Studying the micro- and minidemonstrator model in Cathare-2 software

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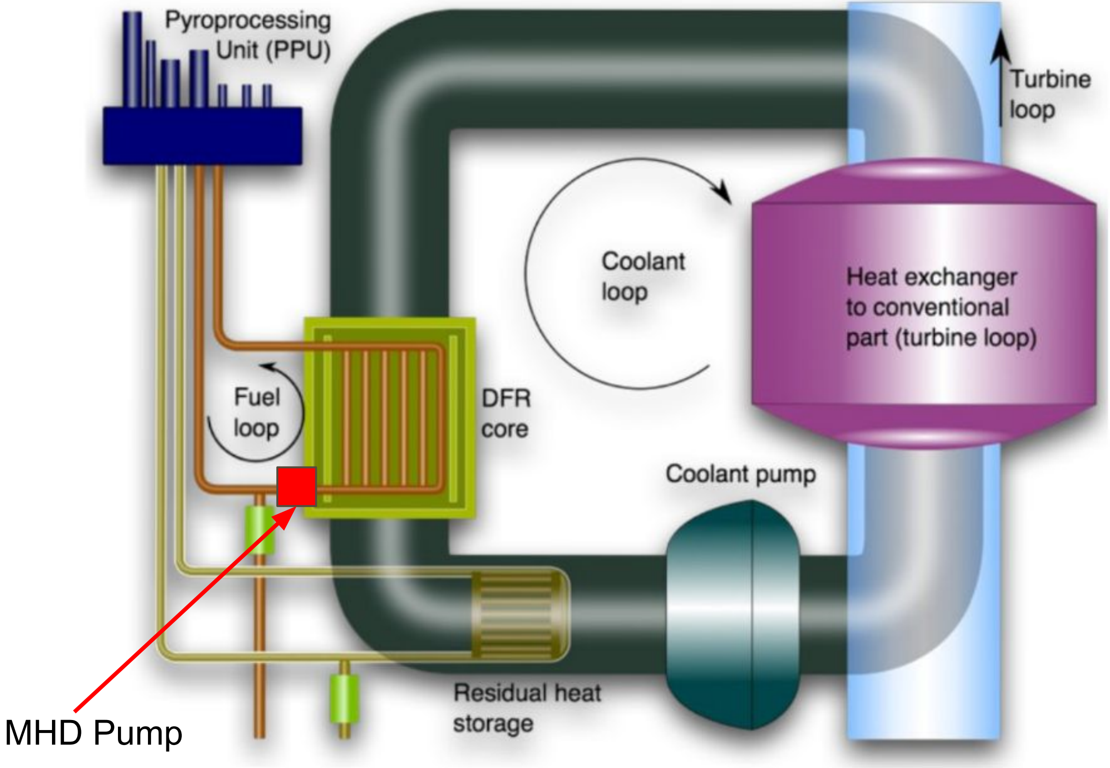
New reactor concepts and safety analyses for the Polish Nuclear Energy Program
POWR.03.02.00-00.I005/17

Agenda

- Introduction
- Microdemonstator
- Cathare-2 software
- Results for micro-minidemonstrator
- MHD pumps for micro- and minidemonstrator
- Summary

Dual Fluid Reactor

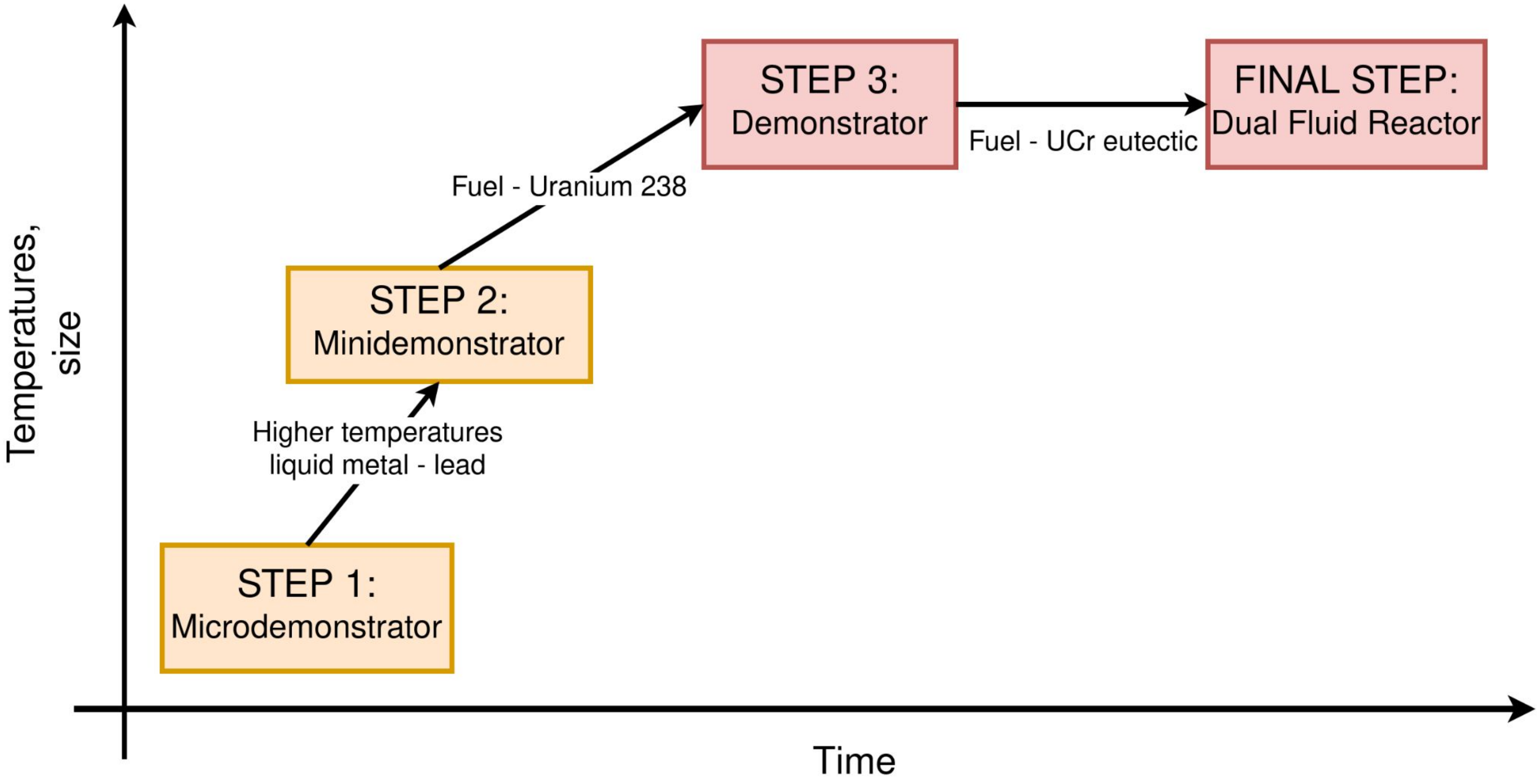
- The design of the DFR combines the molten salt reactor concept with that of a liquid-metal cooled reactor
- The fuel is a liquid metal or molten salt
- The coolant is lead



Dual Fluid Reactor [1]

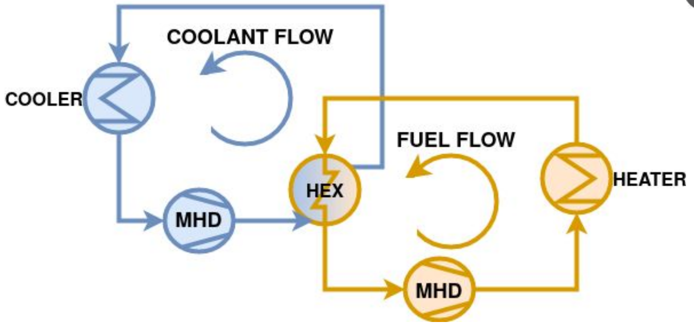
[1] Huke A., Ruprecht G., Weissbach D., Gottlieb S., Hussein A., Czerski K., The Dual Fluid Reactor – A novel concept for a fast nuclear reactor of high efficiency, Annals of Nuclear Energy 2015.

Steps


Temperatures, size
STEP 1: Microdemonstrator
Higher temperatures liquid metal - lead
STEP 2: Minidemonstrator
Fuel - Uranium 238
STEP 3: Demonstrator
Fuel - UCr eutectic
FINAL STEP: Dual Fluid Reactor
Time

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

Similarity numbers

- In order for the demonstrators not to be separate devices but to be successive stages of the DFR, it would be necessary to find a scale of similarity between the models.

- These similarity numbers could be, for example, Reynolds number, Prandtl number, and other dimensionless numbers

Hypotheses

- Using the microdemonstrator, it is possible to estimate the parameters for the minidemonstrator and then for the demonstrator and DFR.

- The magnetohydrodynamic pumps can perform the control and safety function in the DFR.

Goals

- Perform flow calculations for a micro and minidemonstrator.
- Examine how velocity affects heat transfer between loops in the micro- and minidemonstrator.
- Comparison of micro- and minidemonstrator results to find common characteristics
- Propose magnetohydrodynamic pump geometries for the micro- and minidemonstrator.

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.)

Source: https://tiny.pl/96cdr

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

$$A \cdot \alpha_k \cdot \rho_k \left[\frac{\partial V_k}{\partial t} + V_k \frac{\partial V_k}{\partial z} \right] + A \cdot \alpha_k \frac{\partial P}{\partial z} + A \cdot P_i \frac{\partial \alpha_k}{\partial z}$$

$$+(-1)^k A \cdot \beta\alpha(1-\alpha)\rho_m \left[\frac{\partial V_G}{\partial t} - \frac{\partial V_L}{\partial t} + V_G \frac{\partial V_G}{\partial z} - V_L \frac{\partial V_L}{\partial z} \right] \quad \text{added mass term}$$

$$= (-1)^k A \cdot \Gamma(W_i - V_k) \quad \text{interfacial momentum transfer}$$

$$-(-1)^k A \cdot \tau_i \quad \text{interfacial friction}$$

$$-\chi_f \cdot C_k \frac{\rho_k}{2} V_k |V_k| \quad \text{wall regular friction}$$

$$-A \frac{K}{2\Delta Z} \alpha_k \cdot \rho_k \cdot V_k \cdot |V_k| \quad \text{singular friction}$$

$$+A \cdot \alpha_k \cdot \rho_k \cdot g_z \quad \text{gravity force}$$

$$+\frac{R(1-\alpha_k)}{4} \cdot P_i \cdot \frac{\partial A}{\partial z} \quad \text{stratification term}$$

$$+SM_k \quad \text{source term} \qquad \text{(Eq. 5.3.5)}$$

5.3.3 Energy balance equations

$$A \frac{\partial}{\partial t} \left(\alpha_k \rho_k \left[H_k + \frac{V_k^2}{2} \right] \right) + \frac{\partial}{\partial z} \left(A \alpha_k \rho_k V_k \left[H_k + \frac{V_k^2}{2} \right] \right) - A \alpha_k \frac{\partial P}{\partial t}$$

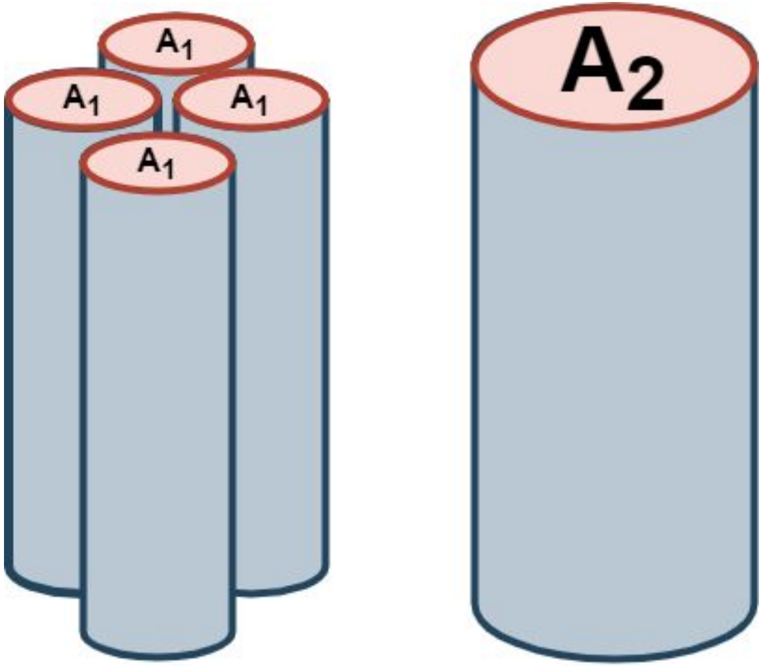
$$= A q_{ke} + \chi_c q_{pk} + (-1)^k A \Gamma \left[H_k + \frac{W_i^2}{2} \right] + A \alpha_k \rho_k V_k g_z + SE_k$$

Source: https://tiny.pl/96cdr

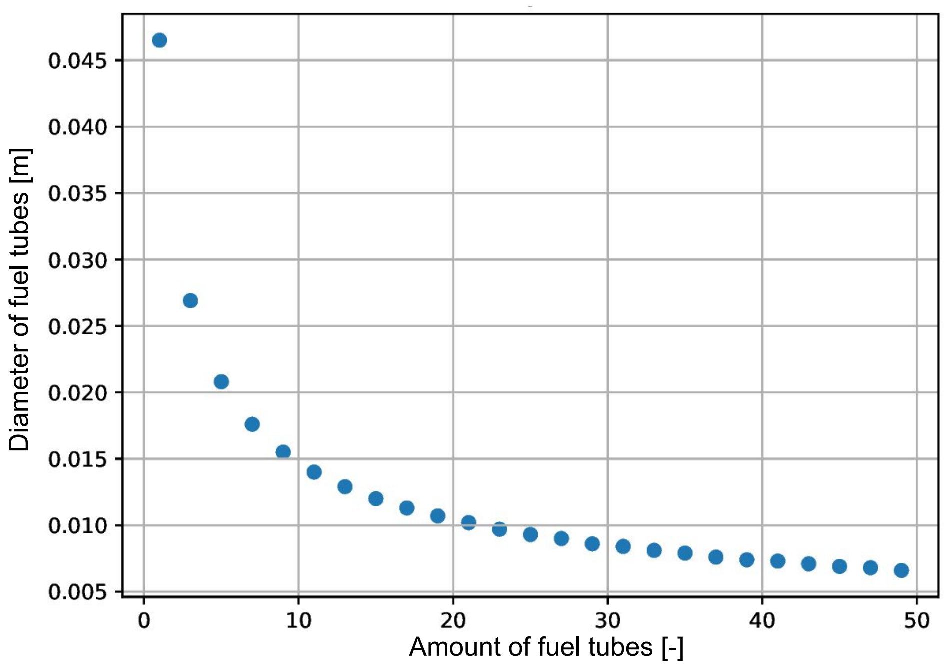
Micro- and minidemonstrator data

	Microdemonstrator	Minidemonstrator
Fuel inlet temperature [^{0}C]	400	1200
Coolant inlet temperature [^{0}C]	200	1000
Liquid metal	Lead - bismuth eutectic	Lead
Core height [m]	0.5	1.0
Fuel velocity range [m/s]	0.1 - 1.0	0.1 - 1.0
Fuel mass flow [kg/s]	0.321 - 3.207	1.888 - 18.881
Coolant mass flow [kg/s]	0.658	3.873

Relationship between diameter and amount of tubes

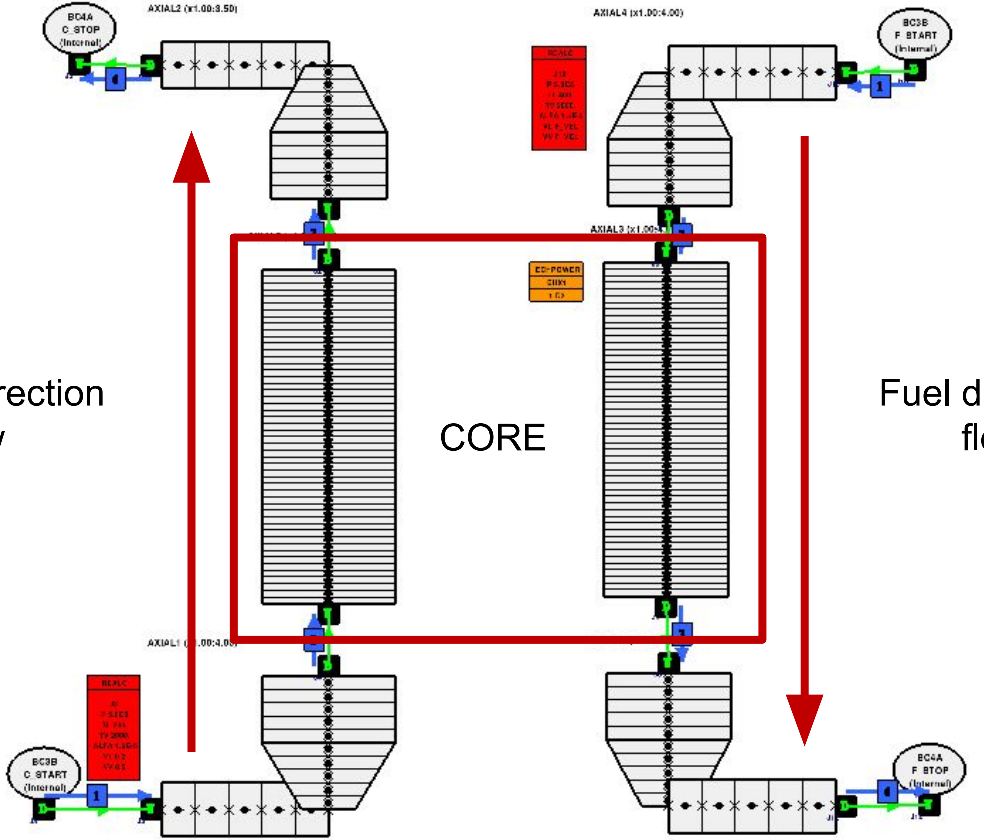


$$4 A_1 = A_2$$



Microdemonstrator CATHARE-2 scheme

Coolant direction flow

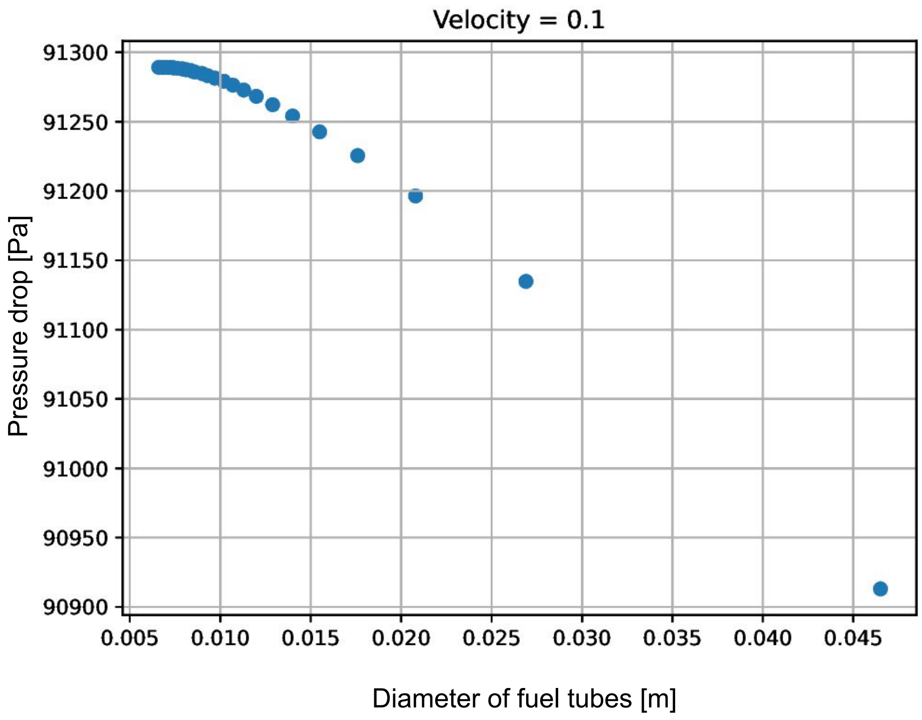


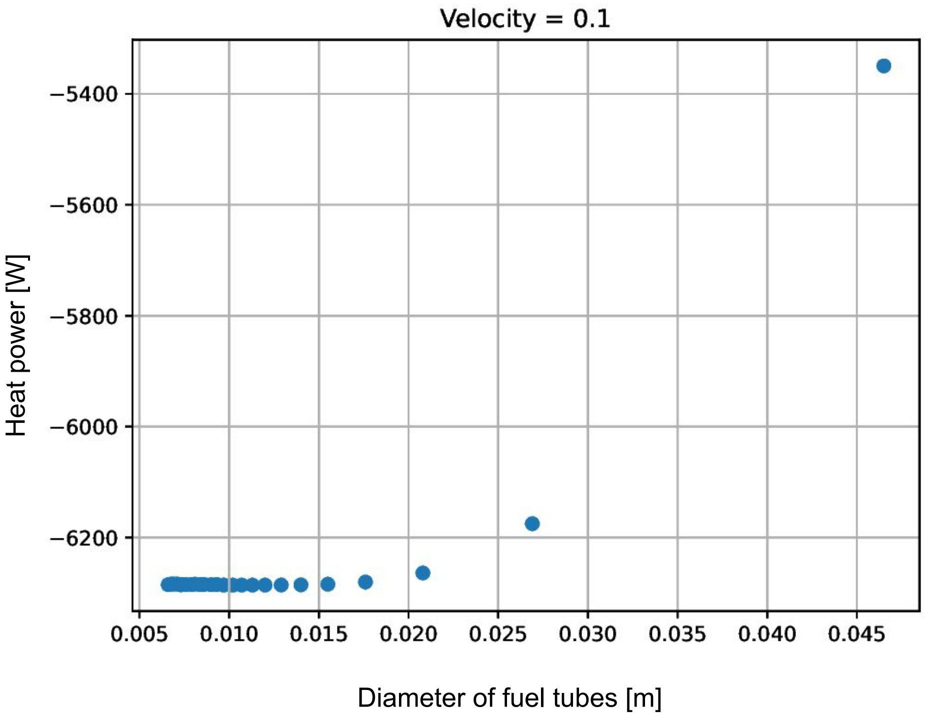
Fuel direction flow

1a. Perform flow calculations for a microdemonstrator.

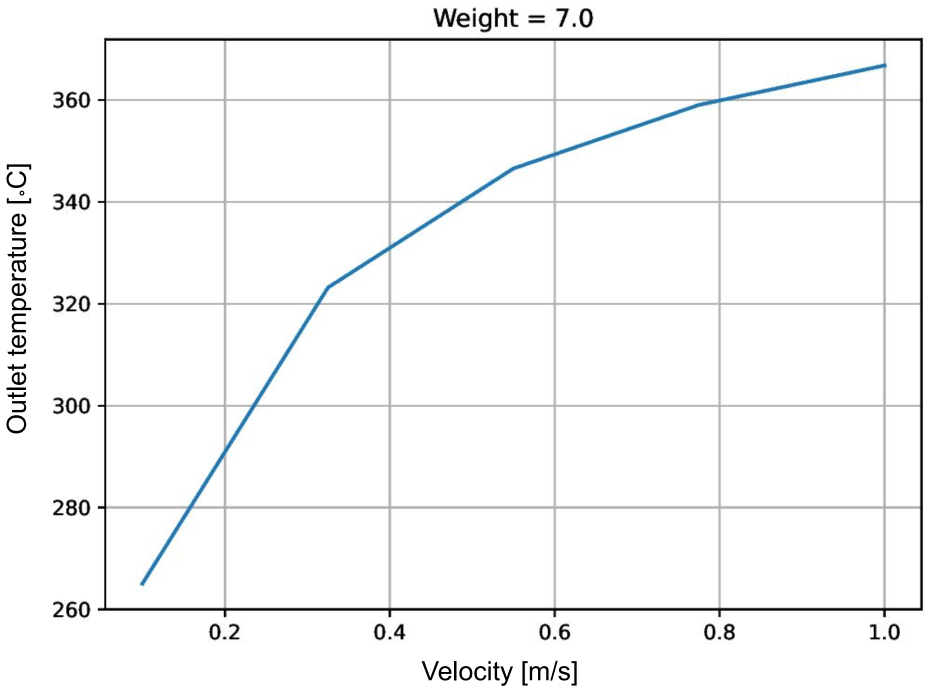
2a. Examine how velocity affects heat transfer between loops in the microdemonstrator.

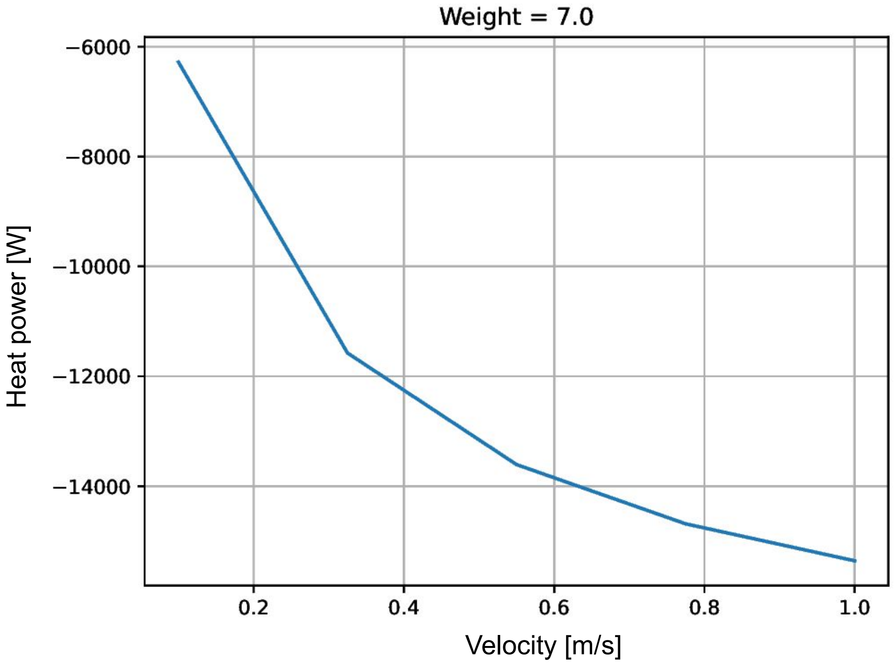
Perform flow calculations for a microdemonstrator





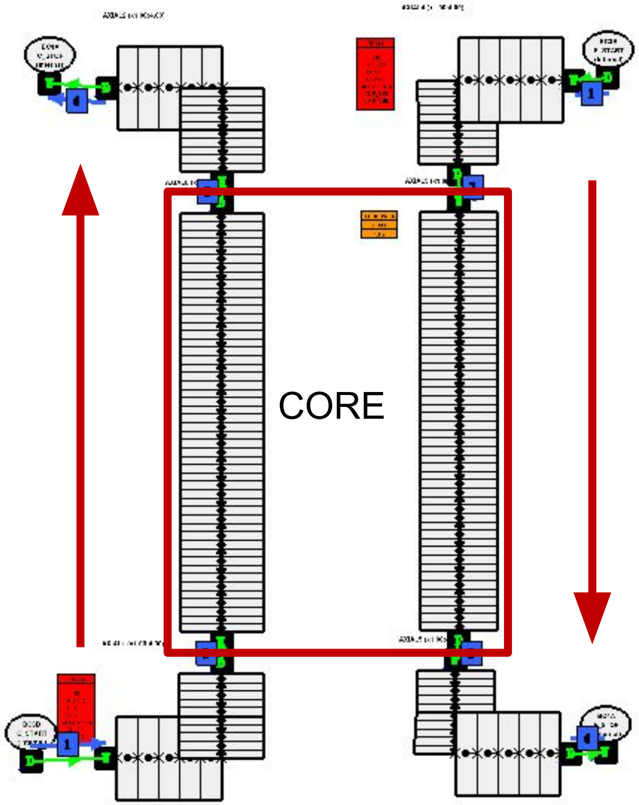
Examine how velocity affects heat transfer between loops in the microdemonstrator





Minidemonstrator CATHARE-2 scheme

Direction of coolant flow



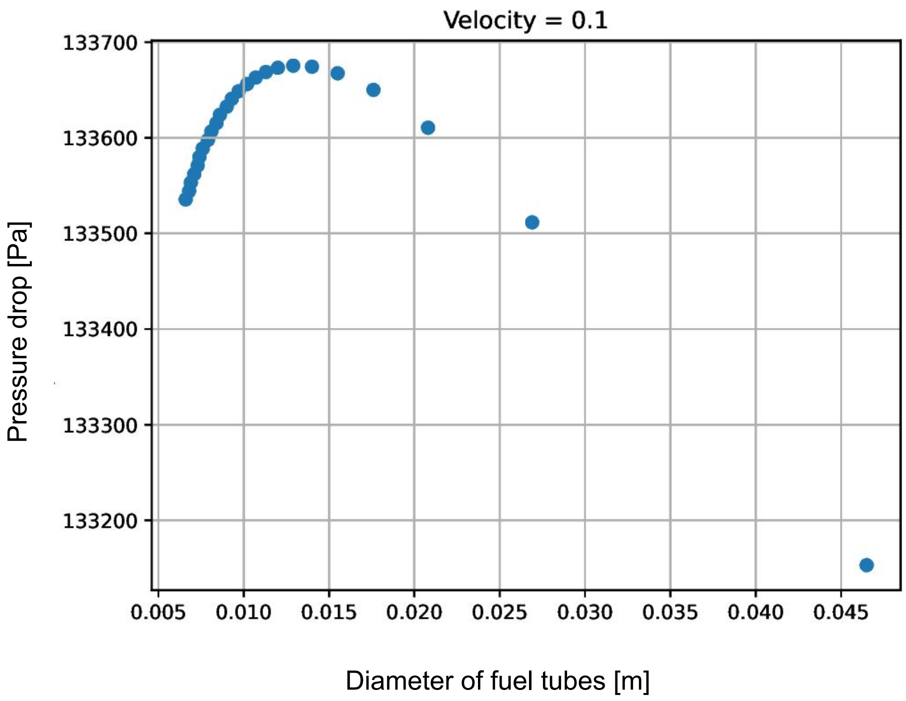
Direction of fuel flow

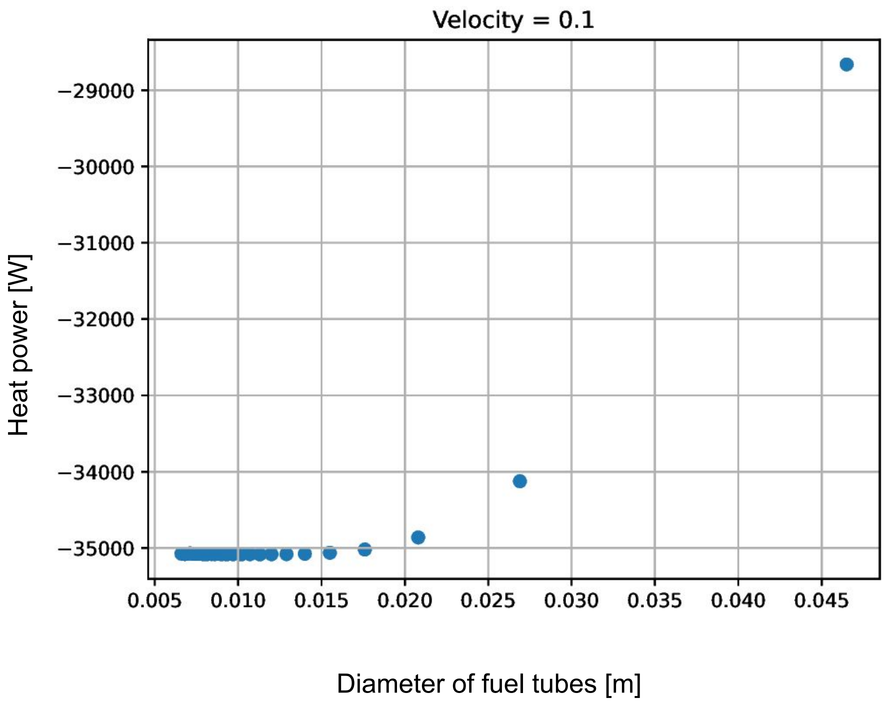
1b. Perform flow calculations for a minidemonstrator.

2b. Examine how velocity affects heat transfer between loops in the minidemonstrator.

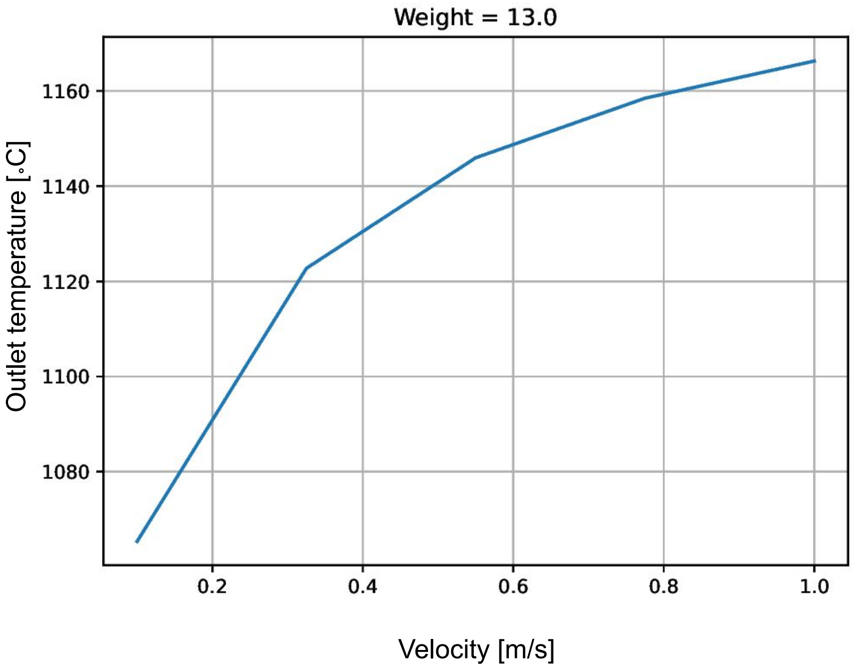
3. Comparison of micro- and minidemonstrator results to find common characteristics

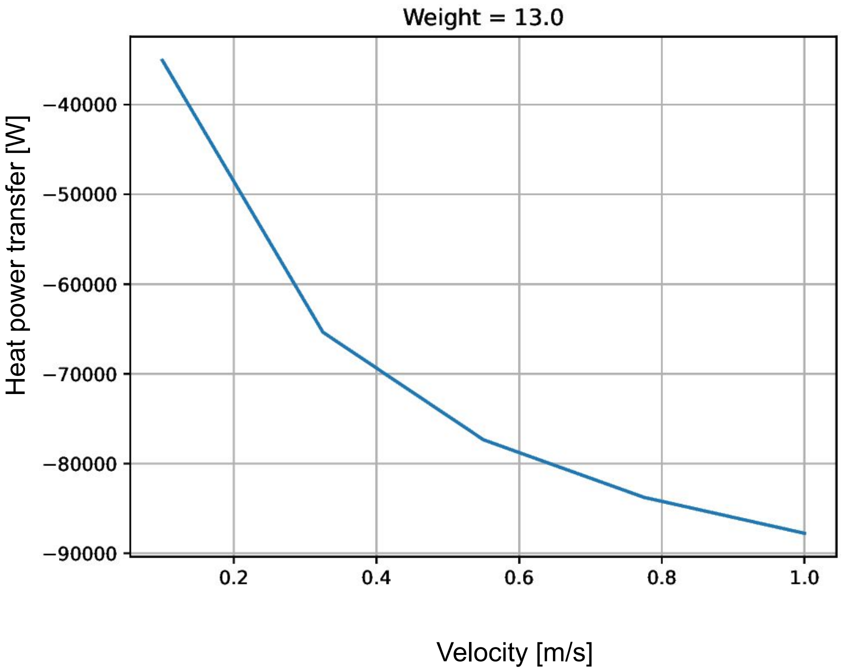
Perform flow calculations for a minidemonstrator



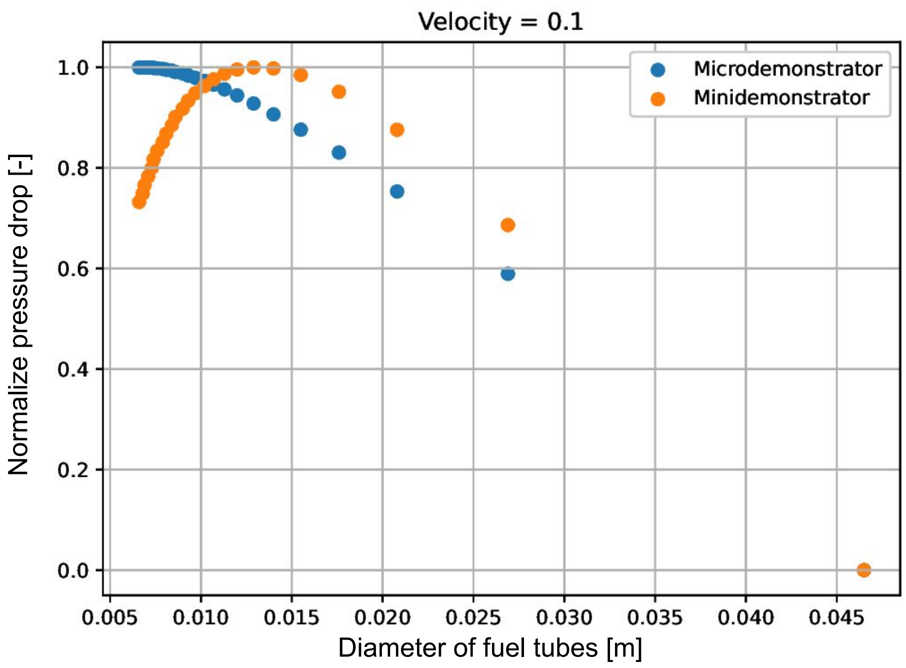


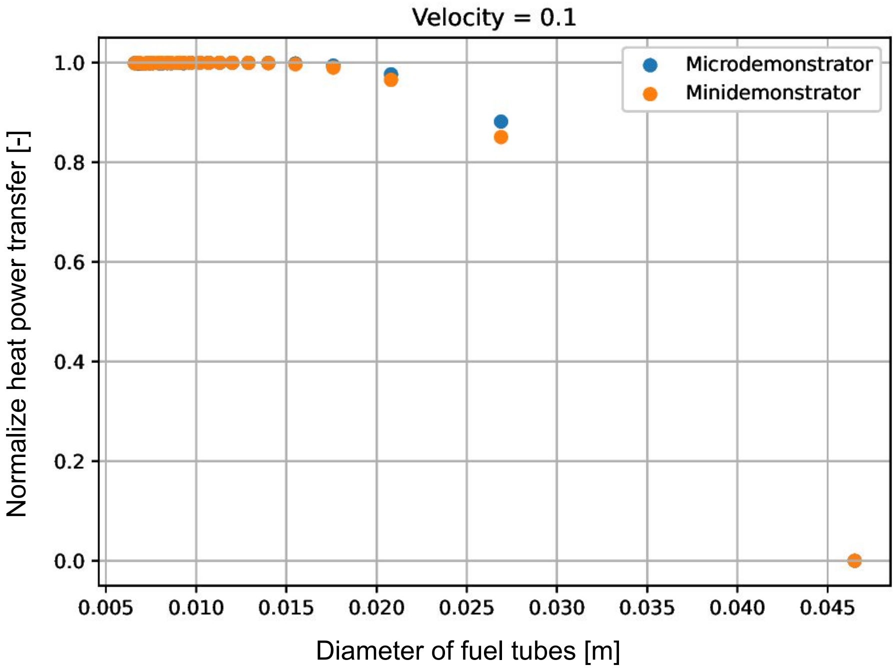
Examine how velocity affects heat transfer between loops in the minidemonstrator



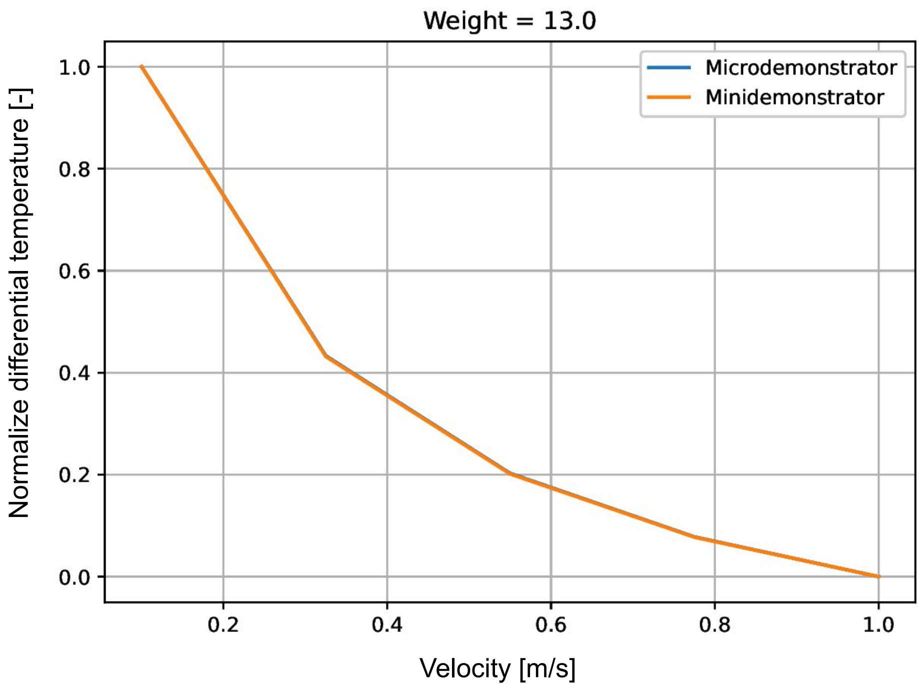


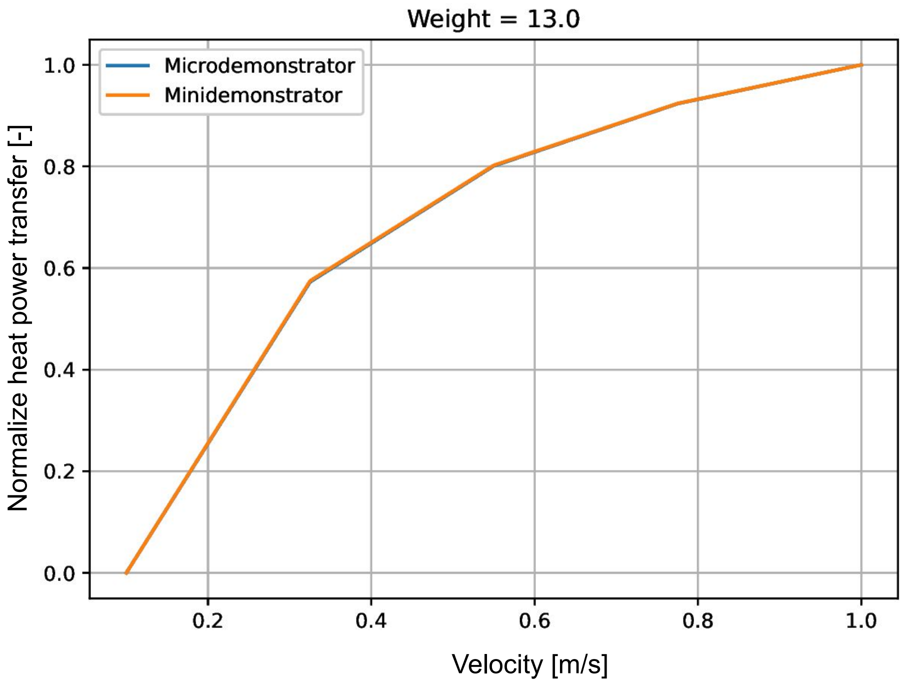
Comparison of micro- and minidemonstrator results to find common characteristics





Comparison of micro- and minidemonstrator results to find common characteristics





Results for micro- and minidemonstrator

	Microdemonstrator	Minidemonstrator
Fuel tubes diameter [m]	0.018	0.013
Heat power [W]	6280.33	35080.25
Pressure drop [Pa]	91225.47	133675.5
Fuel outlet temperature [^{0}C]	265.08	1065.38

4. Propose magnetohydrodynamic pump geometries for the micro- and minidemonstrator.

Optimization of the DC MHD PUMP

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Optimization of the DC magnetohydrodynamic pump for the Dual Fluid Reactor

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ABSTRACT

The metallic version of the Dual Fluid Reactor (DFR) utilizes a Uranium-Chromium liquid eutectic as fuel and liquid Lead as a coolant. The flow velocity of both liquids and their stable operating regime constitute the basic control parameters of the reactor and determine its operational safety. Against, high operating temperatures up to 1300 °C and severe corrosion of construction materials make magnetohydrodynamic pumps the ideal solution for DFR.

The paper focuses on modeling the DC magnetohydrodynamic pump using the analytical Equivalent Circuit Method completed by a metaheuristic approach to minimize the magnitude of the feed electric current. Additionally, the use of the multivariate regression method has enabled to estimate the MHD pump dimensions depending on the input parameters. The analysis has been performed for a large flow velocity range of both metallic liquids and leads to a simple proposal to reduce the feed electric current.

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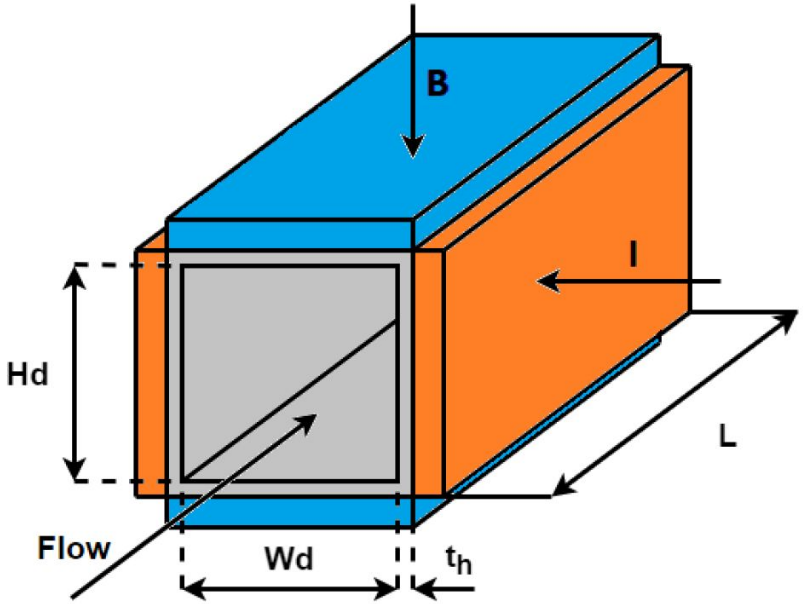
Electromagnetic (MHD) pumps

- Electromagnetic pumps
  - Conduction pumps
    - DC
    - AC
  - Induction pumps
    - FLIP
    - ALIP
  - Thermoelectric pumps



Magnetohydrodynamics pump scheme

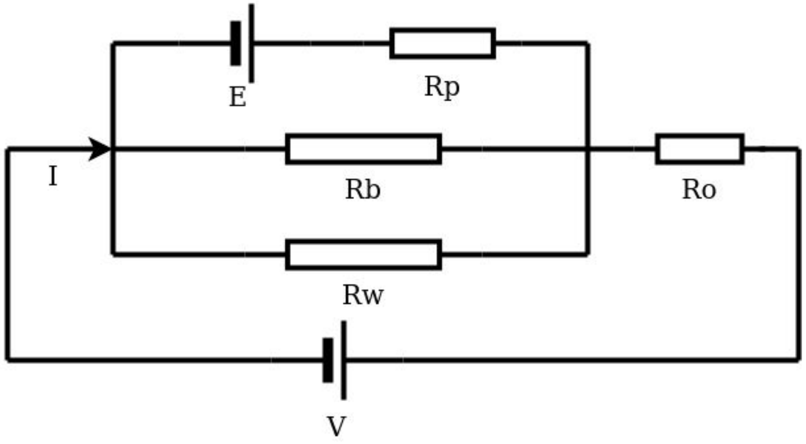
Design methods for MHD pumps

Analytical methods	Numeric methods (CFD)	Metaheuristics methods
• Shercliff's equations • Hunt's equations • Equivalent electrical circuit	• Element differential method • Finite elements method • Finite volume method	• Simulated annealing • Particle Swarm Optimization • Hybrid method

Equivalent circuit for DC conduction pump

- I - current
- V - voltage
- E - electromotive
- Rp - liquid metal resistance
- Rb - resistance of the bypass
- Rw - resistance of the wall
- Ro - outer resistance

ρ_{LM} - resistivity of liquid metal
ρ_w - resistivity of wall material
W_d - width of duct
H_d - height of duct
L - length of duct
t_h - thickness of duct
K_2 - the fringe factor (0.4)



Electric equivalent scheme of DC MHD pump

$$R_p = \frac{\rho_{LM} W_d}{H_d L} \qquad R_w = \frac{\rho_w W_d}{2 t_h L} \qquad R_b = \frac{\rho_{LM}}{K_2 L}$$

Total pressure generated by the DC pump (ECM)

$$\Delta P = \underbrace{\frac{B\,I\,R_{ver}}{(R_{ver}+R_p)H_d}}_{\text{Pressure development}} + \underbrace{\frac{B^2 Q}{(R_{ver}+R_p)H_d^2}}_{\text{Pressure loss due electromotive force}} + \underbrace{\frac{f_d \rho_{LM} L Q^2 (W_d + H_d)}{4(W_d + H_d)^3}}_{\text{Hydraulic pressure loss}}$$

$$C = \frac{B_m R_{ver}}{(R_{ver}+R_p)H_d} \quad B = \frac{B_m^2}{(R_{ver}+R_p)H_d^2} \quad A = \frac{f_d\ \rho_{(LM)}\ (W_d + H_d)}{4(W_d H_d)^3}$$

$$A L_{Loop} Q^2 = C I - BQ - A L_{pump} Q^2$$

$$I = \frac{\Delta P}{C} + \frac{BQ}{C} + \frac{A L_{loop} Q^2}{C}$$

Propose magnetohydrodynamic pump geometries for the micro- and minidemonstrator.

	Microdemonstrator's pump	Minidemonstrator's pump
Width [m]:	0.4	0.4
Height [m]:	0.005	0.005
Length [m]:	0.584	0.850
Current [A]:	993.82	1239.01

Summary

- ☑ Perform flow calculations for a micro and minidemonstrator.
- ☑ Examine how velocity affects heat transfer between loops in the micro- and minidemonstrator.
- ☑ Comparison of micro and minidemonstrator results to find common characteristics
- ☑ Propose magnetohydrodynamic pump geometries for the micro- and minidemonstrator.

Thank you for attention

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