Flow structure in a Rayleigh-Bénard cell with rough plate

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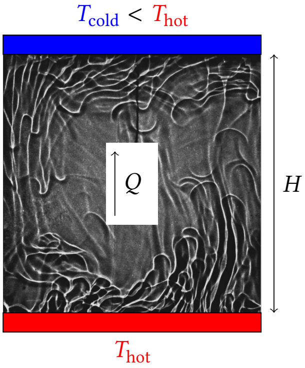
EuHIT collaboration: R. Kaiser, A. Loesch, R. du Puits

Model System: the Rayleigh-Bénard cell



Shadowgraph by Zang, *et al.*, 1997

Control parameters

- Thermal forcing *versus* diffusion :

$$Ra = \frac{g\alpha(T_{hot} - T_{cold})H^3}{\nu\kappa}$$

- Viscous diffusion *versus* Thermal diffusion :

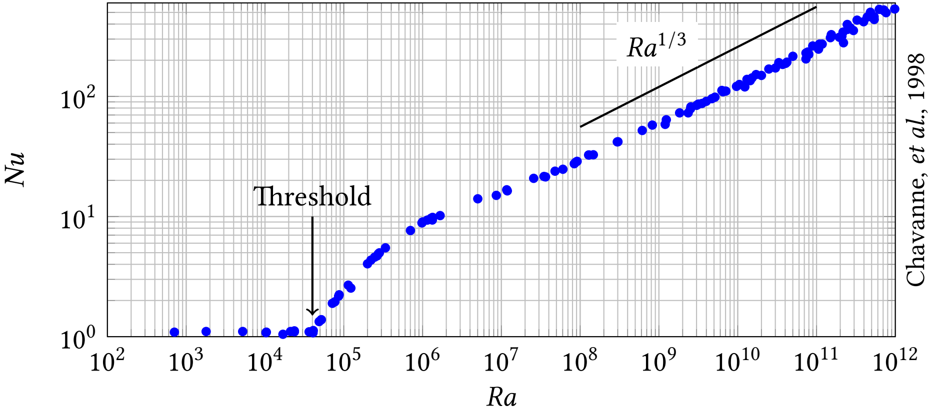
$$Pr = \frac{\nu}{\kappa}$$

System Response

- Normalized thermal flux :

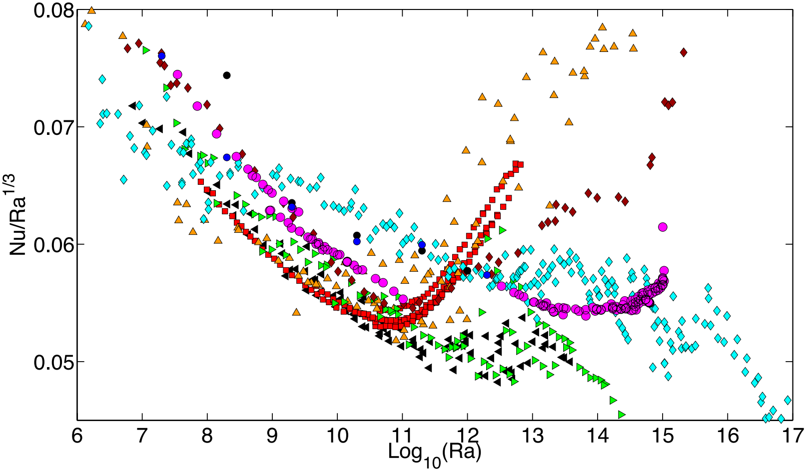
$$Nu = \frac{QH}{\lambda(T_{hot} - T_{cold})}$$

Scaling laws



$$\underbrace{\left(\frac{QH}{\lambda\,(T_{\text{hot}} - T_{\text{cold}})}\right)}_{Nu} = \underbrace{\left(\frac{g\,\alpha\,(T_{\text{hot}} - T_{\text{cold}})\,H^3}{\nu\,\kappa}\right)^{1/3}}_{Ra^{1/3}}$$

$Ra > 10^{12}$?



Chillà & Schumacher, Eur. Phys. J. E (2012) **35**:58

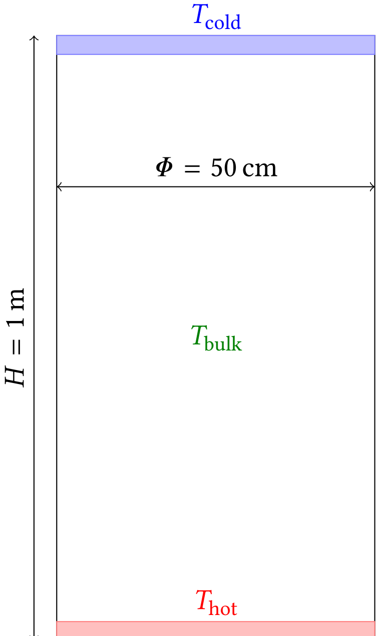
Opened questions

- What is this transition?
  Kraichnan asymptotic regime : $Nu \propto Ra^{1/2}$?
  Transition to turbulence in the boundary layer?
- What triggers or inhibits this transition?
- How to explain to quantitative difference between experiments?

Experimental apparatus

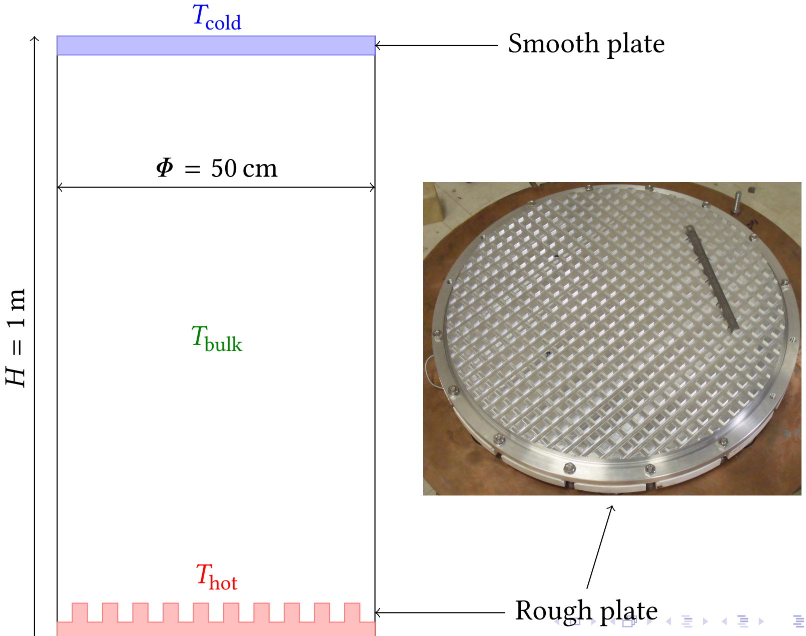
- Large infrastructure needed to reach $Ra > 10^{12}$
  (cryogenic helium or pressurized sulfur hexafluoride)
- Alternative approach: use plate roughness to trigger the transition to turbulence in the boundary layer

Experimental apparatus: the reference smooth cell

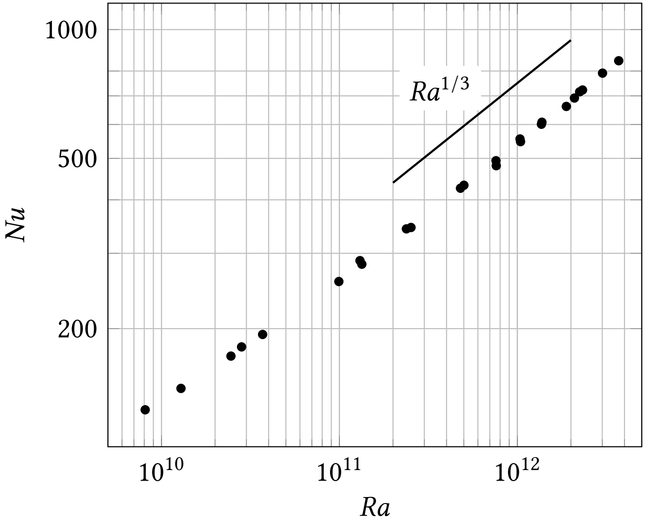


- Working fluid: Water (25 °C ... 70 °C)
- Heat flux: 2 W ... 2 kW
- Rayleigh numbers: $7 \times 10^9 \ldots 4 \times 10^{12}$
- Nusselt numbers: $10^2 \ldots 10^3$

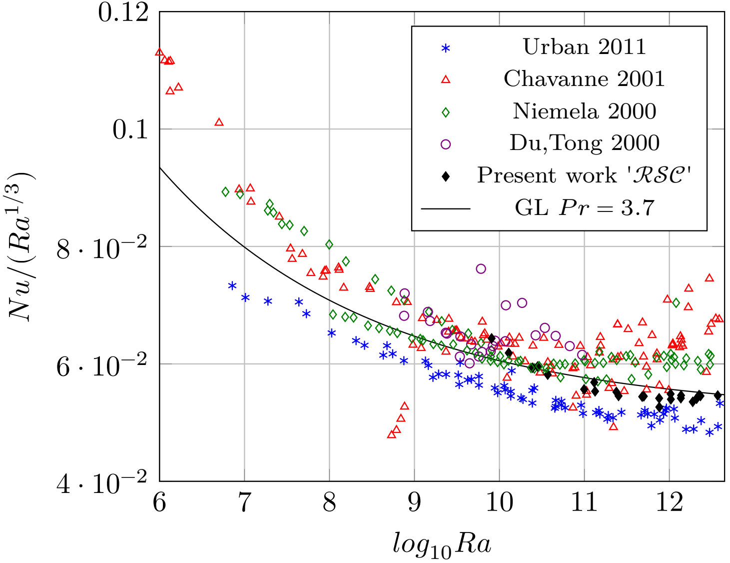
Experimental apparatus



Nu versus Ra scaling in smooth Rayleigh-Bénard cell



Nu versus Ra scaling in smooth Rayleigh-Bénard cell



Nu versus Ra scaling in smooth Rayleigh-Bénard cell

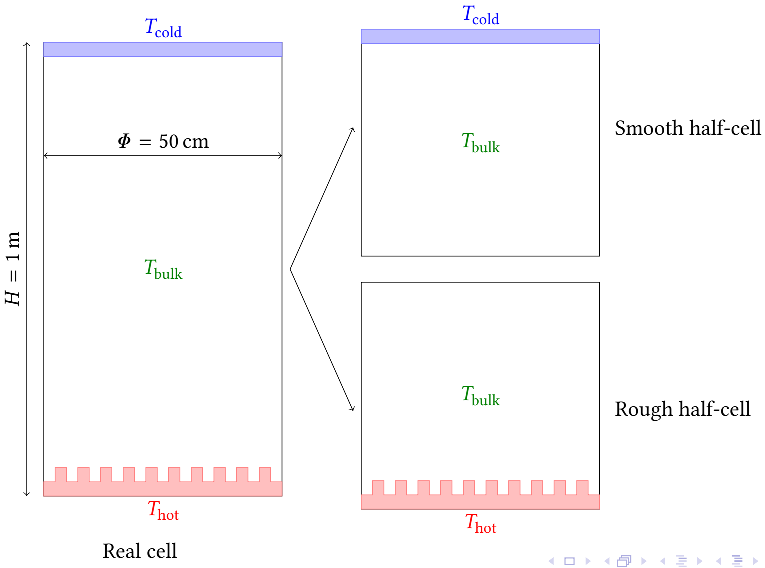
Independance of the plates

- The 1/3 power law :

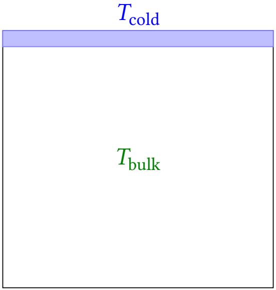
$$\underbrace{\left(\frac{QH}{\lambda\,(T_{\text{hot}} - T_{\text{cold}})}\right)}_{Nu} = \underbrace{\left(\frac{g\alpha\,(T_{\text{hot}} - T_{\text{cold}})H^3}{\nu\kappa}\right)^{1/3}}_{Ra^{1/3}}$$

- Consequence : the observed heat flux Q does not depend on H

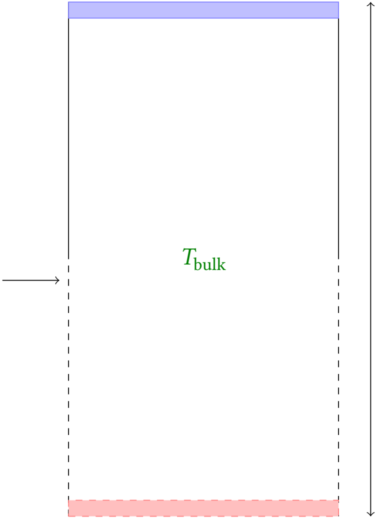
1. The plates do not see each other ($Nu \propto Ra^{1/3}$) ;
2. Each plate only sees the bulk temperature ;
3. $T_{\text{bulk}} \neq \left(T_{\text{hot}} + T_{\text{cold}}\right)/2$



From two independant half-cell to two virtual cells



Real smooth half-cell

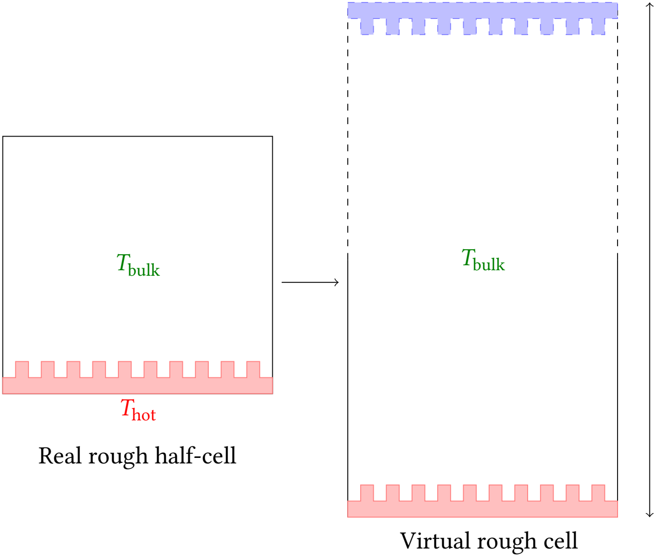


Virtual smooth cell

Symmetric cell :

$$T_{\text{bulk}} = (T_{\text{top}} + T_{\text{bottom}})/2$$
$$\Downarrow$$
$$\Delta T_s = 2 \times (T_{\text{bulk}} - T_{\text{cold}})$$
$$\Downarrow$$
$$Ra_s,\ Nu_s$$

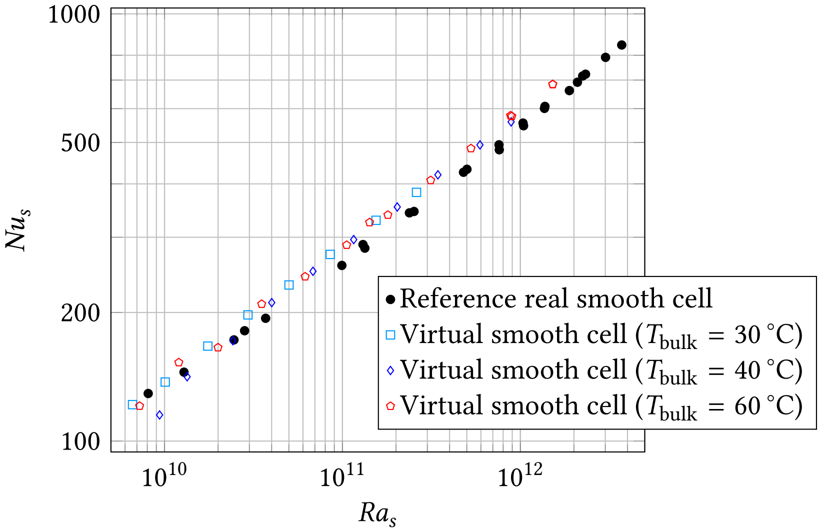
From two independant half-cell to two virtual cells



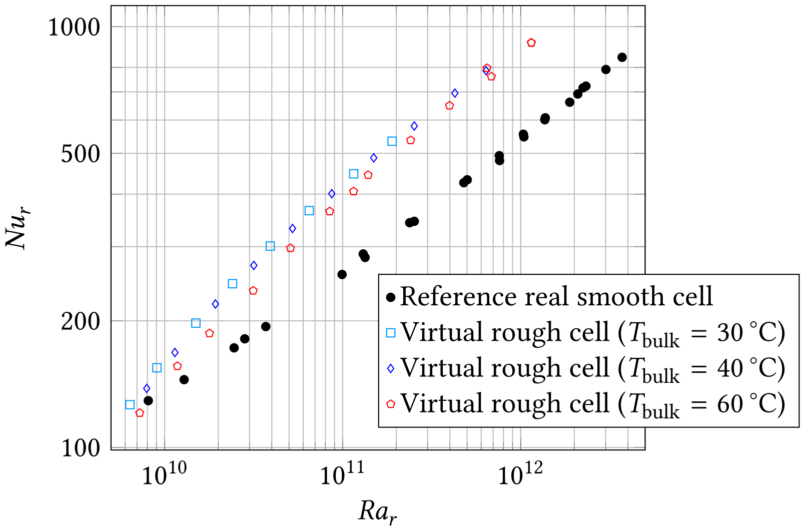
Symmetric cell :

$$T_{bulk} = (T_{top} + T_{bottom})/2$$
$$\Downarrow$$
$$\Delta T_r = 2 \times (T_{hot} - T_{bulk})$$
$$\Downarrow$$
$$Ra_r, Nu_r$$

Virtual smooth cell : Nu_s versus Ra_s



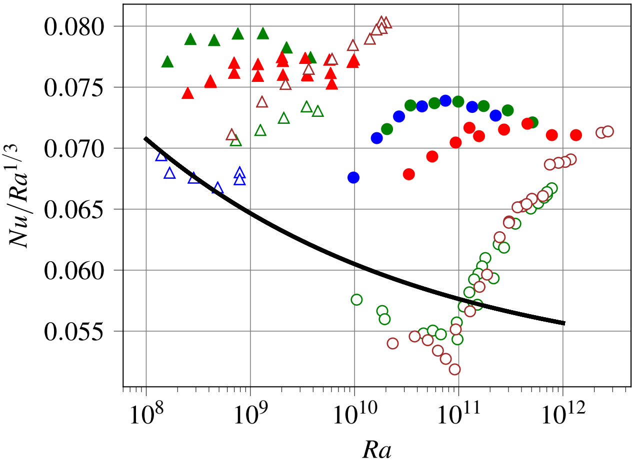
Virtual rough cell : Nu_r versus Ra_r



4 values of h_0/H

$$H = 1\,\text{m and } 20\,\text{cm}$$

$$h_0 = 2\,\text{mm and } 4\,\text{mm}$$



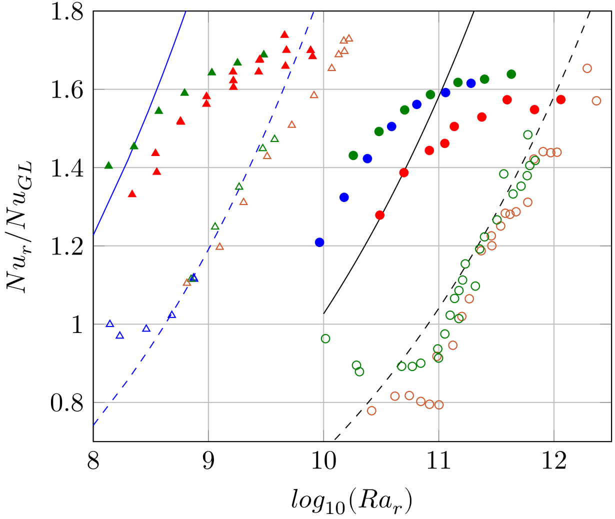
Interpretation: roughness-triggered transition to turbulence

$$Nu = \frac{(2\sigma)^{3/2}}{2} \left(\frac{h_0}{H} \right)^{1/2} Ra^{1/2}$$

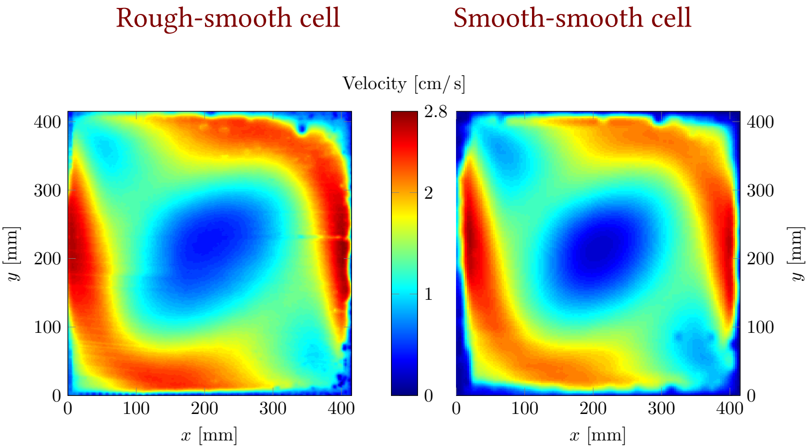
- No free parameters
- Does not depend on the details of the roughness geometry in the fully turbulent limit

Salort, *et al.*, Phys. Fluids (2014) **26**:015112

Roughness-triggered transition to turbulence

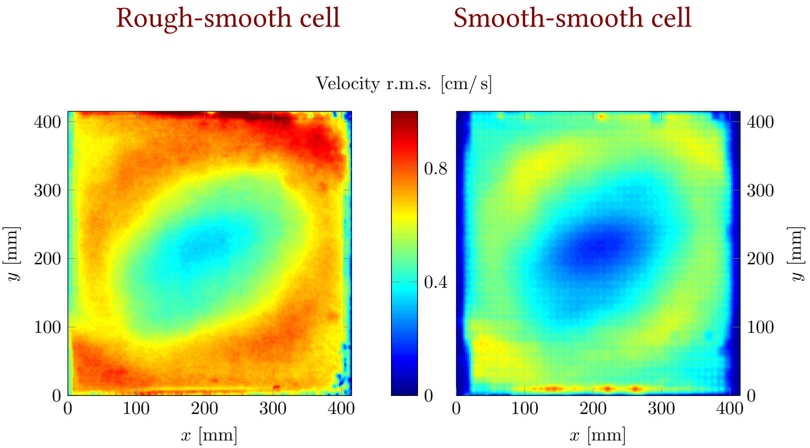


Velocity module maps



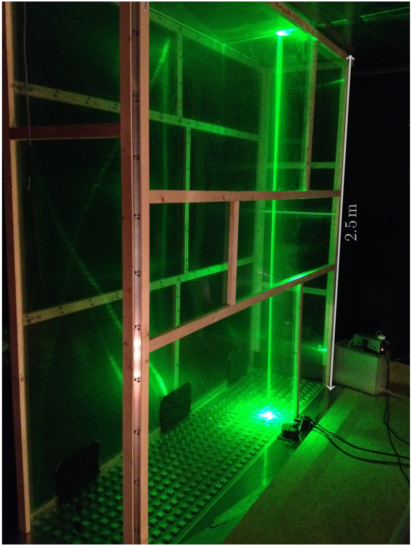
- Similar mean fields in smooth or rough cells
- Additional credits: T. Coudarchet, Q. Ehlinger

Horizontal velocity r.m.s. maps



- Larger velocity fluctuations in rough case
- Additional credits: T. Coudarchet, Q. Ehlinger

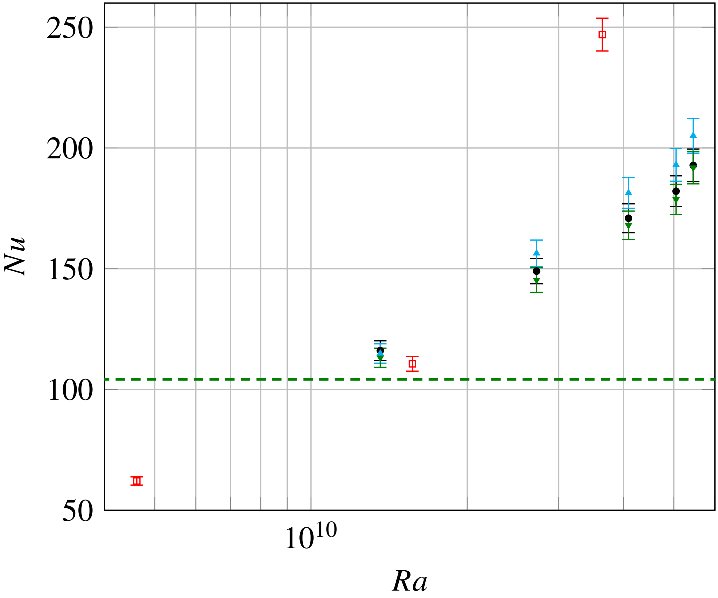
Larger setup in the *Barrel of Ilmenau*



Cell dimensions 6 times larger

- Cell 2.50 m × 2.50 m × 0.60 m
- Roughness :
  3 cm × 3 cm × 1.2 cm
- $Ra = 4.6 \times 10^9 - 4.0 \times 10^{10}$

Heat-transfer enhancement



Raw video - $Ra = 2.8 \cdot 10^{10}$

Detail of the notch

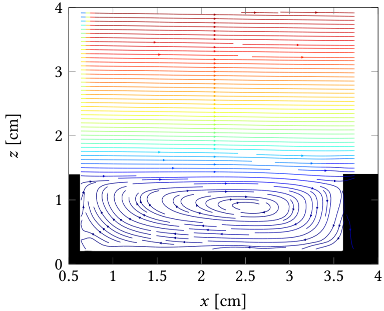


Figure: $Ra = 4.6 \cdot 10^9$

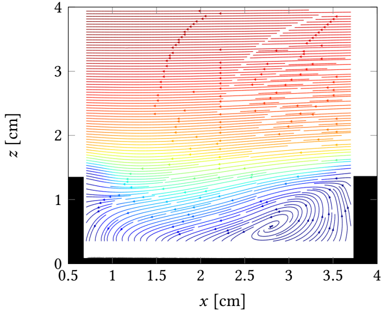
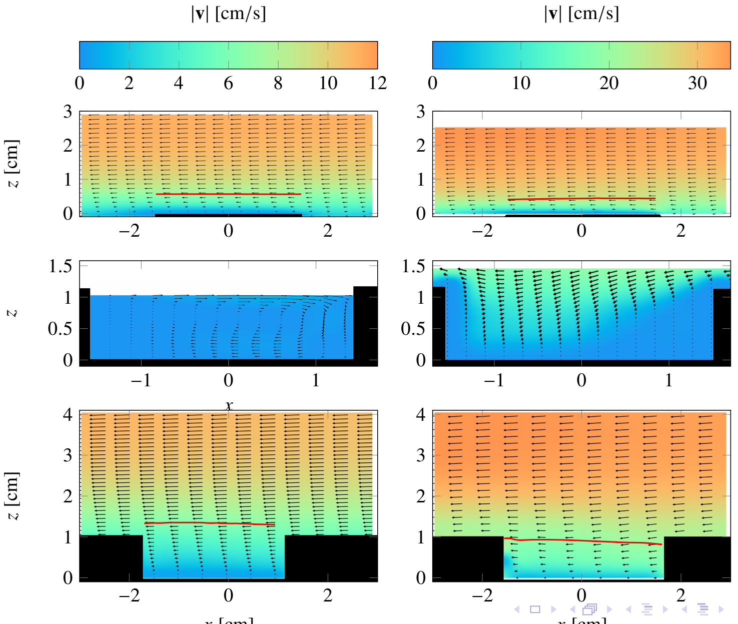


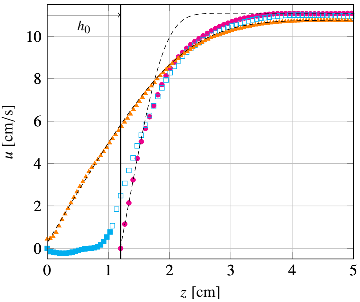
Figure: $Ra = 5.0 \cdot 10^{10}$

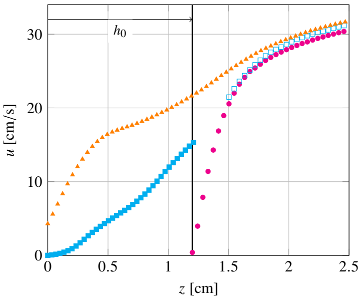
- Slowly recirculating, almost no mixing
- Better mixing, heat-transfer enhancement

Velocity fields

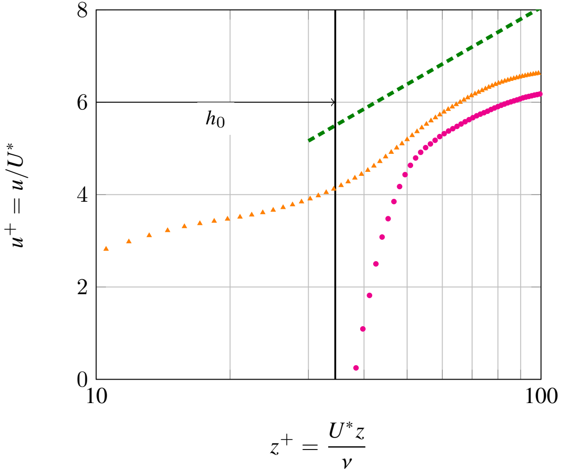


Velocity profiles





Velocity profile at high *Ra*



Green dashed line:

$$u = U^*(2.40 \log z^+ - 3)$$

$$k^+ = \frac{h_0 U^*}{\nu} \sim 40$$

Summary

Lyon Cells

- Heat-transfer enhancement compatible with

$$Nu = \frac{(2\sigma)^{3/2}}{2}\left(\frac{h_0}{H}\right)^{1/2} Ra^{1/2}$$

- Thin boundary layer on the top of the obstacles;
- Similar mean flow, but larger fluctuations.
- Evidence of a second transition and less enhanced heat-transfer
- Effect of the Prandtl number

Summary

Barrel of Ilmenau

- Similar heat-transfer enhancement;
- Thin boundary layer on the top of the obstacles;
- Transition from internal to external convection inside notch;
- Transition to logarithmic velocity profiles;
- Transition to logarithmic temperature profiles.