

# Scale problem of the liquid metal reactors



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New reactor concepts and safety analyses for the Polish Nuclear Energy Program  
POWR.03.02.00-00.I005/17

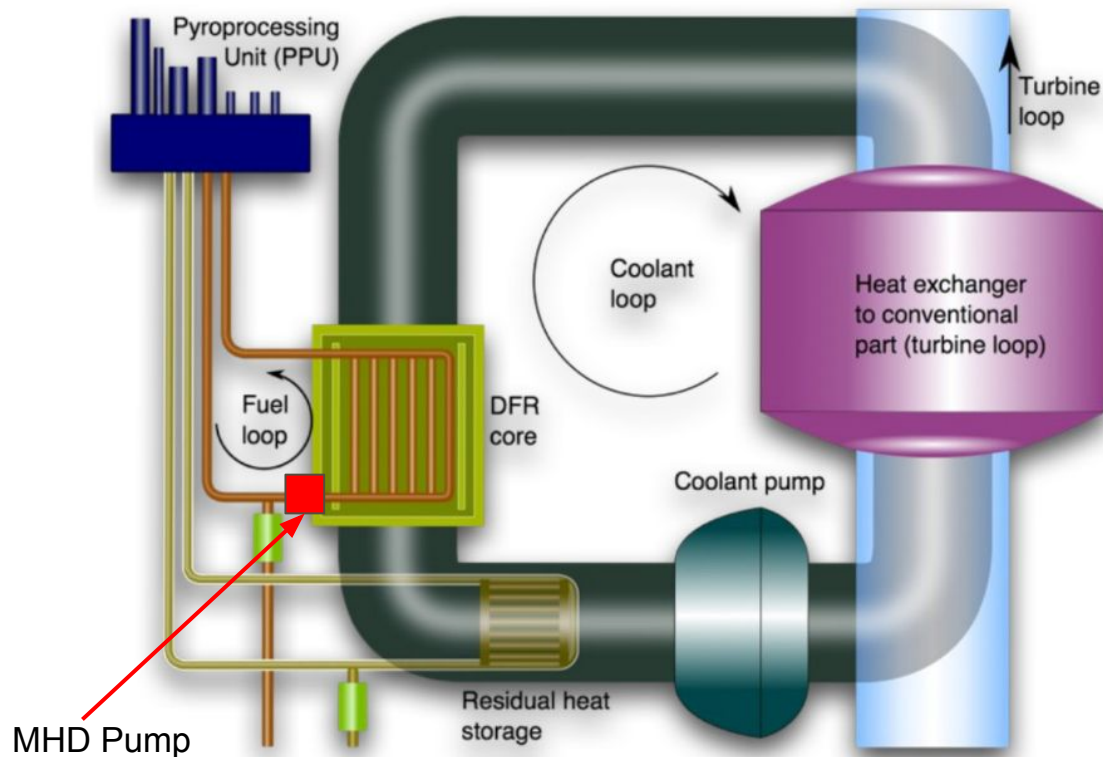


# Agenda

- Introduction
- Microdemonstator
- Cathare-2 software
- Dimensionless numbers
- Results for micro- and minidemonstrator
- Summary

# Dual Fluid Reactor

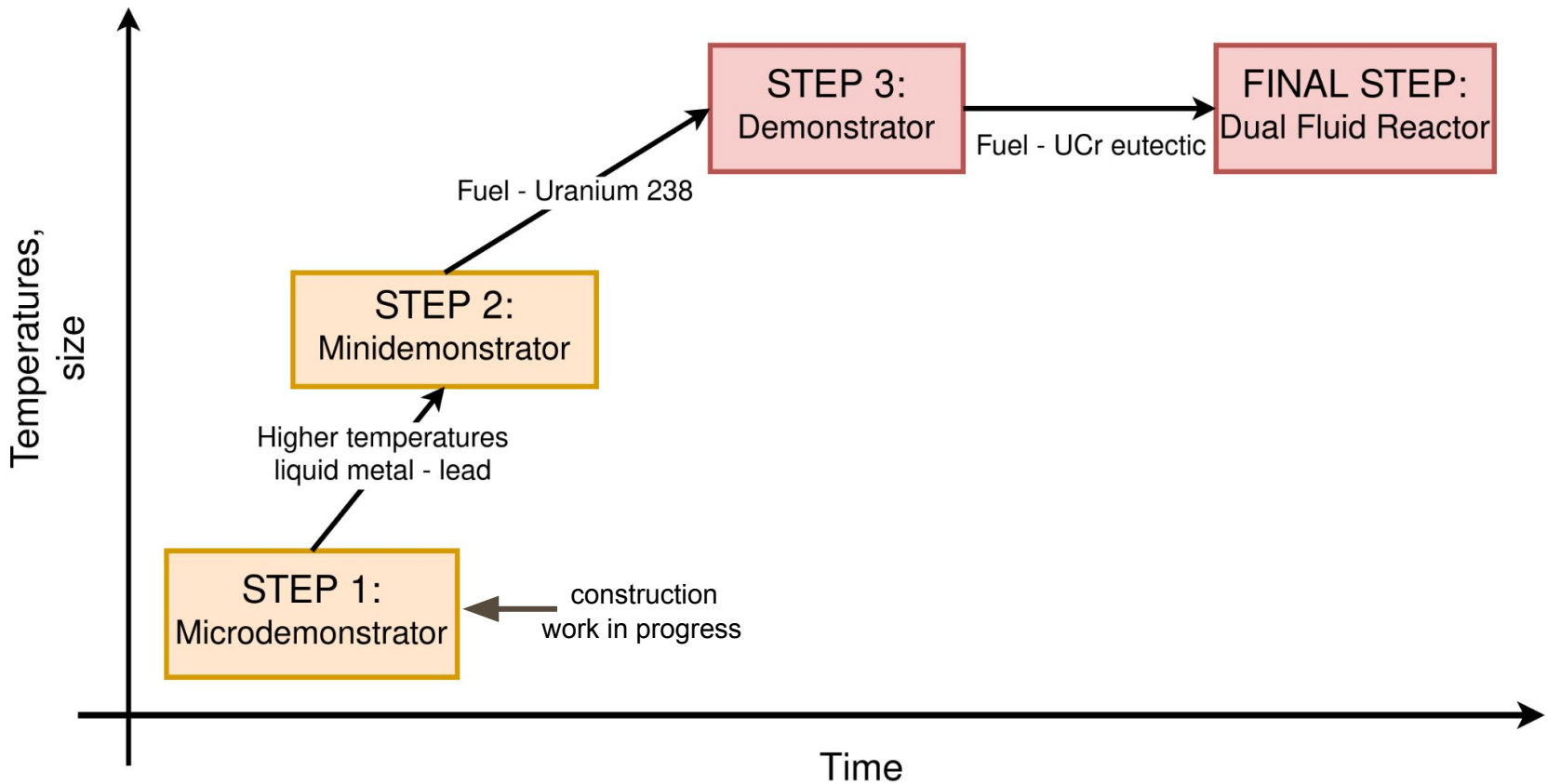
- The design of the DFR combines the molten salt reactor concept with that of a liquid-metal cooled reactor
- The fuel is a liquid metal or molten salt
- The coolant is lead



Dual Fluid Reactor [1]



# Steps



## CONCEPTUAL REPORT

### DUAL LOOP EXPERIMENT - CONCEPT DESCRIPTION

VERSION: 0.20

- Work has begun at NCBJ on the design and construction of a microdemonstrator
- The design was based on the TALL-3D loop only scaled down
- The purpose of the loop is to study the heat transfer between two loops of liquid metal



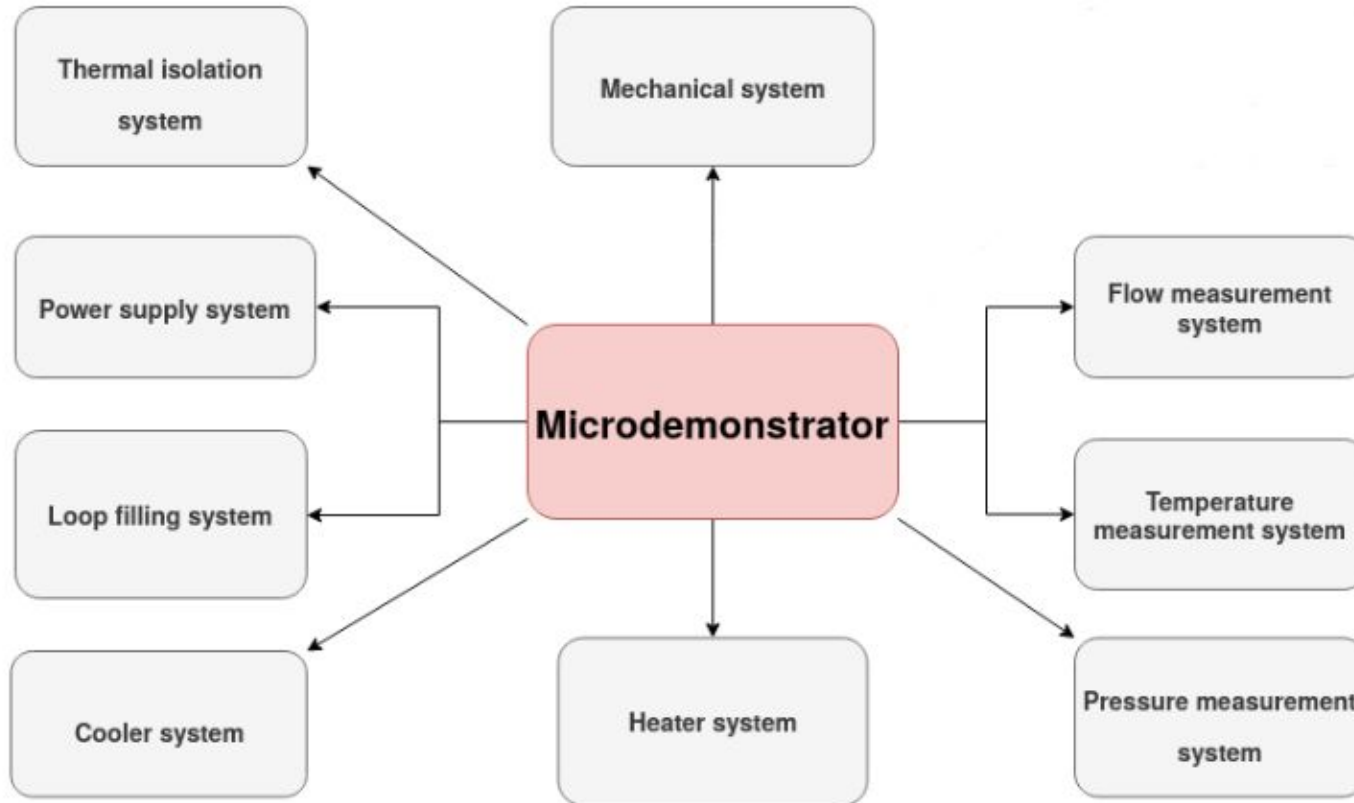
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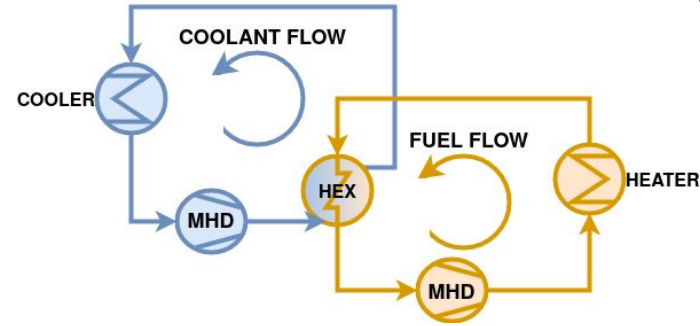
# Diagram of the systems needed to design the microdemonstrator





# Microdemonstrator

- Two loops - fuel and coolant
- Liquid metal - lead bismuth eutectic
- Low temperatures
- Two additional elements - heater and cooler



Microdemonstrator scheme

Microdemonstrator	Minidemonstrator	Demonstrator	DFR
Fuel loop: lead - bismuth eutectic	Fuel loop: lead	Fuel loop: uranium 238	Fuel loop: uranium - chromium eutectic
Coolant loop: lead - bismuth	Coolant loop: lead	Coolant loop: lead	Coolant loop: lead
Low temperatures	Higher temperatures	Highest temperatures	Highest temperatures





# Hypotheses

- Using the microdemonstrator, it is possible to estimate the parameters for the minidemonstrator and then for the demonstrator and DFR.
- Reactivity and heat transfer in DFR is controlled by liquid metal flow in reactor core.



# Cathare-2 software

- CATHARE (Code for Analysis of Thermalhydraulics during an Accident of Reactor and safety Evaluation)
- is a two-phase thermal-hydraulic simulator in development since 1979 at CEA-Grenoble as part of an agreement between the CEA, EDF, AREVA and the IRSN
- The CATHARE2 simulator has a modular structure capable of operating in 0D, 1D or 3D
- It is capable of modelling any type of reactor (PWR, RBMK, VVER, etc.)



# Equations in Cathare-2

- The software is based on a two-phase model with **six equations** (conservation of mass, energy and quantity of movement for each phase)

## 5.3.2 Momentum balance equations

$$\begin{aligned}
 & A \cdot \alpha_k \cdot \rho_k \left[ \frac{\partial V_k}{\partial t} + V_k \frac{\partial V_k}{\partial z} \right] + A \cdot \alpha_k \frac{\partial P}{\partial z} + A \cdot P_i \frac{\partial \alpha_k}{\partial z} \\
 & + (-1)^k A \cdot \beta \alpha (1 - \alpha) \rho_m \left[ \frac{\partial V_G}{\partial t} - \frac{\partial V_L}{\partial t} + V_G \frac{\partial V_G}{\partial z} - V_L \frac{\partial V_L}{\partial z} \right] \quad \text{added mass term} \\
 & = (-1)^k A \cdot \Gamma (W_i - V_k) \quad \text{interfacial momentum transfer} \\
 & \quad - (-1)^k A \cdot \tau_i \quad \text{interfacial friction} \\
 & \quad - \chi_f \cdot C_k \frac{\rho_k}{2} V_k |V_k| \quad \text{wall regular friction} \\
 & \quad - A \frac{K}{2\Delta Z} \alpha_k \cdot \rho_k \cdot V_k \cdot |V_k| \quad \text{singular friction} \\
 & \quad + A \cdot \alpha_k \cdot \rho_k \cdot g_z \quad \text{gravity force} \\
 & \quad + \frac{R(1 - \alpha_k)}{4} \cdot P_i \cdot \frac{\partial A}{\partial z} \quad \text{stratification term} \\
 & \quad + SM_k \quad \text{source term}
 \end{aligned}$$

## 5.3.3 Energy balance equations

$$\begin{aligned}
 & A \frac{\partial}{\partial t} \left( \alpha_k \rho_k \left[ H_k + \frac{V_k^2}{2} \right] \right) + \frac{\partial}{\partial z} \left( A \alpha_k \rho_k V_k \left[ H_k + \frac{V_k^2}{2} \right] \right) - A \alpha_k \frac{\partial P}{\partial t} \\
 & = A q_{ke} + \chi_c q_{pk} + (-1)^k A \Gamma \left[ H_k + \frac{W_i^2}{2} \right] + A \alpha_k \rho_k V_k g_z + SE_k
 \end{aligned}$$

### 5.3.1.1 Liquid and gas mass balance equation

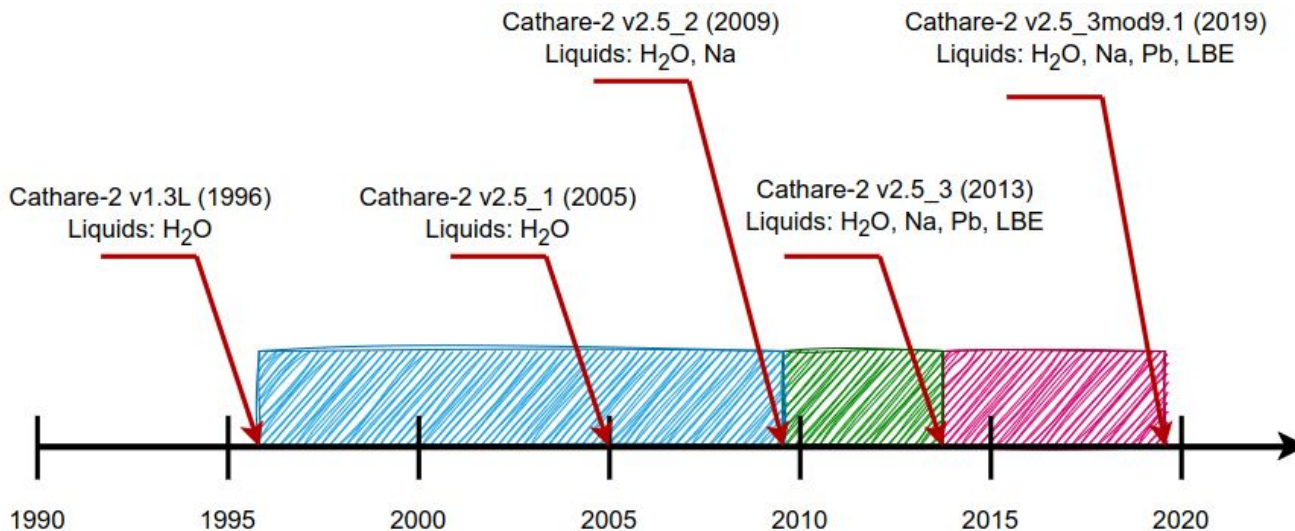
$$\frac{\partial}{\partial t} (A \cdot \alpha_k \cdot \rho_k) + \frac{\partial}{\partial z} (A \cdot \alpha_k \cdot \rho_k \cdot V_k) = (-1)^k \cdot A \cdot \Gamma + S_k$$

where  $k = 0$  for the liquid and  $k = 1$  for the gas.  $\Gamma$  is the mass transfer at the interface ( $\Gamma = -\Gamma_L = \Gamma_G$ )



# Review of the application of Cathare-2 software to liquid metals

Liquid metal	Article	Experiment	Year
Lead-bismuth	Polidori et al.	NACIE LBE-cooled facility (*Cathare-HLM)	2012
Sodium	Anderhuber et al.	GR19 Sodium boiling experiments	2015
Sodium	Alpy et al.	Cathare-2 and SABENA code validation	2016
Sodium	Bubelis et al.	ASTRID like reactor	2017





# Why are we use dimensionless numbers?

- Dimensionless numbers are unitless coefficients, which are used to describe and compare physical systems.
- If the coefficients for the two different models are identical, they can then be considered to be similar to each other.

# Dimensionless numbers

Name	Standard symbol	Definition	Field of application
Archimedes number	Ar	$Ar = \frac{gL^3 \rho_\ell (\rho - \rho_\ell)}{\mu^2}$	fluid mechanics (motion of fluids due to density differences)
Atwood number	A	$A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$	fluid mechanics (onset of instabilities in fluid mixtures due to density differences)
Bejan number (fluid mechanics)	Be	$Be = \frac{\Delta PL^2}{\mu \alpha}$	fluid mechanics (dimensionless pressure drop along a channel) <sup>[3]</sup>
Bingham number	Bm	$Bm = \frac{\tau_y L}{\mu V}$	fluid mechanics, rheology (ratio of yield stress to viscous stress) <sup>[4]</sup>
Biot number	Bi	$Bi = \frac{hL_C}{k_b}$	heat transfer (surface vs. volume conductivity of solids)
Blake number	Bl or B	$B = \frac{u \rho}{\mu(1 - \epsilon)D}$	geology, fluid mechanics, porous media (inertial over viscous forces in fluid flow through porous media)

Bond number	Bo	$Bo = \frac{\rho a L^2}{\gamma}$	geology, fluid mechanics, porous media (buoyant versus capillary forces, similar to the Eötvös number) <sup>[5]</sup>
Brinkman number	Br	$Br = \frac{\mu U^2}{\kappa(T_w - T_0)}$	heat transfer, fluid mechanics (conduction from a wall to a viscous fluid)
Brownell–Katz number	N <sub>BK</sub>	$N_{BK} = \frac{u \mu}{k_{rw} \sigma}$	fluid mechanics (combination of capillary number and Bond number) <sup>[6]</sup>
Capillary number	Ca	$Ca = \frac{\mu V}{\gamma}$	porous media, fluid mechanics (viscous forces versus surface tension)
Chandrasekhar number	C	$C = \frac{B^2 L^2}{\mu_o \mu D_M}$	hydromagnetics (Lorentz force versus viscosity)
Colburn J factors	J <sub>M</sub> , J <sub>H</sub> , J <sub>D</sub>		turbulence; heat, mass, and momentum transfer (dimensionless transfer coefficients)



# Physical phenomena

- Since there are a lot of dimensionless numbers, it was decided to choose the physical phenomena that are most interesting in demonstrators.
- Some of the types of phenomena chosen are flow phenomena: viscosity of fluids, interaction of internal forces
- Thermohydraulic phenomena were also selected: such as convection and thermal conductivity phenomena



# Selected dimensionless numbers

- Reynolds number (**Re**) - fluid mechanics - ratio of inertia forces and fluid viscosity

$$Re = \frac{\rho v L}{\mu}$$

- Euler number (**Eu**) - hydrodynamics - stream pressure as a function of inertial forces

$$Eu = \frac{\Delta P}{\rho v^2}$$

- Prandtl number (**Pr**) - heat transfer - ratio of viscosity diffusion rate to thermal conduction rate

$$Pr = \frac{c_p \cdot \mu}{k}$$

- Nusselt number (**Nu**) - forced convection - ratio of convective to conductive heat transfer

$$Nu = \frac{h \cdot d}{k}$$





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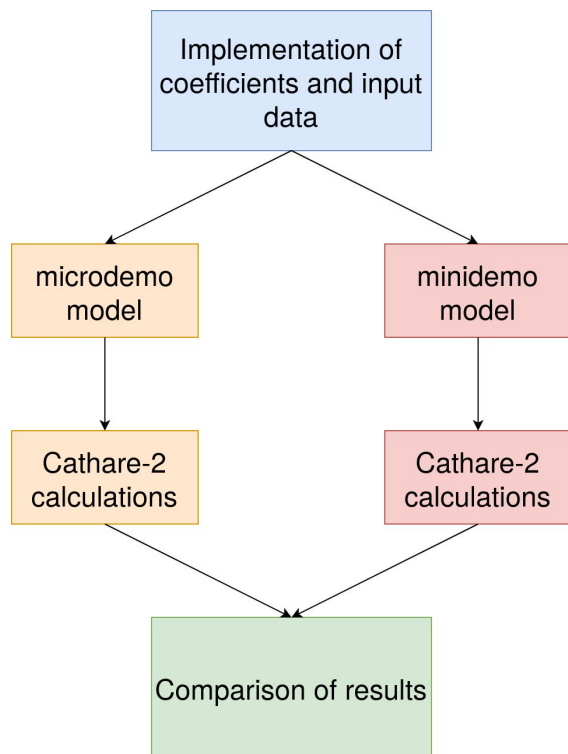
$$Pr = \frac{c_p \cdot \mu}{k}$$

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$$Nu = \frac{h \cdot d}{k}$$



# Simplified calculation algorithm



- At the beginning, input files are prepared
- For the microdemonstrator and minidemonstrator, there can be up to 50 models generated for each model.
- Then the calculations are performed in Cathare-2 on the supercomputer
- Finally, output files and charts are generated



# Demonstrators configurations

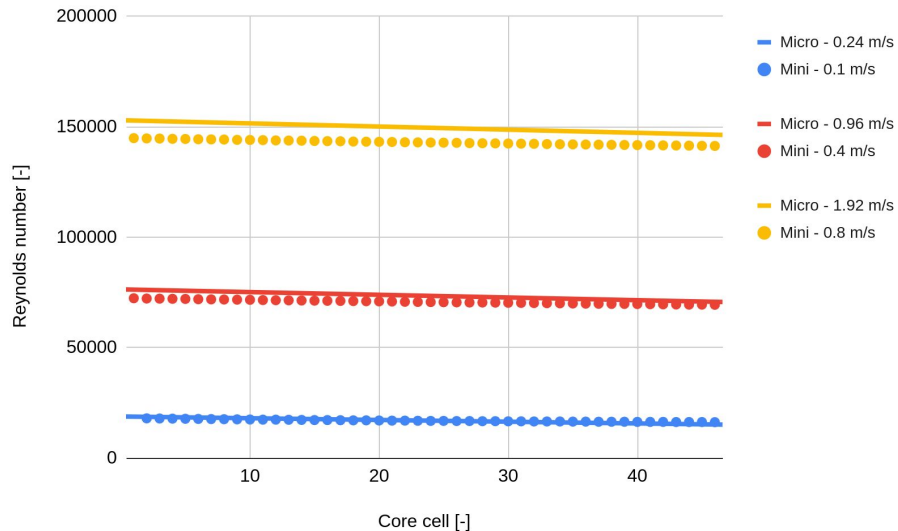
Parameters where Reynolds number is similar between demonstrators

	Microdemonstrator	Minidemonstrator
Velocity range $\left[\frac{m}{s}\right]$	0.24 - 1.92 <sub>(20)</sub>	0.1 - 0.8 <sub>(20)</sub>
Pipe diameter [m]	0.0704	0.0465
Pipe height [m]	0.5	0.5

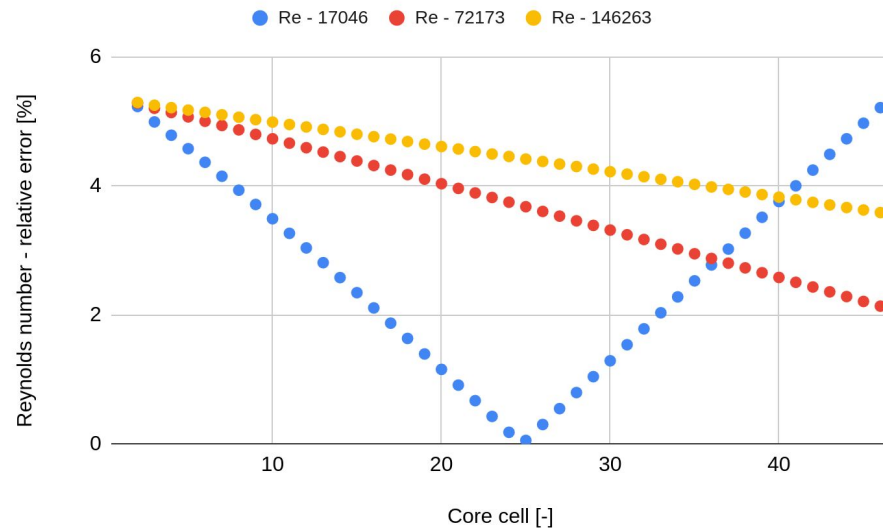
Parameters where Nusselt number is similar between demonstrators

	Microdemonstrator	Minidemonstrator
Velocity range $\left[\frac{m}{s}\right]$	0.1 - 0.8 <sub>(20)</sub>	0.1 - 0.8 <sub>(20)</sub>
Pipe diameter [m]	0.0279	0.0465
Pipe height [m]	0.5	0.5

# Results for the first configuration of demonstrators (similar Reynolds numbers)



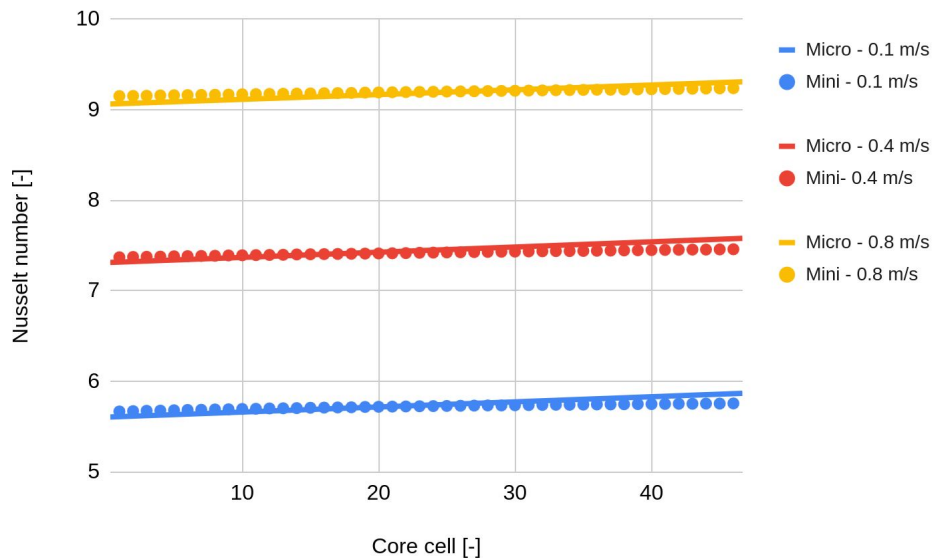
Characterisation of the Reynolds number  
for the computing cell of the core



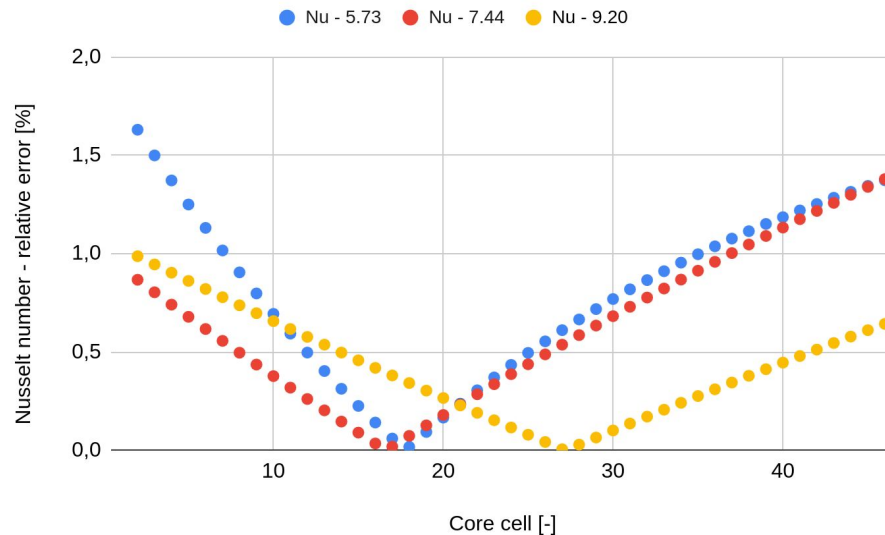
Characterisation of the relative error for the  
computing cell of the core



# Results for the second configuration of demonstrators (similar Nusselt numbers)



Characterisation of the Nusselt number for  
the computing cell of the core



Characterisation of the relative error for the  
computing cell of the core

Results for case where Reynolds number is similar between demonstrators

Reynolds [-]	$\mu$ DEMO flow rate [ $\cdot 10^{-3} \frac{m^3}{s}$ ]	mDEMO flow rate [ $\cdot 10^{-3} \frac{m^3}{s}$ ]
17046	0.389	0.170
72173	1.557	0.679
146263	3.114	1.359

Results for case where Nusselt number is similar between demonstrators

Nusselt [-]	$\mu$ DEMO flow rate [ $\cdot 10^{-3} \frac{m^3}{s}$ ]	mDEMO flow rate [ $\cdot 10^{-3} \frac{m^3}{s}$ ]
5.73	0.061	0.170
7.44	0.245	0.679
9.20	0.489	1.359



# Scalability of forced convection between models

$$Nu^{\mu} \cong Nu^m$$

$$\frac{h^{\mu} d^{\mu}}{k^{\mu}} = \frac{h^m d^m}{k^m}$$

$$h = \frac{Fc}{\Delta T}$$

$$\frac{Fc^{\mu}}{\Delta T^{\mu}} \cdot \frac{d^{\mu}}{k^{\mu}} = \frac{Fc^m}{\Delta T^m} \cdot \frac{d^m}{k^m}$$

## Symbols:

Fc - force convection

d - characteristic length

T - temperature

k - thermal conductivity

h - thermal coefficient

## Subscripts:

μ - referring to μDEMO

m - referring to mDEMO





# Scalability of forced convection between models

$$F_{c^{\mu}} = \frac{d^m}{d^{\mu}} \cdot \frac{T^{\mu}}{T^m} \cdot \frac{k^{\mu}}{k^m} \cdot F_{c^m}$$
$$F_{c^m} = \frac{d^{\mu}}{d^m} \cdot \frac{T^m}{T^{\mu}} \cdot \frac{k^m}{k^{\mu}} \cdot F_{c^{\mu}}$$

$$F_{c^{\mu}} = c \cdot \frac{d^m}{d^{\mu}} \cdot \frac{k^{\mu}}{k^m} \cdot F_{c^m}$$
$$F_{c^m} = \frac{1}{c} \cdot \frac{d^{\mu}}{d^m} \cdot \frac{k^m}{k^{\mu}} \cdot F_{c^{\mu}}$$

## Symbols:

F<sub>c</sub> - force convection

d - characteristic length

T - temperature

k - thermal conductivity

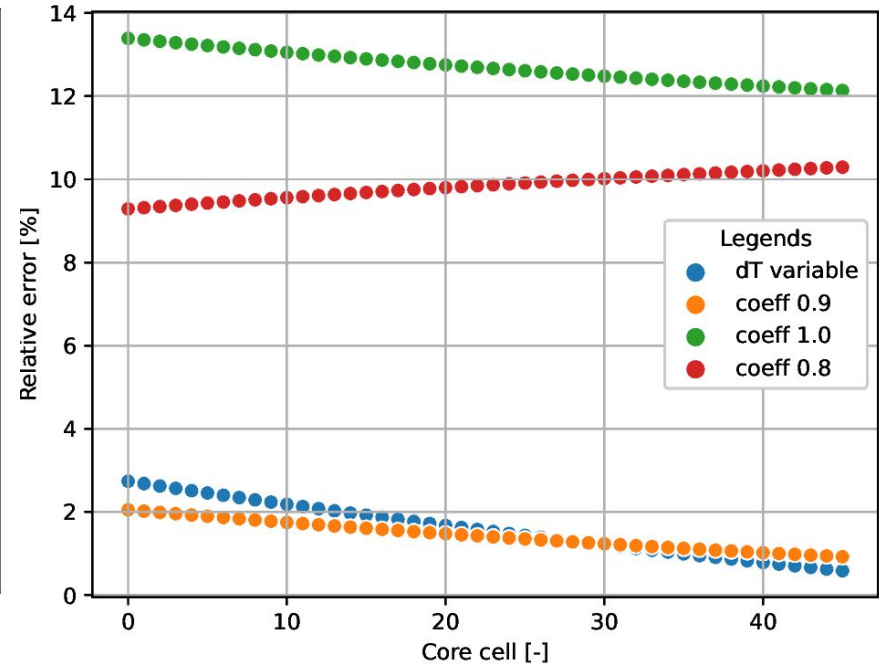
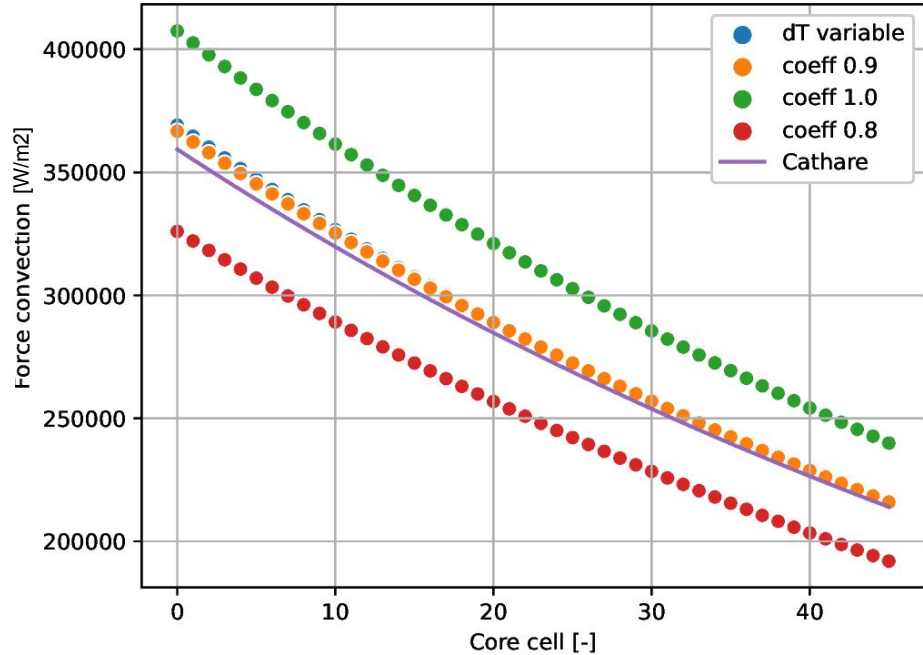
c - temperature ratio coefficient

## Subscripts:

μ - referring to μDEMO

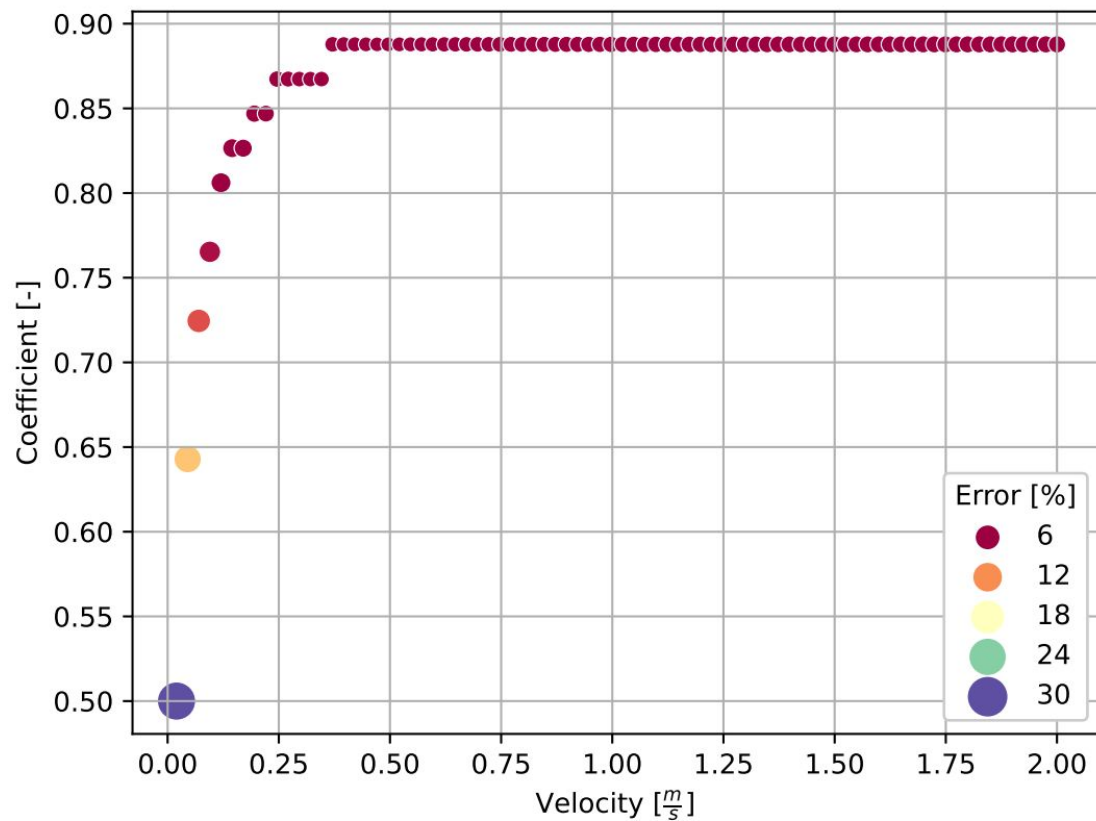
m - referring to mDEMO

# Results for velocity 0.5 m/s





# Characterization of the temperatures ratio to velocity of liquid metal





# Summary

- Micro- and minidemonstrator are based on different temperatures and liquid metals
- The parameters that can be controlled in the calculation to achieve similar Reynolds or Nusselt numbers are core width and flow velocity, the other parameters are related to material properties.
- It is impossible to obtain similarity for both dimensionless numbers at the same time.
- Since the most interesting phenomenon is heat transfer between loops, the similarity of Nusselt numbers is more important than the similarity of Reynolds numbers.
- By using the Nusselt number, it was successful in scaling forced convection between the two models.

## Scale problem of the liquid metal reactors

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### Abstract

The DFR concept is an innovative idea for a nuclear reactor that consists of two loops containing liquid metals. The metallic version (mDFR) would utilize uranium-chromium eutectic as fuel, while the cooling loop would employ liquid lead. Before a DFR can be constructed, the various milestones of the micro and minidemonstrator must be completed. These devices are smaller and do not operate on fissile fuel, however, the results obtained on these devices could be projected onto the reactor itself.

Using dimensionless numbers and Cathare-2 software, a comparative analysis was performed between the demonstrators and compared to the DFR concept. The analysis was performed for different core geometries and for different liquid metal velocities; however, the Nusselt numbers between demonstrators were similar.

**Keywords:** Dual Fluid Reactor, Dimensionless numbers, Cathare-2 software

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# PhD thesis: REACTIVITY CONTROL BY THE PUMPING SYSTEM IN THE DUAL FLUID REACTOR

1. Introduction
  - 1.1. Research background
  - 1.2. Research motivation
2. Theoretical background
  - 2.1. Dual Fluid Reactor
  - 2.2. Demonstrators
  - 2.3. Thermal hydraulics
  - 2.4. Dimensionless number
  - 2.5. Liquid metal magnetohydrodynamics
  - 2.6. Magnetohydrodynamic pumps
3. Methodology
  - 3.1. Single phase flow
  - 3.2. Cathare-2 software
  - 3.3. Equivalent Circuit Methods
  - 3.4. Meta-heuristic algorithms
  - 3.5. Simulated annealing
  - 3.6. Multivariate regression
4. Results
  - 4.1. Demonstrators hydraulic calculations
    - 4.1.1. Cathare-2 models
    - 4.1.2. Similarity of Nusselt numbers
    - 4.1.3. Control of heat exchange via a pumping system
  - 4.2. Magnetohydrodynamic pump optimization
    - 4.2.1. Validation of the ECM
    - 4.2.2. Optimization
    - 4.2.3. Multivariate regression
    - 4.2.4. Flow velocity dependence
5. Conclusions and discussions

# Thank you for attention



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