Convection naturelle à très hauts Rayleigh ($Ra \sim 10^{15}$): simulations LES et expériences en $^4$He cryogénique pour la validation des corrélations d'échange pour le refroidissement passif des SMR

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The passive safety concept of Small Modular Reactors (SMR) is based on the transfer of residual heat from the reactor to a water pool.

Heat exchange occurs by natural convection at Rayleigh numbers ($Ra^*$) between $10^{10}$ and $10^{18}$.

Reliable heat transfer correlations exist to date only up to about $Ra^* < 10^{14}$ with very high uncertainties in the extrapolation to higher $Ra$.

$Ra^* = \frac{g \beta_f Pr_f \phi L_c^4}{\nu_f^2 \lambda_f} = Ra \cdot Nu$

$Ra^* < 10^{11} \rightarrow$ laminar flow

$Ra^* > 10^{14} \rightarrow$ turbulent flow

→ Understanding the heat transfer at very high $Ra^*$ is of fundamental and practical interest.
The challenges:

1. Numerical challenges: @CEA Saclay
   - Validation of a CFD model for turbulent heat transfer at high Ra number.
   - Extremely high calculation cost, this necessitates a robust and efficient solver.

2. Experimental challenges: @CEA Grenoble
   - Potential alternative strategy needs to be addressed to validate the TrioCFD code avoiding a huge dimension experiment (the water pool used for cooling the SMR is decametric in size).
   - Development of validation cryogenic experiments with helium at CEA Grenoble

The CORAYSE project:
- To develop and validate a strategy to predict the heat transfer at very high Ra by using the CFD code TrioCFD.
- To design a cryogenic helium experiment
Numerical simulations – water

Validation in water (exp. data from G.C.Vliet, 1969; Fujii, 1970; Tsuji & Kajitani 2009)

The heat transfer relation are in good agreement with available experimental data.

\[ \theta_w: \ T_{\text{wall}} - T_{\text{bulk}} \]

Numerical simulations – water (2)

Mean temperature

- $\theta_w$: $T_{wall} - T_{bulk}$, $\theta$: $T - T_{bulk}$
- $\delta_h$: enthalpy thickness, $\delta_h = \int_0^\infty \frac{\theta}{\theta_w} dx$

Mean velocity

- $\delta_d$: displacement thickness, $\delta_d = \int_0^\infty \frac{u}{U_m} dx$
- $U_m$: maximum mean velocity
Numerical simulations – water @ Ra* $10^{19}$

- SMR-representative geometry
- Incompressible model

A good agreement:
- in the laminar regime at $y < 0.45$ m ($Ra^* < 10^{13}$) for $\theta_w$ along the heated wall.
- linear trend in the fully developed turbulent regime at $10^{15} < Ra^* < 10^{19}$ (1.2 m < y < 15 m),
- a new correlation with higher power exponent is proposed for $2 \cdot 10^{16} < Ra^* < 10^{19} \rightarrow$ validation needs

S. Yang, U. Bieder, LES of Natural Convection along the Vertical Wall applied for the scale of Small Modular Reactor (Ra*=10^{19}), Advancement in Thermal hydraulics, 2022.
Use of cryogenic helium

Interest in using cryogenic helium

- \((\beta_f Pr_f / \nu_f^2)\) liquid water \(\approx 10^9\)
- \((\beta_f Pr_f / \nu_f^2)\) cryogenic helium \(\approx 10^{16}\)

Liquid He allows to reduce:

- The size by a factor \(~20\),
- The power by a factor \(~10,000\)

Refrigeration station @DSBT

- 800W @4.5 K
- 30 g/s
- Subcooled bath pumping

\[ R_a = g \beta_f Pr_f \frac{\Delta T L_c^3}{\nu_f^2} \]

Figures: (a) 400W refrigeration cold box, (b) cryoline, (c) multi-test cryostat
Numerical simulations – cryogenic $^4$He

- Bulk temperature 4.2 K. $\Delta T$ 0.6 K for Boussinesq hyp.

- Comparison:
  - Transitional Ra (no trigger is used)
  - Nu due to $Pr$ (Air 0.7, sHe 5.7, our work 0.87)
  - Assessment of the boundary layer thickness $\rightarrow$ sensor positioning $\sim$ 1 µm

- Further work is necessary to consolidate the analysis (i.e. $Q_w$=const.) and the experimental validation is considered as paramount

Songzhi Yang, Alain Girard, Nicolas Luchier, Ulrich Bieder, Etienne Studer, 3D LES of natural convection in the side-heated vertical wall with cryogenic Helium up to $Ra=10^{15}$, 17th international heat transfer conference, 2023
$^4$He cryogenic experiment

- **Cryogenic $^4$He:**
  4,2 K & 2,4 bar

- **Liquid helium bath:**
  3,6 K (from SHREK)

- **Test vessel:**
  diam. 780 mm aluminum alloy 5083

- **Cu heated plate:**
  900 x 200 x 30 mm

- **Injected power (estimated):** ~100 W

- Possibility of a heated cylinder instead (2D axisymmetric) or any shape

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![Diagram of complete assembly](image)

Complete assembly

Helium bath @3,6 K

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![Diagram of vertical heated plate](image)

Vertical heated plate

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![Diagram of CG centering system](image)

CG centering system
Sensors

**Objective for velocity sensors**: microfabricated cold wires for TOF measurement

**Legacy sensors @DSBT:**
- Hot wires used at low temperature are of Wollaston type (JP Moro/DES–STMF process)
- Microfabricated hot wires were also developed at DSBT (Princeton process), work at room temperature, but are not reliable for cryogenic operation.

**New sensor & new process:**
- Thin film of NbN (PVD@PTA), possibly on Invar
- TOF sensor: Length of the sensor: 50–100 µm; thickness: 500 nm. Masks under development.
- Thin BL (~1 cm) → positioning ~ µm in a 500 mm cell

Left: Legacy DSBT hotwires (JP Moro). Right: Princeton type

Left: new DSBT TOF sensor (ongoing). Right: NbN thin film resistivity
Conclusions and further developments

Interests: Very high Ra natural convection flow is critical for SMR safety applications & fundamental research purposes

Status:

• **Simulations:** further analysis is required in cryo He
• **Experiment:** ongoing development (sizing, manufacturing plans). Procurement started
• **Sensors:** ongoing development. A real challenge!

Further developments & timeline

• **2024:** go-ahead with the cryogenic experiment
• **2025:** experiment troubleshooting & 1st runs
• Broad scientific collaboration: why don’t you join us?

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Thanks for your attention

Any question?