Flow structure in a Rayleigh-Bénard cell with rough plate

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Model System: the Rayleigh-Bénard cell

Control parameters

- Thermal forcing *versus* diffusion:
  \[ Ra = \frac{g \alpha (T_{\text{hot}} - T_{\text{cold}}) H^3}{\nu \kappa} \]

- Viscous diffusion *versus* Thermal diffusion:
  \[ Pr = \frac{\nu}{\kappa} \]

System Response

- Normalized thermal flux:
  \[ Nu = \frac{Q H}{\lambda (T_{\text{hot}} - T_{\text{cold}})} \]
Threshold

\[
\left(\frac{QH}{\lambda(T_{\text{hot}} - T_{\text{cold}})}\right) = \left(\frac{g \alpha (T_{\text{hot}} - T_{\text{cold}}) H^3}{\nu \kappa} \right)^{1/3}
\]

Chavanne, et al., 1998
$Ra > 10^{12}$?

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: $7 \times 10^9$ ... $4 \times 10^{12}$
- Nusselt numbers: $10^2$ ... $10^3$
Experimental apparatus

- $T_{\text{cold}}$
- $T_{\text{bulk}}$
- $T_{\text{hot}}$
- $H = 1 \text{ m}$
- $\Phi = 50 \text{ cm}$

Smooth plate

Rough plate
Nu versus Ra scaling in smooth Rayleigh-Bénard cell

\[ Ra^{1/3} \]
Nu versus Ra scaling in smooth Rayleigh-Bénard cell

Urban 2011
Chavanne 2001
Niemela 2000
Du,Tong 2000
Present work 'RSC'

GL \( Pr = 3.7 \)
Nu versus Ra scaling in smooth Rayleigh-Bénard cell

Independance of the plates

- The 1/3 power law:

\[
\frac{QH}{\lambda (T_{\text{hot}} - T_{\text{cold}})} = \left( \frac{g \alpha (T_{\text{hot}} - T_{\text{cold}}) H^3}{\nu \kappa \sqrt[3]{Ra}} \right)^{1/3}
\]

- 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. \(T_{\text{bulk}} \neq (T_{\text{hot}} + T_{\text{cold}}) / 2\)
From two independent half-cell to two virtual cells

Real smooth half-cell

\[ T_{\text{cold}} \]

\[ T_{\text{bulk}} \]

Virtual smooth cell

Symmetric cell:

\[ T_{\text{bulk}} = \frac{(T_{\text{top}} + T_{\text{bottom}})}{2} \]

\[ \Delta T_s = 2 \times (T_{\text{bulk}} - T_{\text{cold}}) \]

\[ Ra_s, Nu_s \]
From two independent half-cell to two virtual cells

Symmetric cell:

\[ T_{\text{bulk}} = \left( T_{\text{top}} + T_{\text{bottom}} \right) / 2 \]

\[ \Delta T_r = 2 \times (T_{\text{hot}} - T_{\text{bulk}}) \]

\[ Ra_r, Nu_r \]
Virtual smooth cell: $Nu_s$ versus $Ra_s$

- Reference real smooth cell
- Virtual smooth cell ($T_{bulk} = 30 \, ^\circ C$)
- Virtual smooth cell ($T_{bulk} = 40 \, ^\circ C$)
- Virtual smooth cell ($T_{bulk} = 60 \, ^\circ C$)
Virtual rough cell: $Nu_r$ versus $Ra_r$
4 values of $h_0/H$

$H = 1$ m and 20 cm

$h_0 = 2$ mm and 4 mm
Interpretation: roughness-triggered transition to turbulence

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

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

Roughness-triggered transition to turbulence

\[\log_{10}(Ra_r) \]

\[\frac{Nu_r}{Nu_{GL}}\]
Velocity module maps

Rough-smooth cell

Smooth-smooth cell

Similar mean fields in smooth or rough cells

Additional credits: T. Coudarchet, Q. Ehlinger
Horizontal velocity r.m.s. maps

Rough-smooth cell

Smooth-smooth cell

Velocity r.m.s. [cm/s]

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 $2.50 \text{ m} \times 2.50 \text{ m} \times 0.60 \text{ m}$
- Roughness:
  $3 \text{ cm} \times 3 \text{ cm} \times 1.2 \text{ cm}$
- $Ra = 4.6 \times 10^9 - 4.0 \times 10^{10}$
Heat-transfer enhancement

![Graph showing heat-transfer enhancement](image)
Raw video - \( Ra = 2.8 \cdot 10^{10} \)
Detail of the notch

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

- Slowly recirculating, almost no mixing

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

- Better mixing, heat-transfer enhancement
Velocity fields

\[ |\mathbf{v}| \text{ [cm/s]} \]

\[ x \text{ [cm]} \]

\[ z \text{ [cm]} \]
Velocity profiles

$h_0$

$u$ [cm/s]

$z$ [cm]
Velocity profile at high $Ra$

Green dashed line:

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

\[ k^+ = \frac{h_0 U^*}{\nu} \approx 40 \]
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.