DE LA RECHERCHE À L'INDUSTRIE

Molten Corium Concrete Interaction: Investigation of convective heat transfer in a pool with gas sparging

Manon BOTTIN

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BACKGROUND

- Main findings in MCCI experiments with prototypical materials:

- For LCS concretes: significant gas release and low pool viscosity

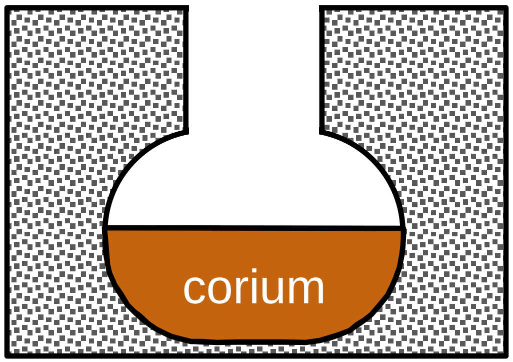
  ➢ experiments showed a rather isotropic concrete ablation

- For siliceous concretes: low gas flow rate and increased viscosity

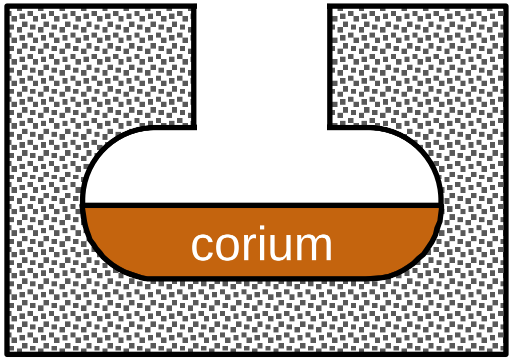
  ➢ anisotropic trends were experimentally observed: lateral ablation is predominant compared to the one at the bottom of the pool.

→ What is the influence of viscosity and gas release on local heat transfer and then on heat flux distribution and therefore on concrete ablation?

Isotropic ablation trend for LCS concrete



Anisotropic ablation trend for siliceous concrete



REVIEW ON HEAT TRANSFER CORRELATIONS

- List of existing correlations:

BALI (Bonnet [2000]), Kutateladze-Malenkov (Kutateladze & Malenkov [1984]), **Deckwer [1980]** (Correlation that best reproduces the experimental data according to Tourniaire [2006])

- Deckwer semi-theoretical model :

Solving heat equation along the wall in a bubble column leads to the following expression of the heat transfer coefficient:

$$h \propto \left(\frac{\lambda \rho C_p}{t}\right)^{1/2}$$

With *t* being the contact time between a fluid element and the wall. This time is associated to the fluctuations of the micro scale eddies of turbulence. Considering their length and velocity scales according to Kolmogorov theory of isotropic turbulence, *t* writes:

$$t = (\rho/\mu\varepsilon)^{1/2}$$

With ε the energy dissipation rate proportional to the injected power by the gas in the pool: $\varepsilon = g.J_g$. We then obtain:

$$h \propto \lambda^{1/2}\rho^{3/4}{C_p}^{1/2}g^{1/4}{J_g}^{1/4}\mu^{-1/4}$$

In a non-dimensional form (with Stanton, Reynolds, Froude and Prandtl numbers), with fitting coefficient 0.1:

$$\boldsymbol{St = 0.1\left(ReFrPr^2\right)^{-0.25}}$$

REVIEW ON HEAT TRANSFER EXPERIMENTS

B. Tourniaire, *«A heat transfer correlation based on a surface renewal model for molten core concrete interaction study»*, Nuclear Engineering and Design, vol. 236, pp. 10-18, 2006

- Main experiments on two-phase flow heat transfer investigation within a heated bubbling pool:

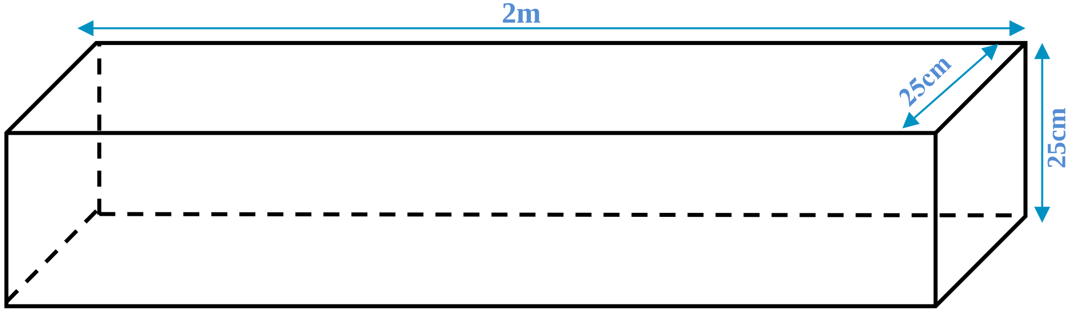
- The BALI Ex-Vessel tests (Bonnet [2000])
- The Duignan et al. tests (Duignan et al. [1990])
- The Kutateladze - Malenkov tests (Kutateladze & Malenkov [1984])
- The Kölbel tests (Kölbel [1958])

→ no experiment with gas injected simultaneously through the bottom and the lateral walls on representative viscosity and gas velocity ranges, with representative geometry and heating

→ the CLARA program, financed by EDF, IRSN, GDF-Suez and CEA, launched in 2007

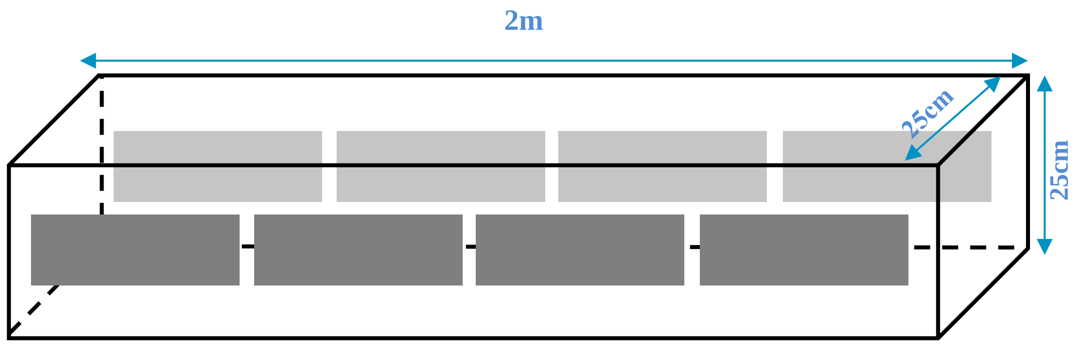
CLARA FACILITY

Objective: Measurement of heat transfer distribution



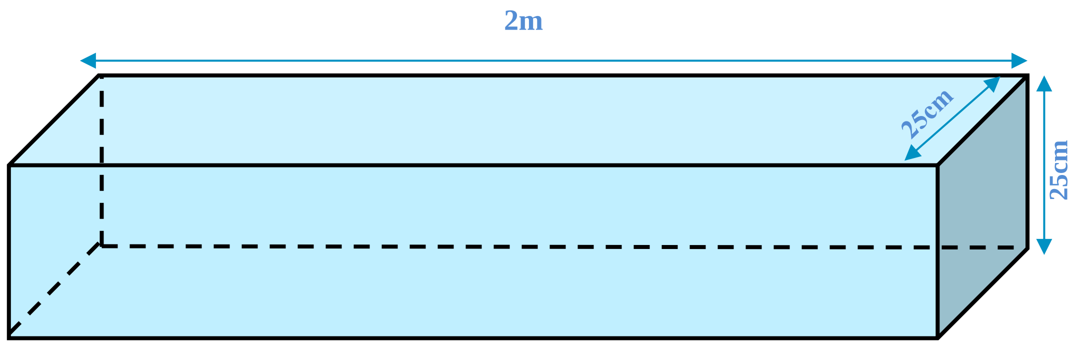
- Plexiglas container of pool dimensions: 200 x 25 x 25 cm

CLARA FACILITY



- Plexiglas tray of pool dimensions: 200 x 25 x 25 mm
- Pool volumetrically heated by electric current

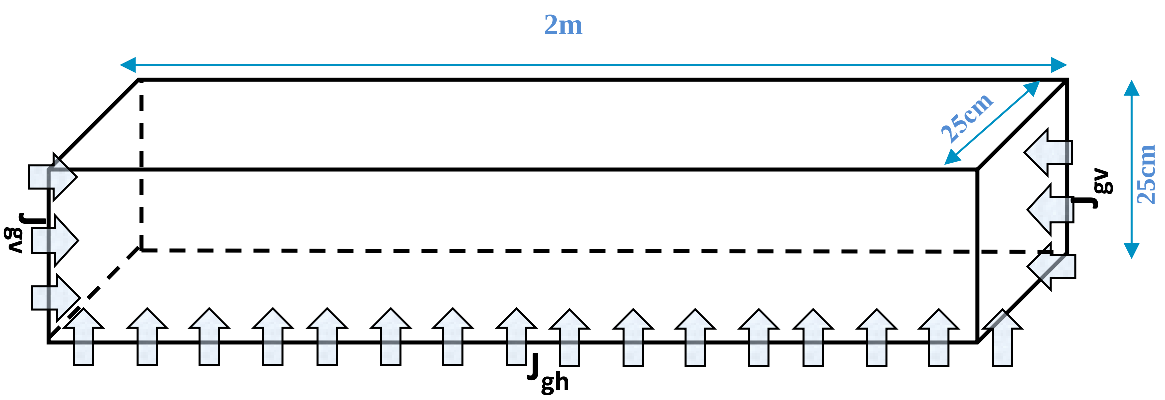
CLARA FACILITY



- Plexiglas tray of pool dimensions: 200 x 25 x 25 mm
- Pool volumetrically heated by electrodes
- Solutions of water with addition of HEC (to vary viscosity)

Fraction of HEC added to water (% weight)	0	0,75	1,2	2,3	4,1
Corresponding average viscosity (mPa.s, at 22°C)	1	9	25	100	1000

CLARA FACILITY



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Jgh, Jgv (Ncm/s)	0	0.7	2	4	7

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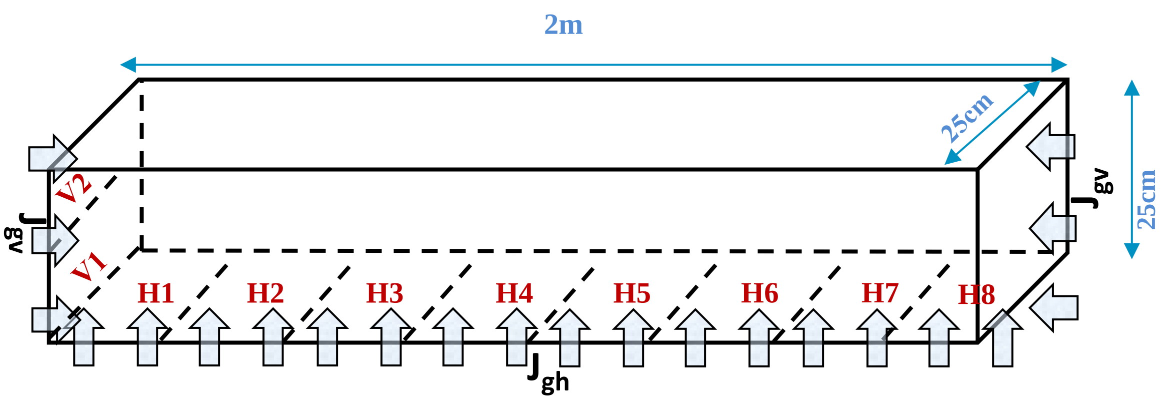

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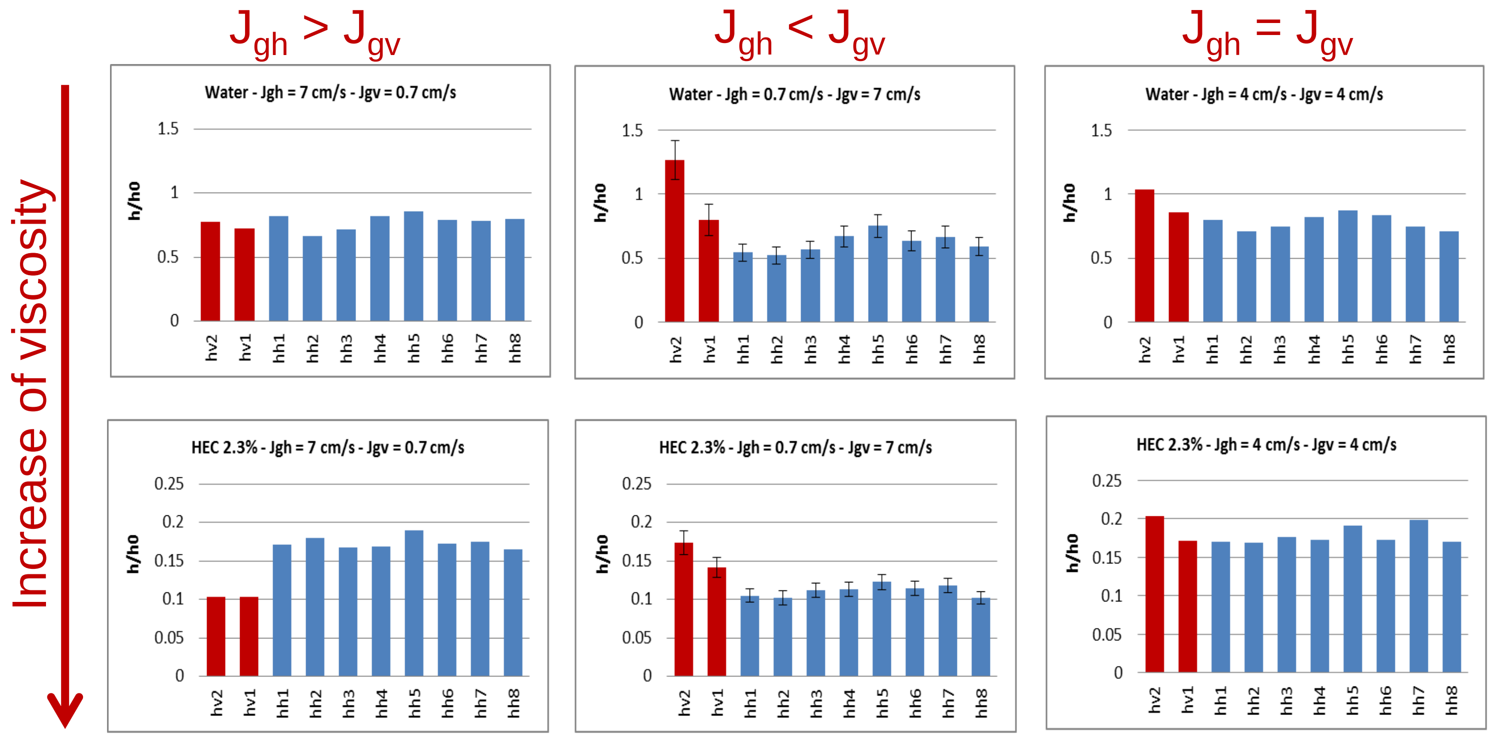
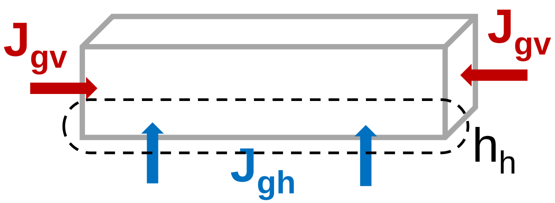
- Heat exchangers on the bottom horizontal wall (H) and 1 lateral vertical wall (V) to cool the pool, ensure an uniform wall temperature and measure the heat transfer coefficients

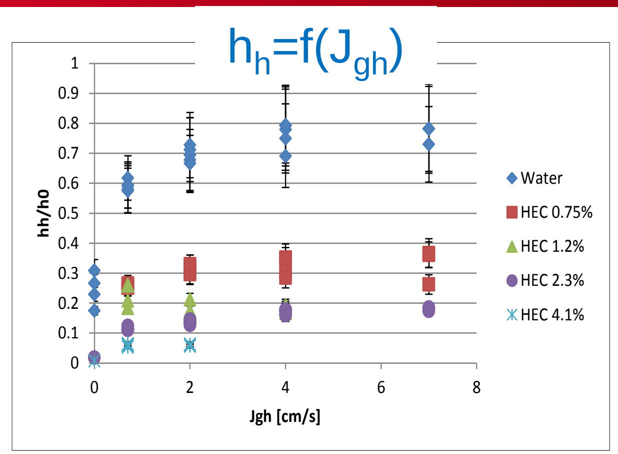
HEAT TRANSFER DISTRIBUTION

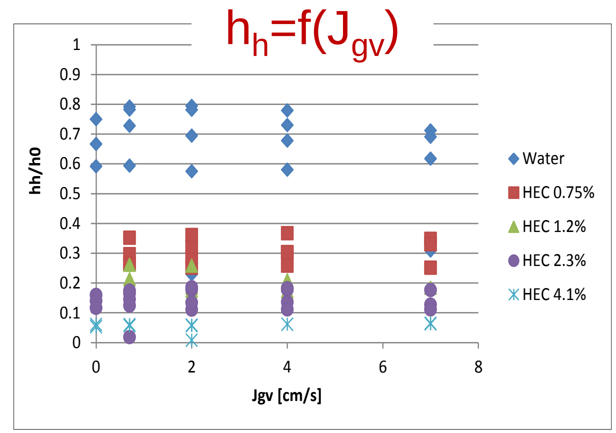


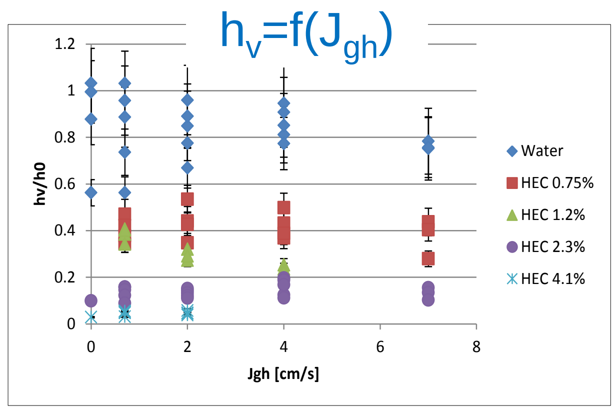
- Horizontal heat transfer coefficient (h_h) is almost constant along the horizontal wall
- Vertical heat transfer coefficient (h_v) is more important in the half upper part (h_{v2}) of the vertical wall than in the lower one (h_{v1}) and the increase of J_{gv} increases this difference
- For the same gas velocities conditions, the increase of concentration implies a decrease of heat transfer along all the walls
- The increase of HEC concentration implies a decrease of the h_v/h_h ratio, regardless of the gas injection rate(s)

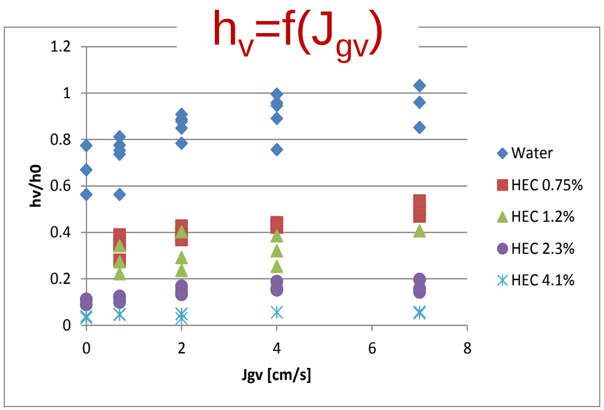
INFLUENCE OF GAS VELOCITY











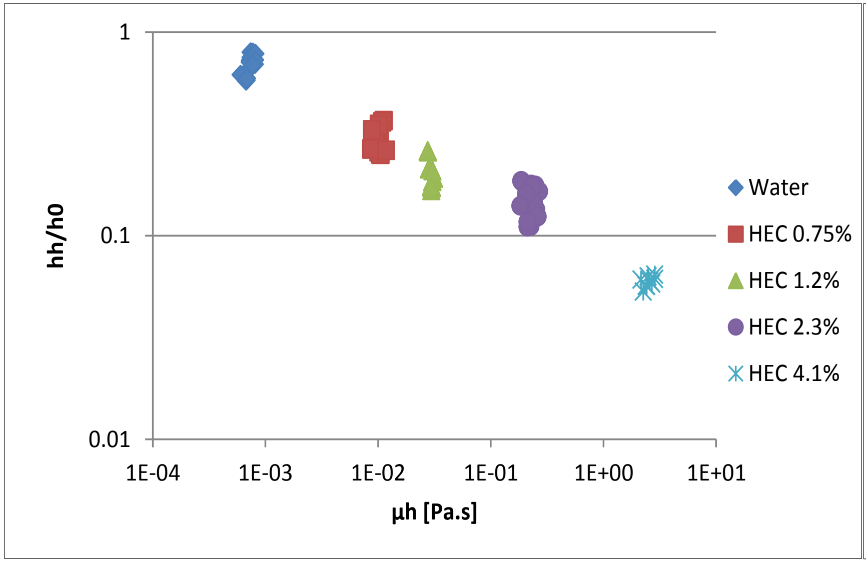
- Heat transfer increases with decreasing HEC concentration (viscosity)
- Heat transfer increases with the increase of the **local** gas velocity (no clear influence on the heat transfer along the opposite walls)
- The increase of h_h with J_{gh} seems to plateau out (same observation in Journeau & Haquet [2009])

INFLUENCE OF VISCOSITY

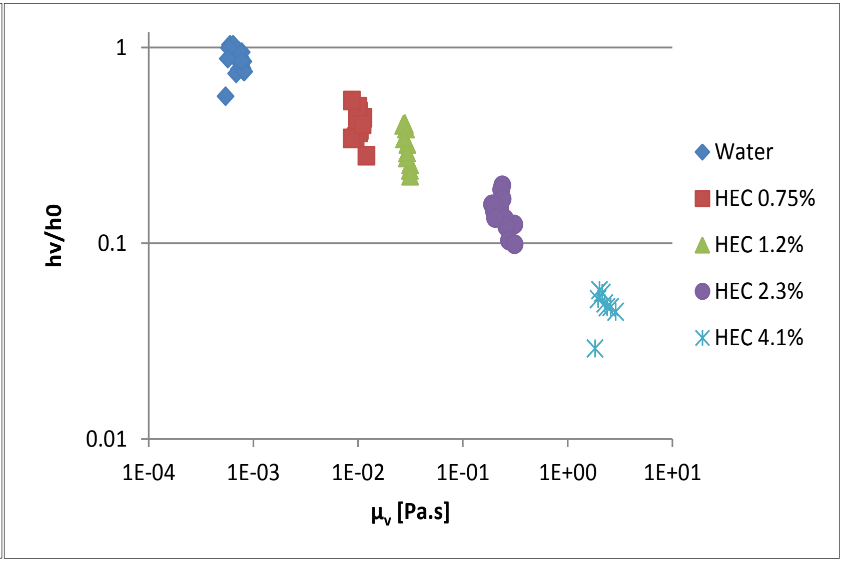
Ostwald fluid: $\mu = K\dot{\gamma}^{n-1}$ with average shear stress: $\dot{\gamma} = \left(\frac{g\rho j_g}{K}\right)^{\frac{1}{n+1}}$ (Sánchez Pérez et al. [2006])

$\mu_h = f(J_{gh})$ for horizontal heat transfer, $\mu_v = f(j_{gv})$ for vertical heat transfer

HORIZONTAL

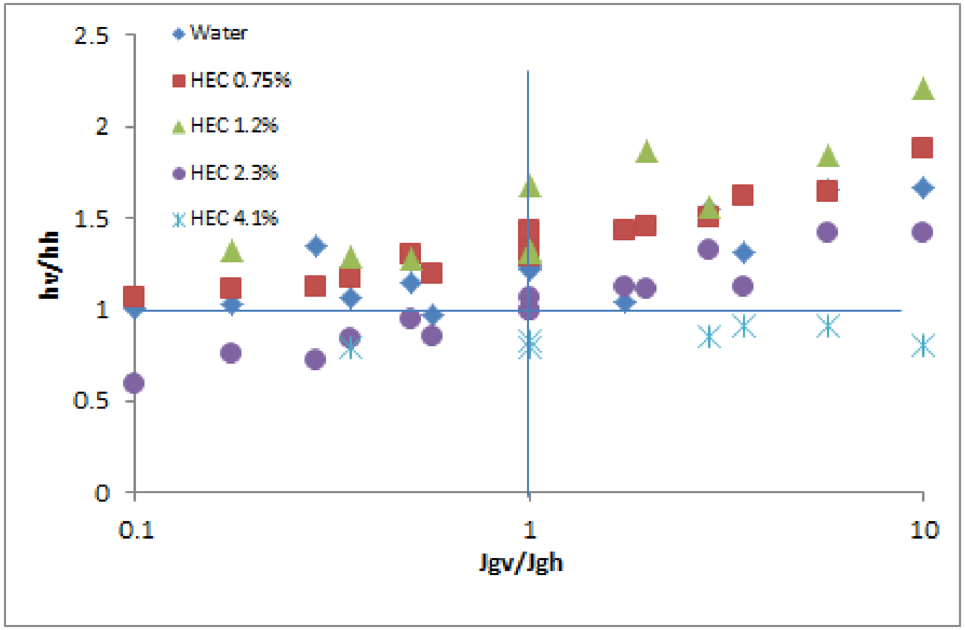


VERTICAL



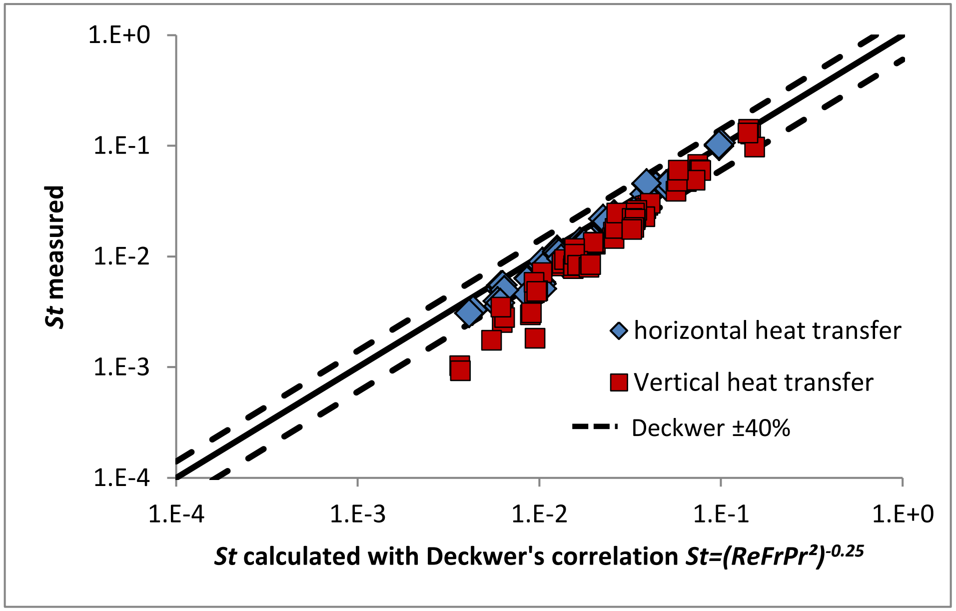
- Strong influence of the fluid viscosity: heat transfer decreases with increasing viscosity in a form of a power law

h_v/h_h RATIO VS. J_{gv}/J_{gh} RATIO



- The ratio ranges between 0.5 and 2 → no important anisotropy observed.
- The ratio increases whatever the viscosity: heat transfer promoted laterally when J_{gv}/J_{gh} increases
- For the 3 lowest viscosities, the ratio is between 1 and 2: heat exchange is slightly promoted laterally.
- For the most viscous fluids, the ratio can be below 1: heat is preferably transferred through the bottom wall.

COMPARISON TO DECKWER'S CORRELATION



For small Stanton numbers, which globally corresponds to high viscosities, the Deckwer correlation overestimates heat transfer. Several possible explanations:

- Does not take into account the sources of creation of turbulence (bubble injection)
- Kolmogorov turbulent dissipation law not suitable for wall non-turbulent viscous flow
- Validity of this model questionable for very low and very high Pr numbers
- Possible presence of a gas film wall
- Model developed for bubble column (no lateral injection)

PROPOSITION OF NEW CORRELATIONS

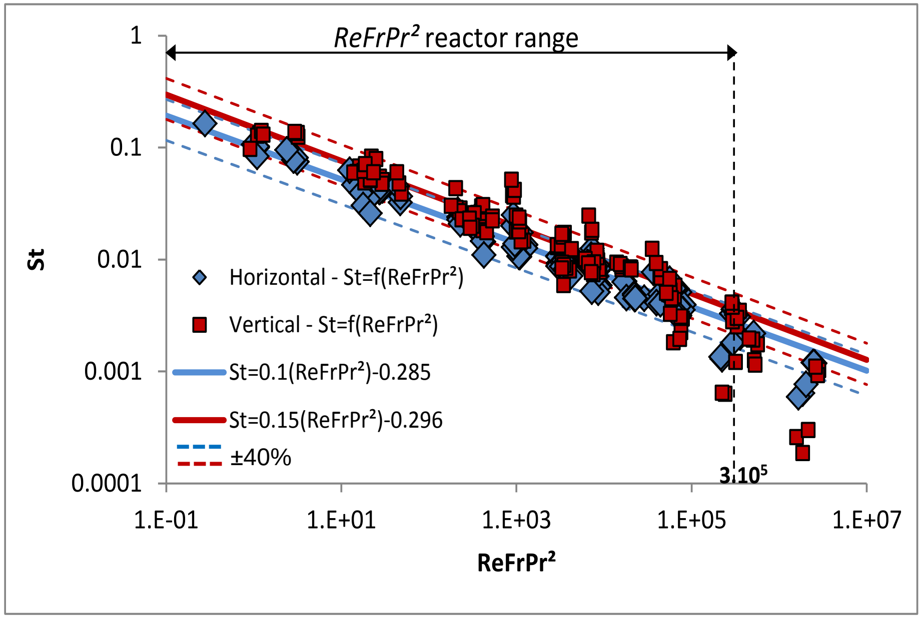
- Proposition of 2 new correlations :

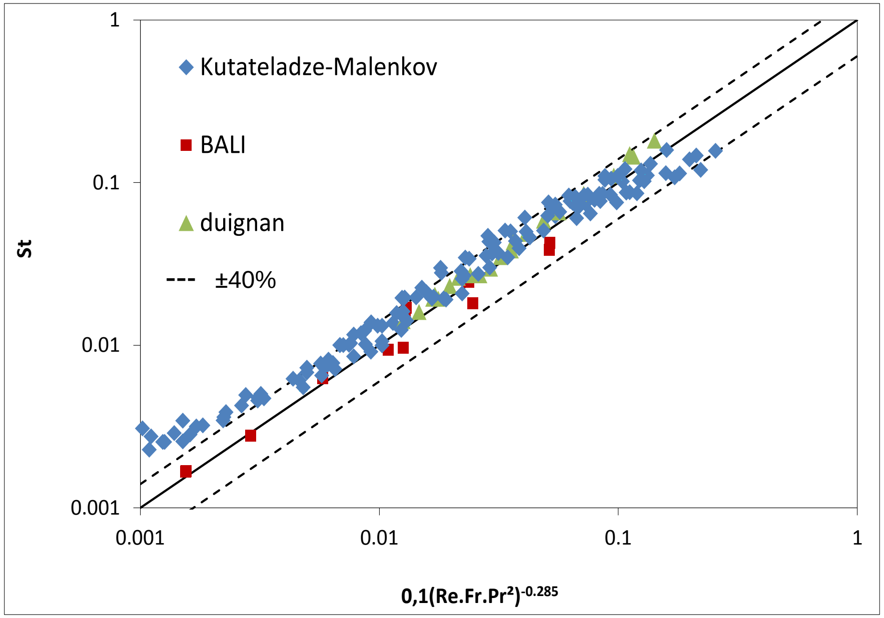
  $St=0.1(ReFrPr^2)^{-0.285}$ for the heat transfer at the bottom wall

  $St=0.15(ReFrPr^2)^{-0.296}$ for the heat transfer at the lateral wall

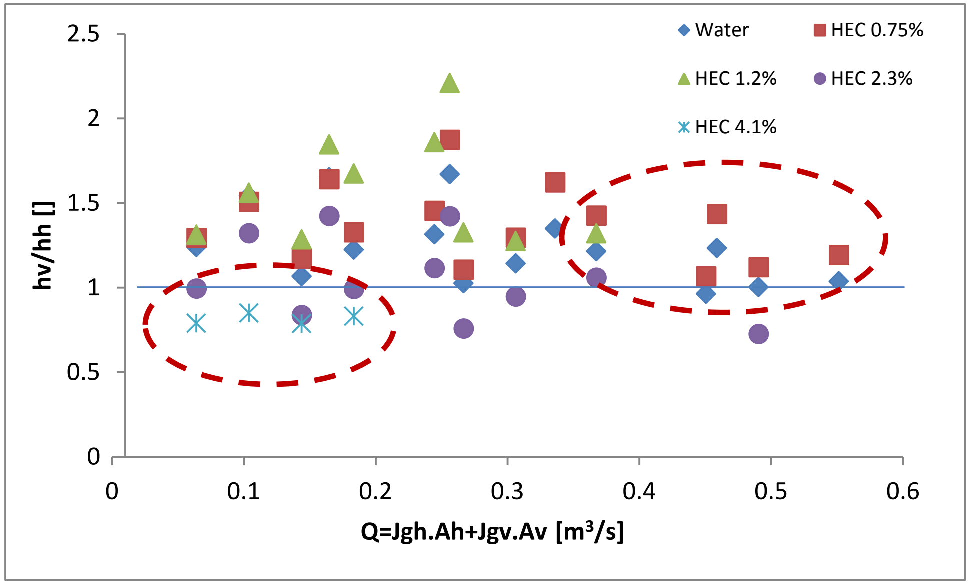
- Better agreement but still discrepancies for high $ReFrPr^2$ numbers

- Comparison with literature data → good agreement





COMPARISON WITH EXPERIMENTS WITH PROTOTYPICAL MATERIALS



Experiments with prototypical materials | **CLARA**

LCS concrete → high J_g & low μ
Isotropic trend

h_v/h_h slightly higher than 1
Slight anisotropic trend

Siliceous concrete → low J_g & high μ
Anisotropic trend

h_v/h_h slightly lower than 1
Heat transfer slightly promoted at the bottom

Trends in CLARA are different from those observed in prototypical corium pools experiments
→ Convection in a bubbly more or less viscous pool is not the predominant mechanism in MCCI
→ Behavior of interfaces (crusts?) ?

CONCLUSIONS AND PROSPECTS

Phenomenology

- Heat flux distribution: homogeneous heat transfer along the bottom wall, more important in the upper region of the lateral wall than in the lower one
- Predominant influence of increasing viscosity on heat transfer with a decrease in the form of a power law
- Much more limited and local influence of the gas velocity on the heat exchange (which increases with increasing gas flow-rate)
- Lateral heat exchange promoted for the lowest viscosities while heat is preferably transferred at the bottom for the most viscous fluids

Modelling

- Insufficient agreement between the CLARA results and Deckwer correlation
- Proposition of two new correlations showing better agreement with experimental data:

$St=0.1(ReFrPr^2)^{-0.285}$ for the heat transfer at the bottom wall

$St=0.15(ReFrPr^2)^{-0.296}$ for the heat transfer at the lateral wall

CONCLUSIONS AND PROSPECTS

Comparison with the prototypical materials experiments

- Exhibition of opposite behaviors between experiments with prototypical materials and the CLARA tests showing that heat transferred by convection is not the predominant mechanism leading to ablation trends

Possible prospects

- Further CLARA experiments with velocity measurements or enhanced visualization would lead to a better representation of the fluids circulation patterns
- A better knowledge of phenomena occurring at the interface (crusts) is required
- Possible improvement of the proposed correlations by taking into account all the involved phenomena (sources of turbulence creation, lateral injection, phenomenology in viscous fluids, …)
- Possibility to adapt the CLARA facility to investigate other phenomena: stratification, top quenching, focusing effect,…

Thank you for your attention

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VISCOSITY & REACTOR RANGE

Viscosity

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	K (Pa.s^n)				n-1			
	22°C	42°C	K=aT+b		22°C	42°C	n-1=cT+d	
			a	b			c	d
Water	0.001	0.0006	-0.00002	0.00144	0	0	0	0
HEC 0.75%	0.017	0.008	-0.00045	0.0269	-0.03	-0.01	0.001	-0.052
HEC 1.2%	0.061	0.03	-0.00155	0.0951	-0.07	-0.06	0.0005	-0.081
HEC 2.3%	0.58	0.27	-0.0155	0.921	-0.17	-0.12	0.0025	-0.225
HEC 4.1%	6.2	2.5	-0.185	10.27	-0.32	-0.24	0.004	-0.408
HEC 8%	28	13	-0.75	44.5	-0.46	-0.36	0.005	-0.57

μ_h=f(J_{gh}) for horizontal heat transfer, μ_v=f(j_{gv}) for vertical heat transfer. μ_h and μ_v don't vary much.

Reactor range

- The maximum corium density is ρ =8000 kg/m^3
- The maximum corium viscosity is μ=1 Pa.s
- The maximum superficial gas velocity is Jg=0.1 m/s
- The maximum corium heat capacity is cp=1200 J/kg/K
- The minimum corium heat conductivity is k=2 W/m/K

As ReFrPr² can be rewritten ρ.μ.Jg^3.cp²/g/k², the maximum value of ReFrPr² on the reactor range is then about 3.10^5.