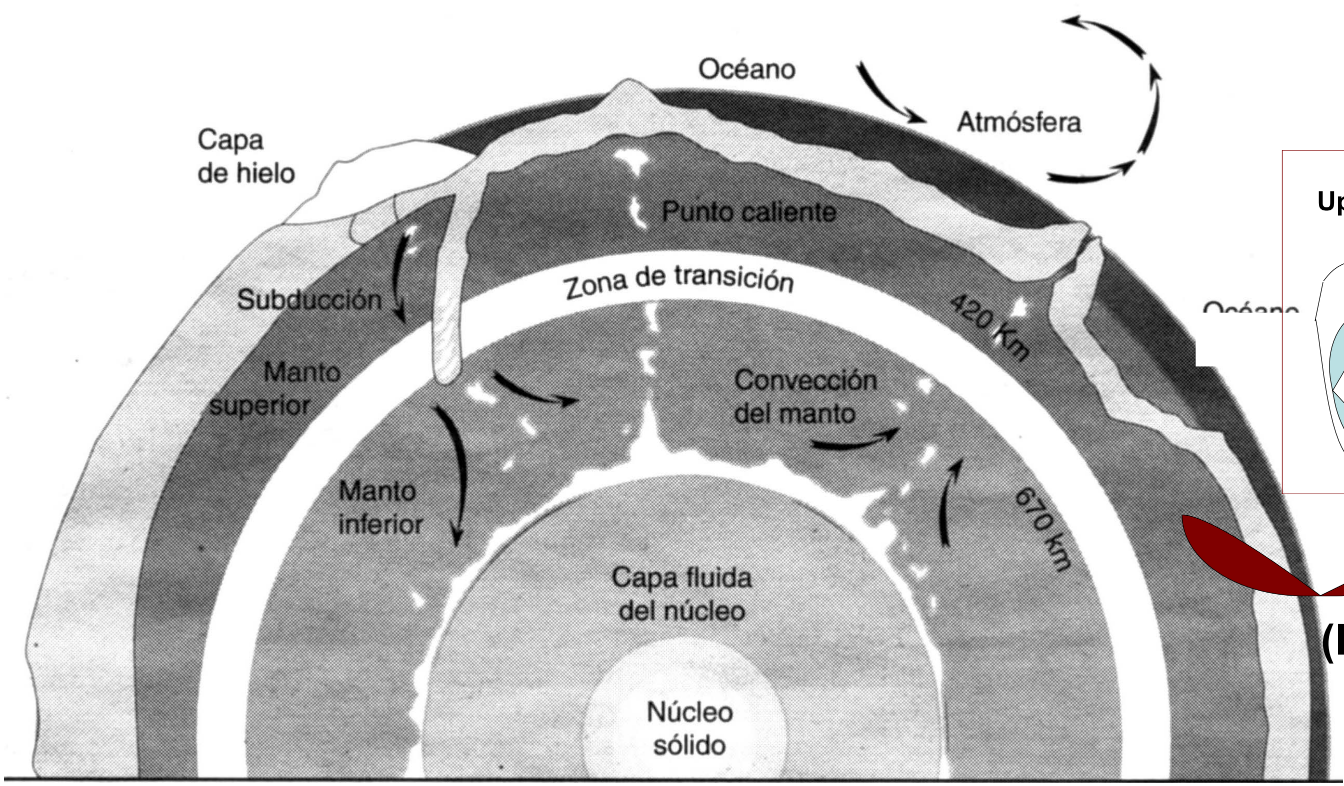




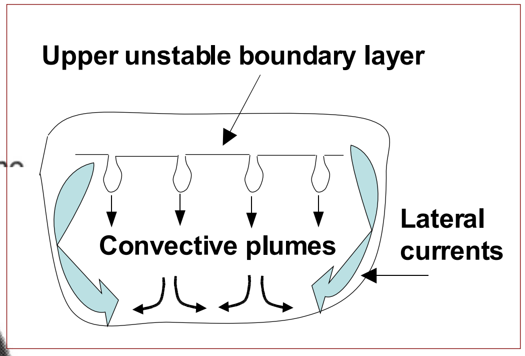
1. Fluid magnetic dynamo

Fluid-Magnetic Dynamo (FMD)

Sketch of the Convective Motions in the Earth: Magma Chambers and Magma Eruption



Magma chamber



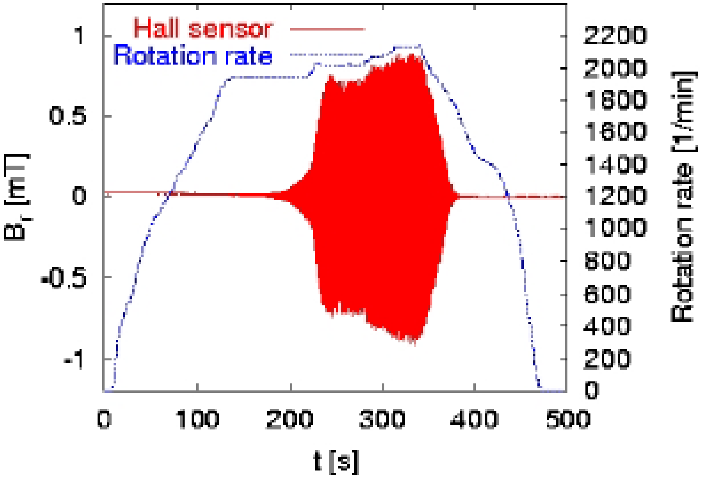
(Brandeis & Jaupart, 1986)

Fluid-Magnetic Dynamo (FMD)

- FMD is believed to be the origin of all magnetic fields in Earth and most celestial bodies

- The basic mechanism of the field self-excitation and sustenance:
  - Thermal convection + Earth rotation drive liquid metallic core from its interior out to the mantle
  - This motion through the already existing magnetic field induces electric current, which amplifies the original field, preventing its decay with time.

- This "model", established in twenties, was not proved until first successful experiment in 1999 in Riga (Latvia) and afterwards in Karlsruhe (Germany)



Fluid-Magnetic Dynamo (FMD)

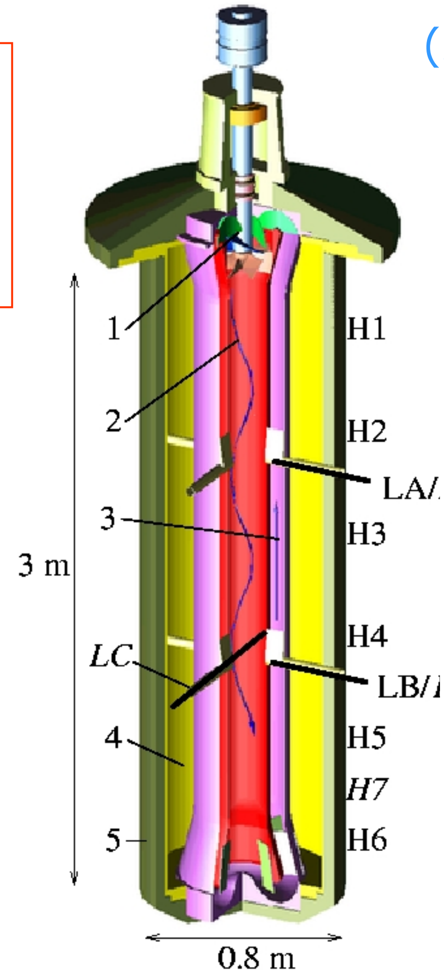
Riga Experiments (sodium)
(*Gailitis et al. 1999*)

Major challenge for experiments:
Achieving critical $Re_m = UL/\eta = 10\text{-}10^3$,
where $\eta = 1/\mu\sigma$ (μ=magnetic permeability,
σ=electric conductivity)

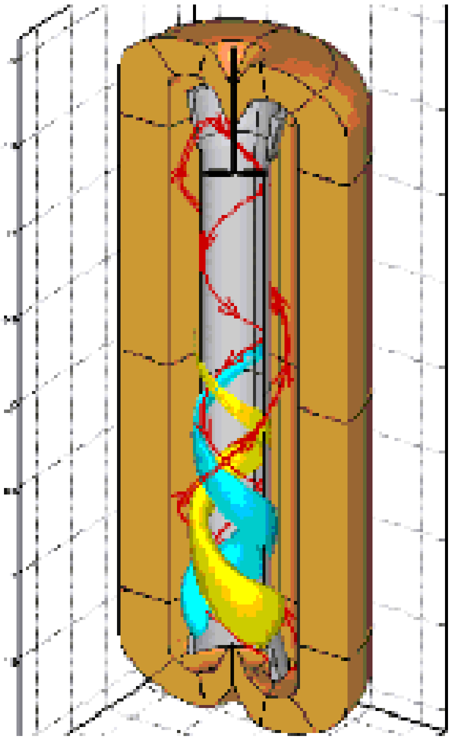
Note:
$\eta \geq 0.1\ m^2/s$ hence $UL \sim 1\text{-}10$
(difficult for liquid metals)

In Riga experiment:
$Re_m \sim 20$, $Re \sim 10^6$

Computer simulations: DNS of magnetic field + URANS of velocity field (mutually coupled)!



Computer Simulations of Riga FMD
(*Kenjeres & Hanjalic, 2005*)



T-RANS-"DNS" of the Riga Fluid-Magnetic Dynamo (FMD)

T-RANS model for hydrodynamic field

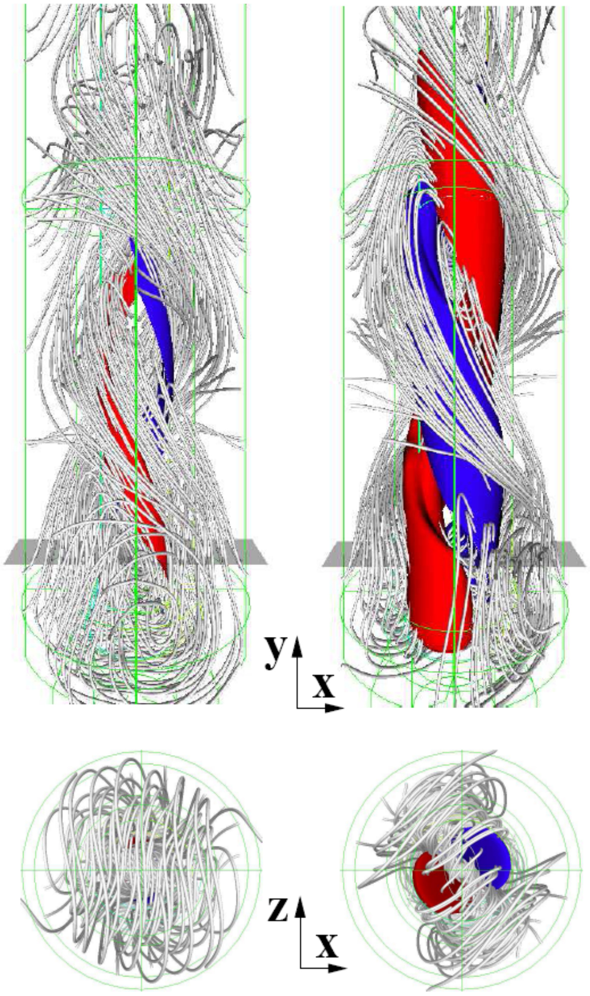
$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\nu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] - \frac{1}{\rho}\frac{\partial p}{\partial x_i} - \underbrace{\frac{1}{\rho\mu_0}\left(B_k \frac{\partial B_i}{\partial x_k} - B_k \frac{\partial B_k}{\partial x_i}\right)}_{F^L = 1/\rho\mu_0 (\nabla\times \mathrm{B})\times \mathrm{B}}$$

Closed with k-ε with magnetic source terms

$$S_k^M = -\frac{\sigma}{\rho} B_0^2 k \exp\left(-C_1^M \frac{\sigma}{\rho} B_0^2 \frac{k}{\varepsilon}\right); \quad S_\varepsilon^M = S_k^M \frac{\varepsilon}{k}$$

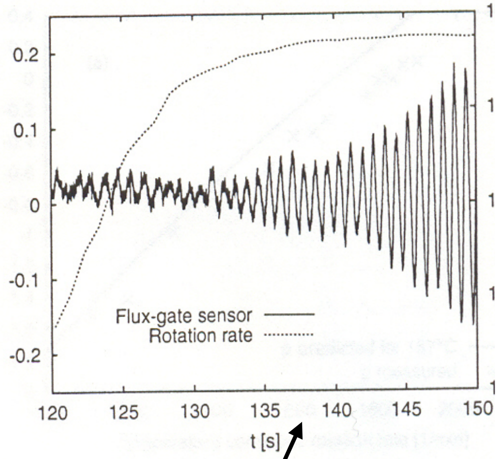
Magnetic induction equation ("DNS")

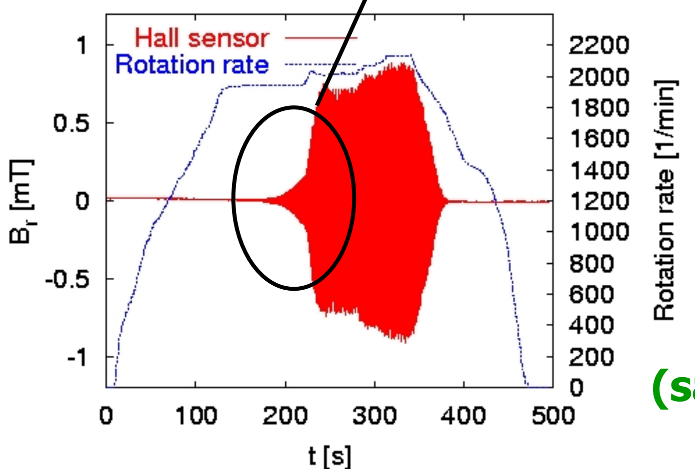
$$\frac{\partial B_i}{\partial t} + U_j \frac{\partial B_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{1}{\mu_0\sigma}\frac{\partial B_i}{\partial x_j}\right) + B_j \frac{\partial U_i}{\partial x_j}$$



RIGA FMD: Numerical confirmation

Riga Experiments
(*Gailitis et al. 1999*)

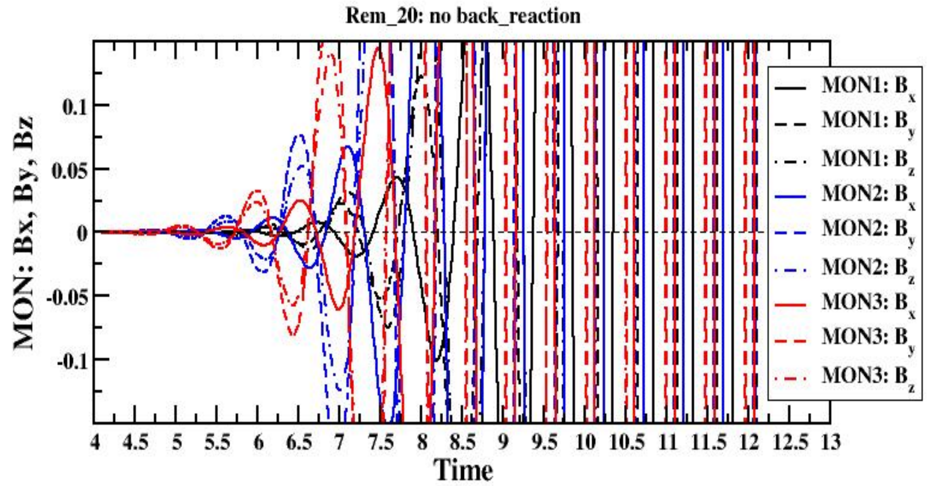


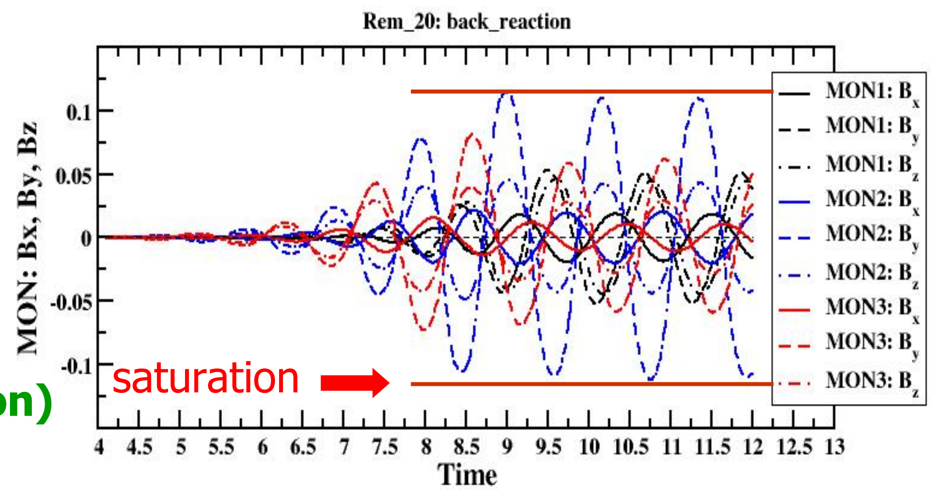


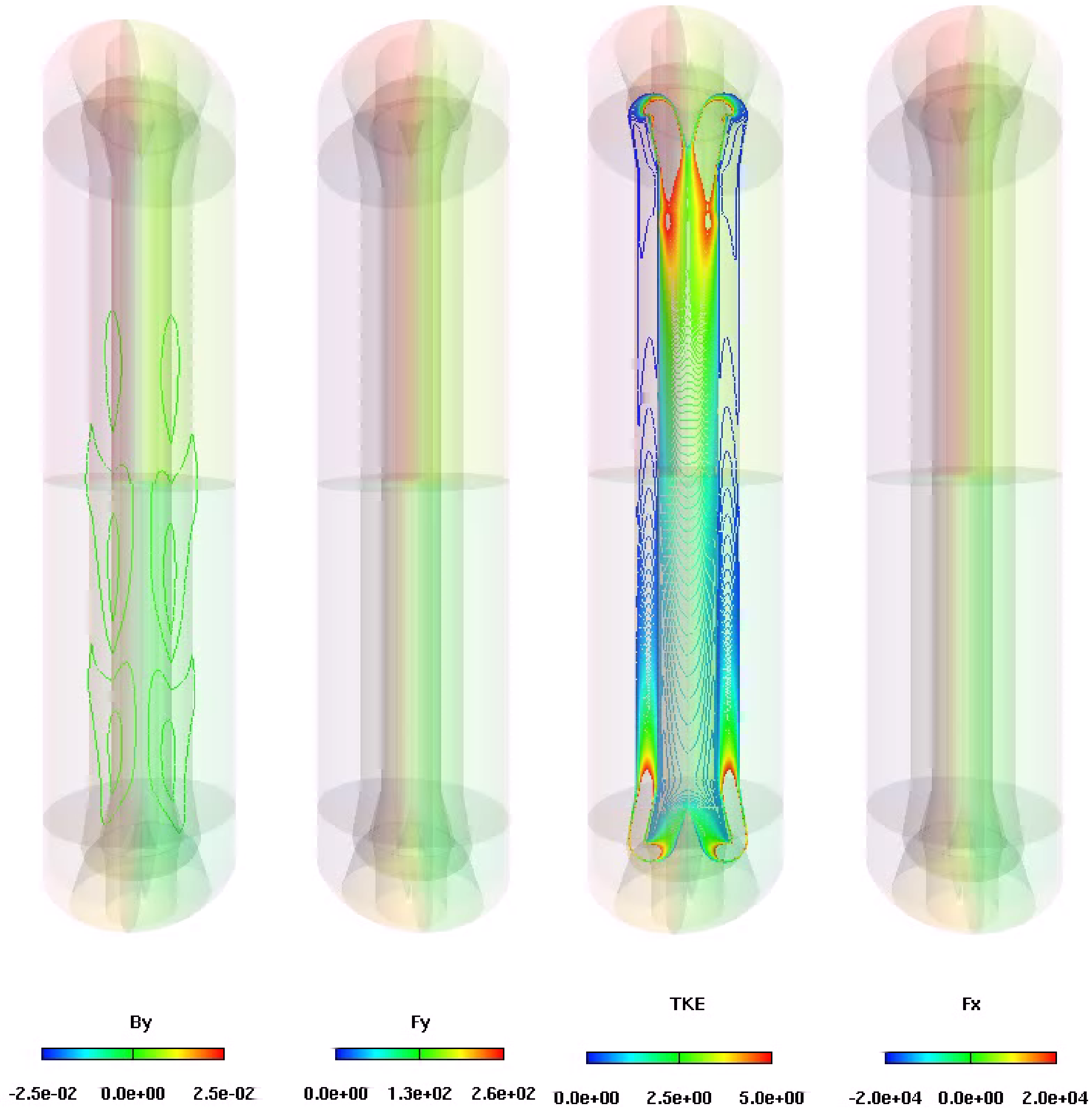
Kinematic regime

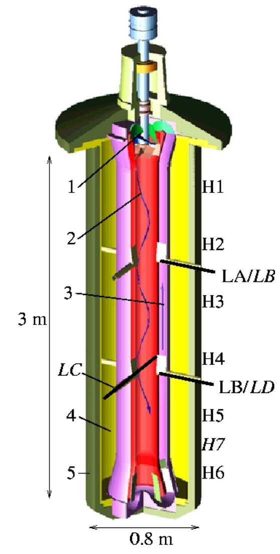
True (saturation) regime

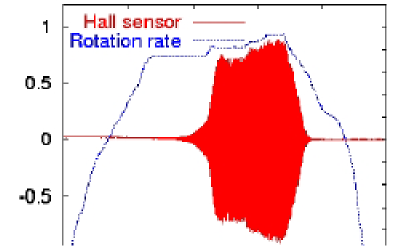
Computer Simulations
(*Kenjeres & Hanjalic, 2005*)

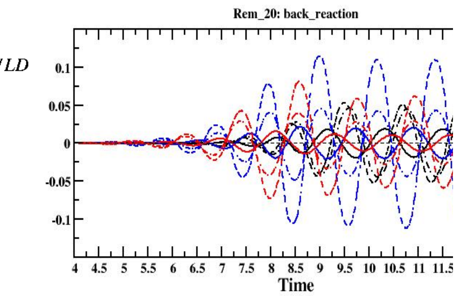


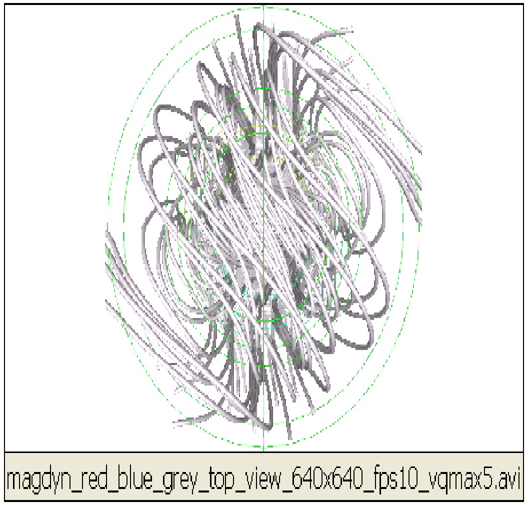












Kenjeres & Hanjalic, 2006

Concluding Remarks

- Three sets of examples illustrate potentials and limitations of Experiments and Computer Simulations/Modelling, but also their complementarity and synergy potential;

- The robustness and repeatability will keep experiments irreplaceable in *detecting* new physics, gathering new information and databases

- Computer simulations (DNS, LES): indispensable tool for collecting high-resolution 4D information (a true research tool for *explaining* new physics), but limited to small Re and Ra Nos

- Semi-empirical models and mixed approaches (URANS, VLES, hybrid RANS/LES) complement and extrapolate DNS, LES and Experiments, though will hardly ever be accepted as a trustworthy research instrument!

- Judiciously combined, they can generate invaluable synergy!

Concluding Remarks, cont.

- Computer visualization and animations, pioneered by experimentalist, but reached full blossom with computer simulations, is growing into its own branch of science:
  - they can reveal events, phenomena, structures etc., which may be just too complex for abstract imaging in ones mind.

- This all has been made possible primarily by Computer Simulation, but the abundance of information is creating new problems:

"Having terabytes of data at your disposal greatly increases the chances that you can find the answers to even the toughest questions – if you do not mind searching for a needle in a giant haystack"

(*G. Ehrenman, Mechanical Engineering (ASME), February 2005*).

Deficiency of the Basic EDM for Buoyant Flows

- **Isotropic eddy-diffusivity model (EDM) for heat flux ("Simple Gradient Diffusion Hypothesis", SSGD) :**

$$\overline{\theta u_j} = -\frac{\nu_t}{\sigma_T^t}\frac{\partial T}{\partial x_j} \equiv -\frac{\nu_t}{\sigma_T^t}\nabla T$$

- **Consider two generic situations:**

  1. A fluid layer heated from below, $g_i \,||\, \nabla T$

  Outside the thin layers, $\nabla T \approx 0$ (or = 0!),

  yet, the vertical heat transport

  2. Vertical heated walls, $g_i \perp \nabla T$

  Buoyancy source of *k* (and ε)

  yet, the vertical $\nabla T \approx 0$!

$$q_i = -\overline{\theta u_i} \neq 0!$$

$$G = \beta g_i \overline{\theta u_i} \neq 0,$$