Turbulent transitions in thermal convection

Équipe Convection – Laboratoire de physique ENSL

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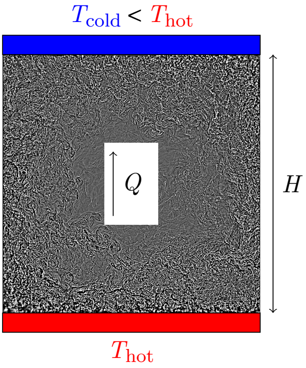
Model System : the Rayleigh-Bénard cell



Control parameters

- Thermal forcing *vs* diffusion :

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

- Viscous *vs* Thermal diffusion :

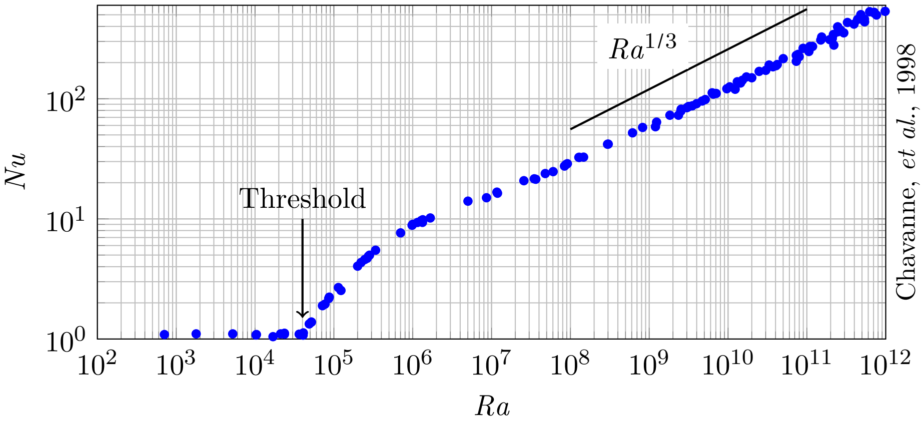
$$Pr = \frac{\nu}{\kappa}$$

System Response

- Normalized thermal flux :

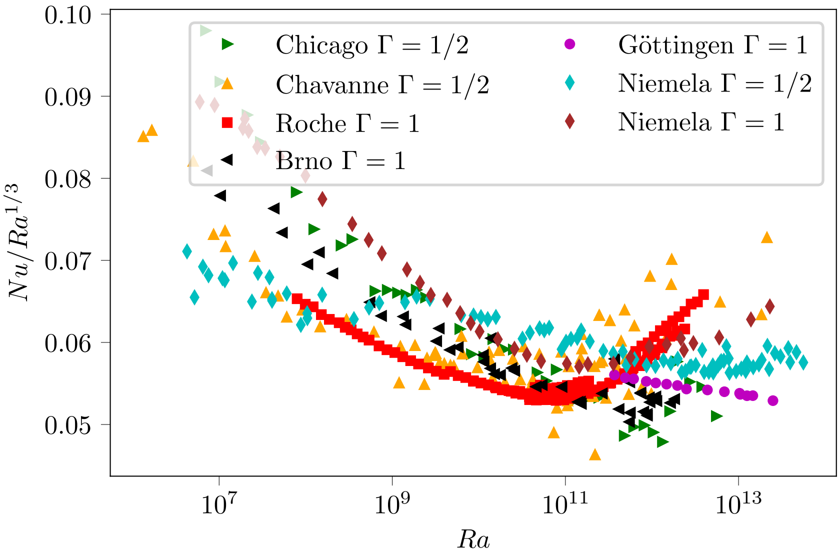
$$Nu = \frac{QH}{\lambda(T_{\text{hot}} - T_{\text{cold}})}$$

Scaling laws



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

$Ra > 10^{12}$?



Chicago Γ = 1/2
Chavanne Γ = 1/2
Roche Γ = 1
Brno Γ = 1
Göttingen Γ = 1
Niemela Γ = 1/2
Niemela Γ = 1
0.10
0.09
0.08
0.07
0.06
0.05
Nu/Ra^1/3
10^7
10^9
10^11
10^13
Ra

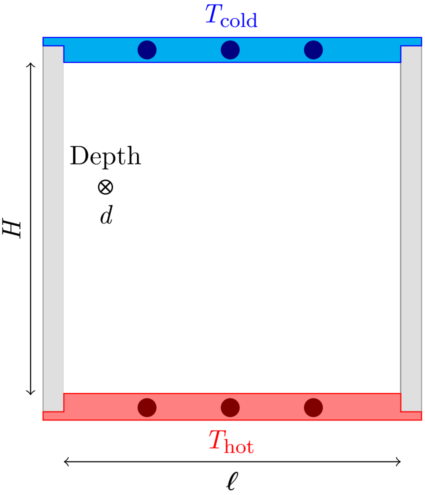
Open questions

- 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

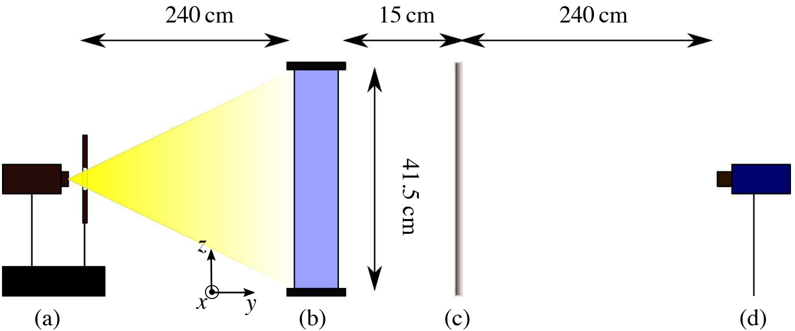
- Large infrastructure and/or special working fluid needed to reach $Ra > 10^{12}$
- Alternative approach : use plate roughness to trigger the transition to turbulence in the boundary layer

Experimental setup : rectangular cell



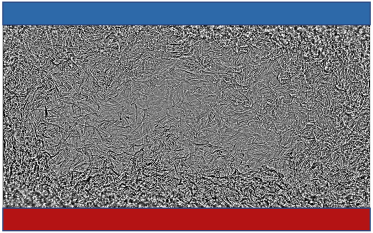
- **Room temperature**
  $H = \ell = 41.5\,\mathrm{cm},\ d = 10\,\mathrm{cm}$
  Water :
  $3 < Pr < 7\,;\ 10^9 < Ra < 10^{11}$
  Fluorocarbon :
  $10 < Pr < 15\,;\ 10^{10} < Ra < 10^{12}$
- **Liquid helium**
  $H = 4.8\,\mathrm{cm},\ \ell = 5\,\mathrm{cm},\ d = 1.5\,\mathrm{cm}$
  $0.5 < Pr < 0.71\,;$
  $3 \times 10^9 < Ra < 3 \times 10^{10}$

Non-invasive technique : shadowgraphy

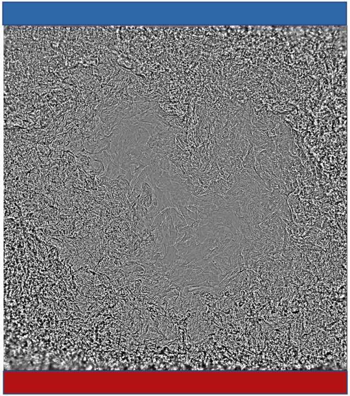


$$\frac{I(x,z)}{I_0} \approx \int_0^d \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} \right) (\ln n) \, \mathrm{d}y$$

Shadowgraph in Fluorocarbon

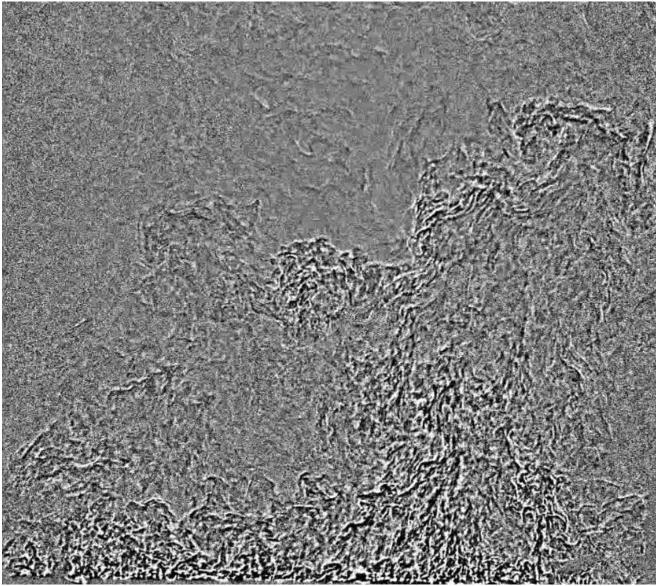


- $\Gamma = 2$
- $Ra = 9.10^{10}$

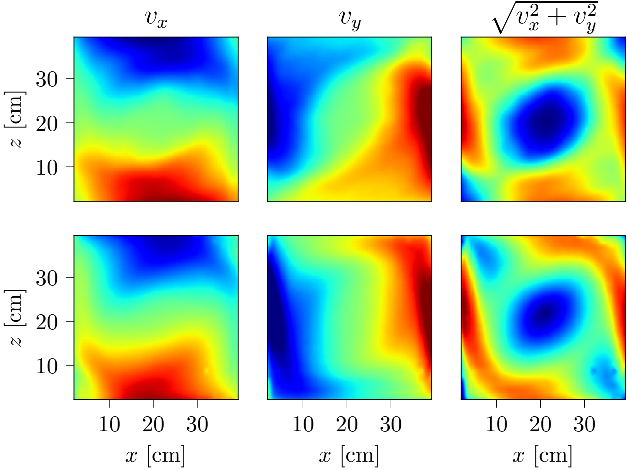


- $\Gamma = 1$
- $Ra = 2.10^{12}$

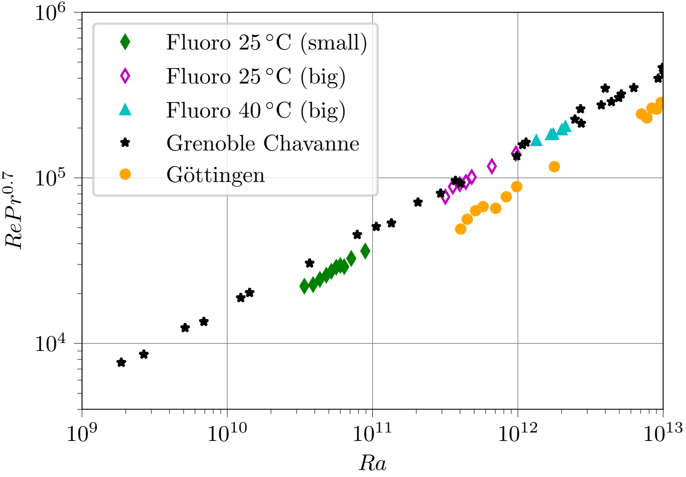
Shadowgraph in liquid helium



CIV on shadowgraph (top) vs PIV (bottom)



Reynolds number scaling



Friction coefficient

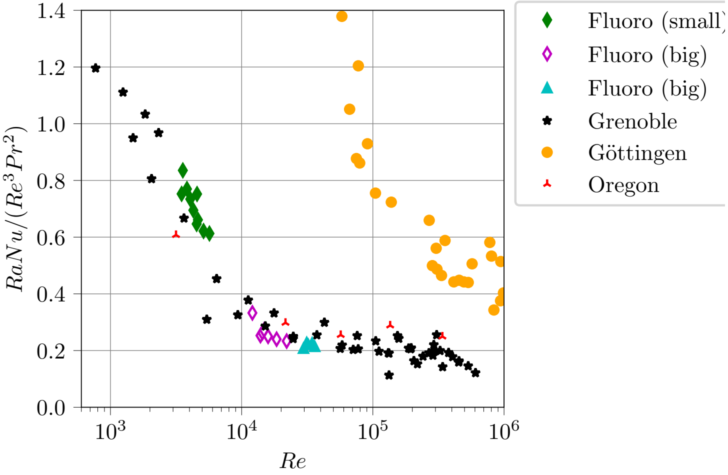
- Balance of kinetic energy

$$\epsilon = \frac{\nu^3}{h^4}(Nu - 1)RaPr^{-2}$$

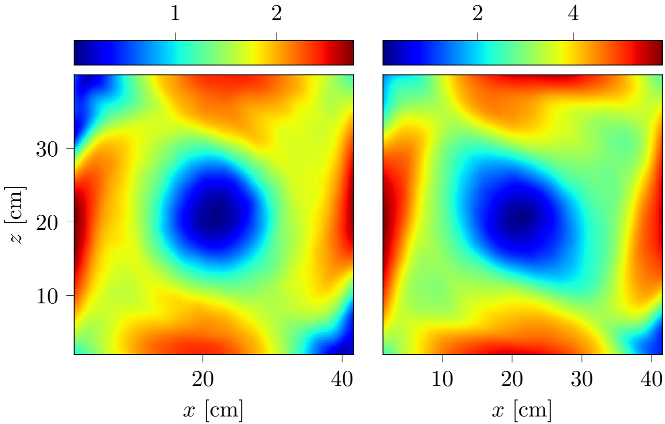
- Coefficient de friction

$$\frac{(Nu-1)RaPr^{-2}}{Re^3} = \frac{\nu(\mathbf{grad}\,\mathbf{u})^2}{u^3/h}$$

Friction coefficient

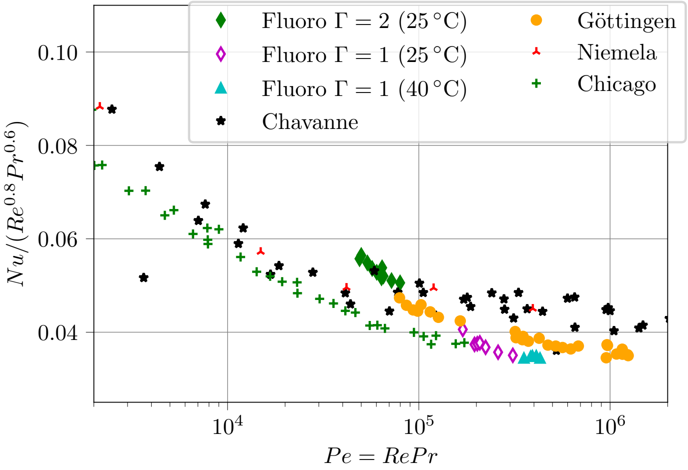


Mean field at the transition



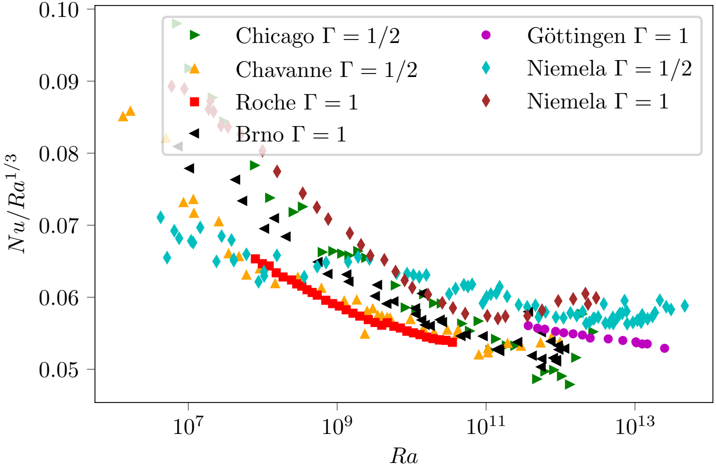
Velocity fields in the $\Gamma = 1$ cell with FC770. Left : $Ra = 3.6 \times 10^{11}$. Right : $Ra = 2.1 \times 10^{12}$.

Péclet number as the control parameter



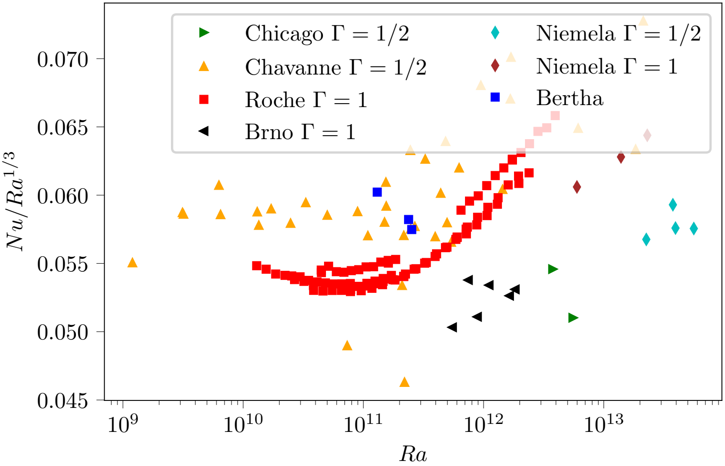
$Pr \leq 1$ in Boussinesq conditions

$$\Delta\lambda/\lambda < 0.1,\ \Delta\mu/\mu < 0.1,\ \Delta\alpha/\alpha < 0.1,\ \Delta c_p/c_p < 0.1,\ \Delta\kappa/\kappa < 0.1,$$
$$\Delta\rho/\rho < 0.1,\ \alpha\Delta T < 0.1$$



$Pr \geq 1$ in Boussinesq conditions

$$\Delta\lambda/\lambda < 0.1,\ \Delta\mu/\mu < 0.1,\ \Delta\alpha/\alpha < 0.1,\ \Delta c_p/c_p < 0.1,\ \Delta\kappa/\kappa < 0.1,$$
$$\Delta\rho/\rho < 0.1,\ \alpha\Delta T < 0.1$$



Conclusions

- Threshold in terms of Reynolds or Péclet number : role of geometry and Prandtl number ;
- Transition in the $Nu - Ra$ plane not very sharp ;
- Transition of friction from $1/\sqrt{Re}$ to plateau ;
- No dramatic change of mean velocity field.