

Optimization of the Direct Current magnetohydrodynamic pump for the Dual Fluid Reactor



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

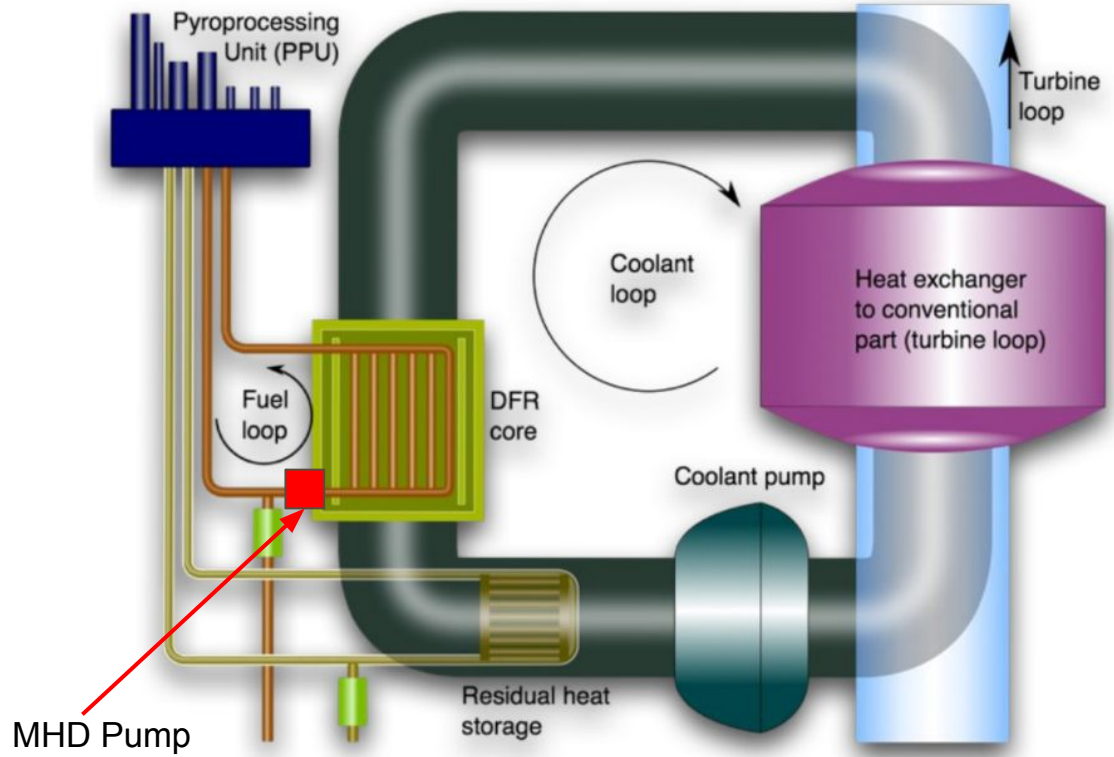


Agenda

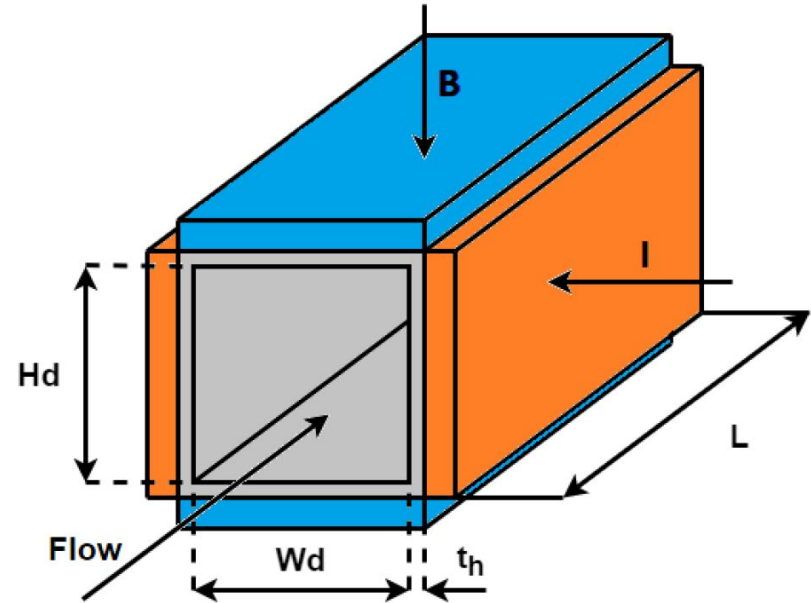
1. Dual Fluid Reactor
2. Magnetohydrodynamic pumps (MHD)
3. Equivalent Circuit Method
4. Simulated Annealing
5. Polynomial approximation
6. Multivariate regression
7. Summary

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



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



Magnetohydrodynamics pump scheme

Purpose of the work

- For the analysis, a **DC conduction pump** was chosen because it is **the simplest to analyze** and the **flow of liquid metal is continuous**.
- There are **no industrial pumps** for temperatures **above 800-900 °C**
- The disadvantage of these pumps is their power supply (**high current and low voltage**)
- Therefore, it was decided to perform pump geometry optimization to achieve the lowest possible current value.
- This information **is needed for design** (power supply construction) **and economic purposes** (lower power supply cost).

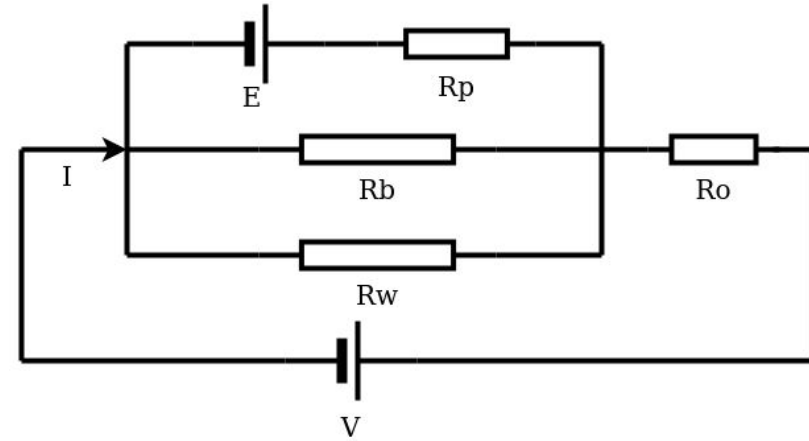
Design methods for MHD pumps

Analytical methods	Numeric methods (CFD)	Metaheuristics methods
<ul style="list-style-type: none">● Shercliff's equations● Hunt's equations● Equivalent electrical circuit	<ul style="list-style-type: none">● Element differential method● Finite elements method● Finite volume method	<ul style="list-style-type: none">● Simulated annealing● Particle Swarm Optimization● Hybrid method

Equivalent circuit for DC conduction pump

- I - current
- V - voltage
- E - electromotive
- R_p - liquid metal resistance
- R_b - resistance of the bypass
- R_w - resistance of the wall
- R_o - 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

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

Total pressure generated by the DC pump (ECM)

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

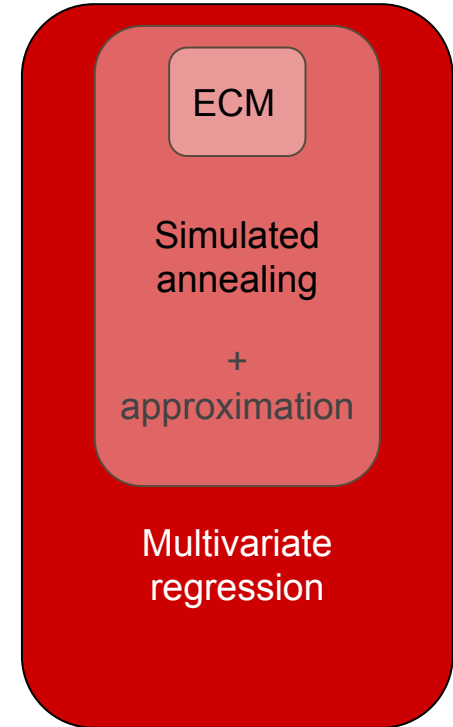
$$C = \frac{B_m R_{ver}}{(R_{ver} + R_p) H_d} \quad B = \frac{B_m^2}{(R_{ver} + R_p) H_d^2} \quad A = \frac{f_d \rho_{(LM)} (W_d + H_d)}{4(W_d H_d)^3}$$

$$A L_{Loop} Q^2 = C \boxed{I} - B Q - A L_{pump} Q^2$$

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

Stages of work performed

1. ECM implementation and validation
2. Simulated Annealing implemented and integrated with ECM code.
3. Optimization of three pump models with simulated annealing and approximation.
4. Development of more general models for pump design (Multivariate regression)



Input data for calculations

	Lee and Kim (2017)	Borges et al. (2010)	Sierchula et al. (2019)
Medium	Na	Pb	U-Cr
$T [^{\circ}C]$	300.0	500.0	1100.0
$\rho [\frac{kg}{m^3}]$	880.51	10470	15722
$\mu [mPa \cdot s]$	3.40	1.78	8.81
$\rho' [\cdot 0.1 \mu\Omega \cdot m]$	1.72	2.1	796.2
$\rho'_w [\cdot 0.1 \mu\Omega \cdot m]$	12.6	9.47	12.00
$\dot{m} [\frac{kg}{s}]$	0.044	1.260	2515.520
$\Delta P [Pa]$	5000.0	34600.0	15000.0
$R_{ver} [\cdot 10^{-4}]$	1.30	0.35	0.26
$t_h [m]$	0.001	0.002	0.01
$W_d [m]$	0.0384	0.03	0.4
$H_d [m]$	0.0018	0.01	0.2
$L [m]$	0.09	0.07	0.9

Lee and Kim (2017)	Borges et al. (2010)
$\rho = 880.51 \frac{kg}{m^3}$ $\mu = 3.40 mPa \cdot s$ $\rho' = 0.172 \mu\Omega \cdot m$	$R_p = 9.00 \cdot 10^{-6}$ $R_w = 1.01 \cdot 10^{-4}$ $R_b = 5.25 \cdot 10^{-5}$ $t_h = 0.002 m$

Uranium - Chromium eutectic

- Fuel mixture: Cr = 4.78%, ^{235}U = 12.80%, ^{238}U = 82.42%.
- The lowest melting point temperature
- No density, dynamic viscosity and resistivity data were found in the literature for the mixture Cr = 4.78%

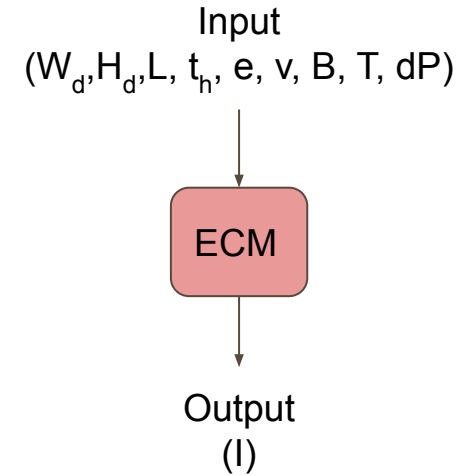
- Approximated density
 - $\rho = 1000(-0.00088 T + 16.69)$

- Approximated dynamic viscosity
 - $\mu = -6.42 \cdot 10^{-8} T^3 + 0.00027 T^2 - 0.389 T + 195.46$

- Resistivity (Cr = 4.97%)
 - $\rho' = (0.02 T + 57.61) \cdot 10^{-6}$

Validation

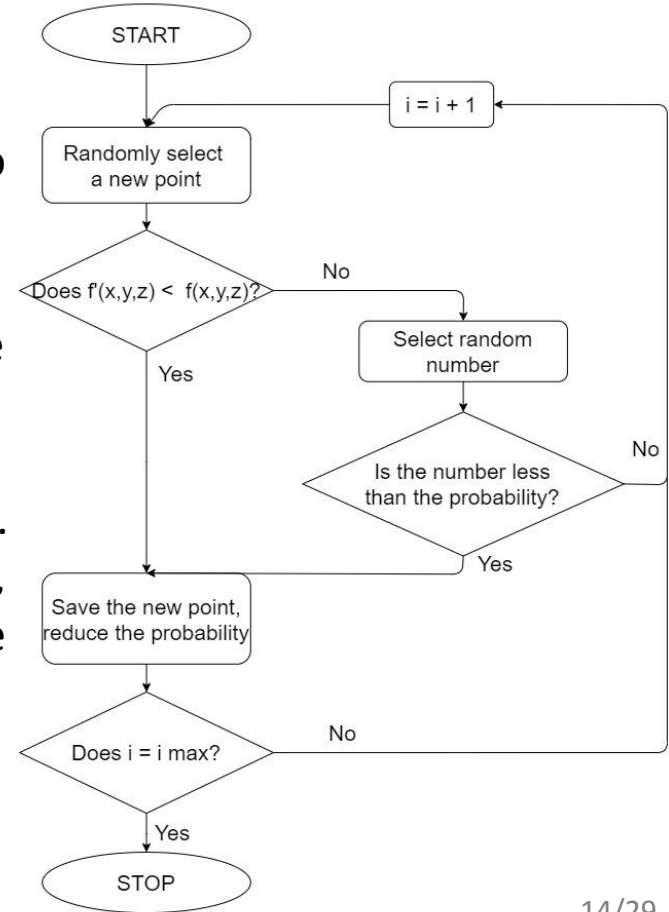
	Result from the article	Result of the calculation
Lee and Kim (2017)	116	116.15
Borges et al. (2010)	800	805
Sierchuła et al. (2019)	-	64700



Simulated annealing

It was decided to use simulation annealing method to optimize the pump geometry.

1. New point draw for analysis.
2. Check if the new point achieves a better score than the previous one.
3. If true: record the result, reduce the probability, start the loop again.
If not: there is some probability of accepting the result, otherwise - the loop will be repeated without saving the result.

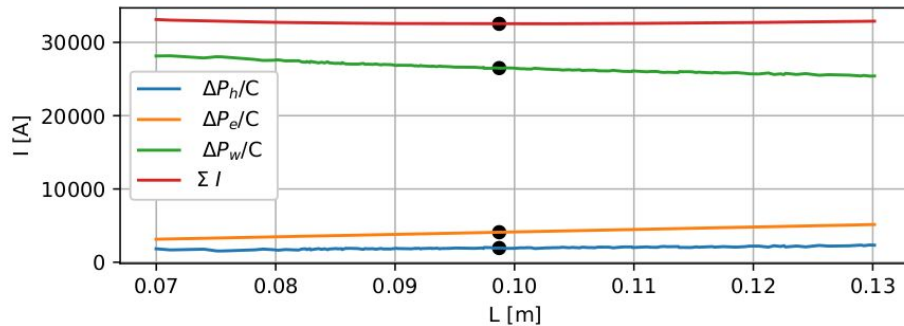
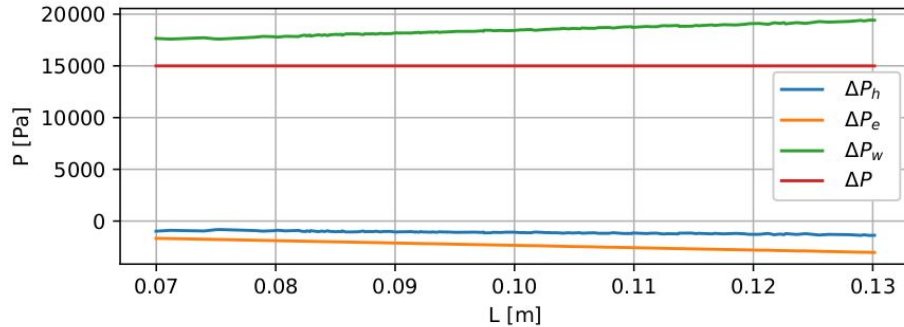




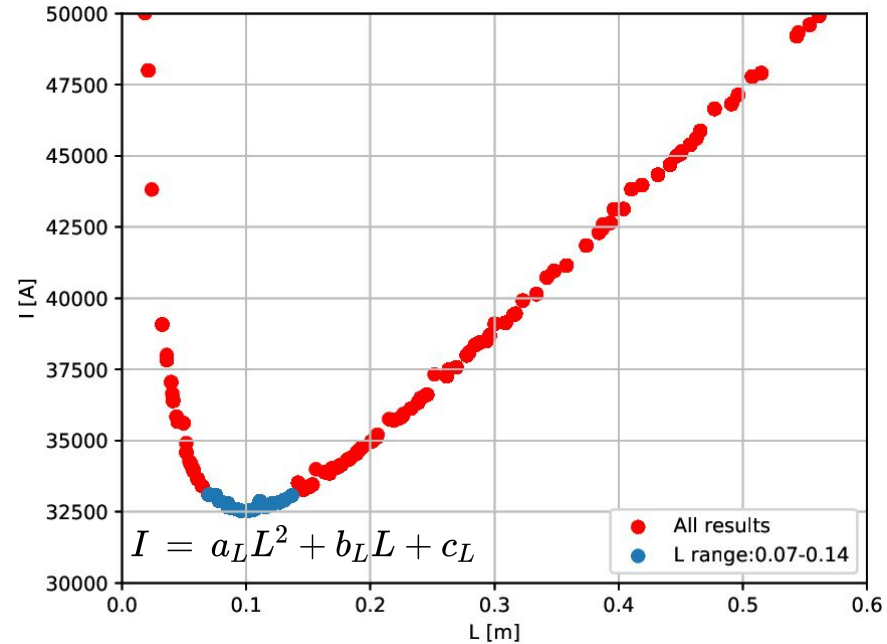
Results from simulated annealing

	Lee and Kim (2017)	Borges et al. (2010)	Sierchuła et al. (2019)
$W_d[m]$	0.0691	0.2992	0.7068
$H_d[m]$	0.0010	0.0010	0.1132
L [m]	0.0492	0.0506	0.0988
$I_{val}[A]$	116.15	805	64700
$I_{SA}[A]$	91.09	476.38	32957.63
δI [%]	-21.6	-40.8	-49.1

Results from simulated annealing



Pressures and currents for optimized pump length



Correlation of total minimum current to optimized length

- From the first equation, determine the value of the pump channel length for which the current reaches its lowest value, and from the second equation, determine the current flux, and from the third minimum current.

$$L = \frac{-b_L}{2a_L}$$

$$H_d = \frac{I}{\rho'' L}$$

$$\rho'' = \frac{-b_{\rho''}}{2a_{\rho''}}$$

$$W_d = \frac{A}{H_d}$$

$$I = a_{\rho''} \rho''^2 + b_{\rho''} \rho'' + c_{\rho''}$$

- From the fourth equation for current flow, the height of the pump channel is determined, and from the equation for area, the width of the pump channel is determined.



Results from polynomial approximation

	Lee and Kim (2017)	Borges et al. (2010)	Sierchuła et al. (2019)
$W_d[m]$	0.073	0.298	0.758
$H_d[m]$	0.001	0.001	0.105
L [m]	0.052	0.051	0.100
$I_{val}[A]$	116.15	805	64700
$I_{SA}[A]$	91.09	476.38	32957.63
$I_{PA}[A]$	91.107	476.402	32530.483
δI [%]	$18.663 \cdot 10^{-3}$	$4.618 \cdot 10^{-3}$	-1.3

- Simulated annealing achieves results for some parameters (T , dP , A , v , B)
- If one of them changes, the whole simulation annealing has to be done over again
- It was decided to derive a global equation by which the optimized geometry could be determined without using simulated annealing
- **Applied** multivariate regression

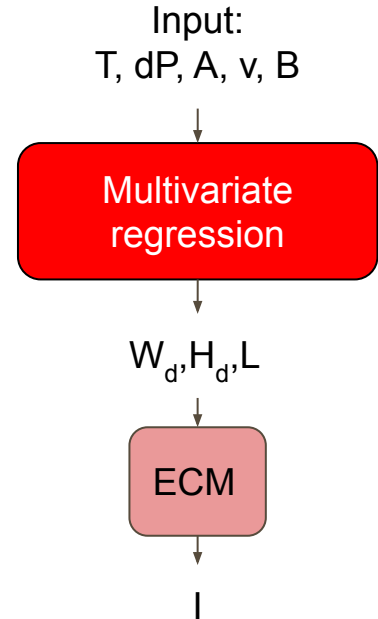
Multivariate regression

- Using results obtained by simulated annealing (for Borges and Lee), and from polynomial optimization (Sierchula), multivariate regression was used.
- The general equations of the linear multivariate models for the three pumps are presented below.

$$H_d = a_1 + b_T T + b_{\Delta P} \Delta P + b_A A + b_v v - b_B \sqrt{B}$$

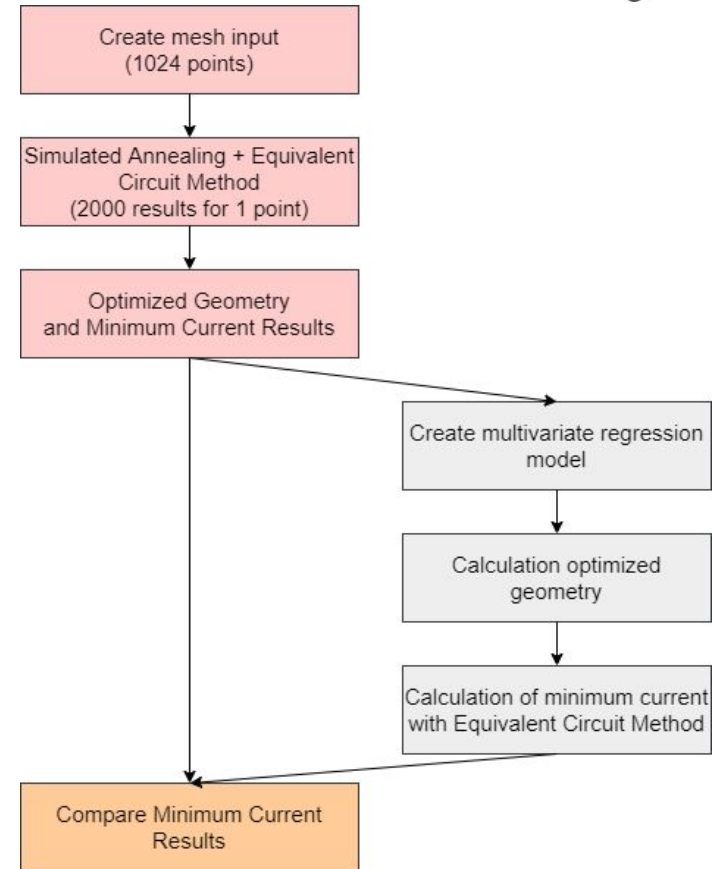
$$W_d = \frac{A}{H_d}$$

$$L = a_2 + b_{T2} T + b_{\Delta P2} \Delta P + b_{A2} A + b_{v2} v - b_{B2} \sqrt{B}$$



Working steps in multivariate regression

1. Create a five-dimensional coordinate grid consisting of 1024 points.
2. Calculate the minimum current value and optimal geometry for each point.
3. A multivariate regression model was created from the results.
4. Comparison of results from both methods



Scope of application

Range 1 - arbitrary

		Medium	T [$^{\circ}C$]	$\Delta P [Pa]$	A [m^2]	v [$\frac{m}{s}$]	B [T]
Lee and Kim (2017)	324	Na	366.7-500	4000-6000	$(6.7-13.8) \cdot 10^{-5}$	0.1-0.7	0.1-0.7
Borges et al. (2010)	576	Pb	500-700	34600-36000	$(0.15-0.6) \cdot 10^{-3}$	0.1-0.7	0.1-0.7
Sierchuła et al. (2019)	432	UCr	1100-1300	10000-15000	0.08-0.16	0.1 - 1.4	0.1-1.4

Range 2 - $\pm 20\%$

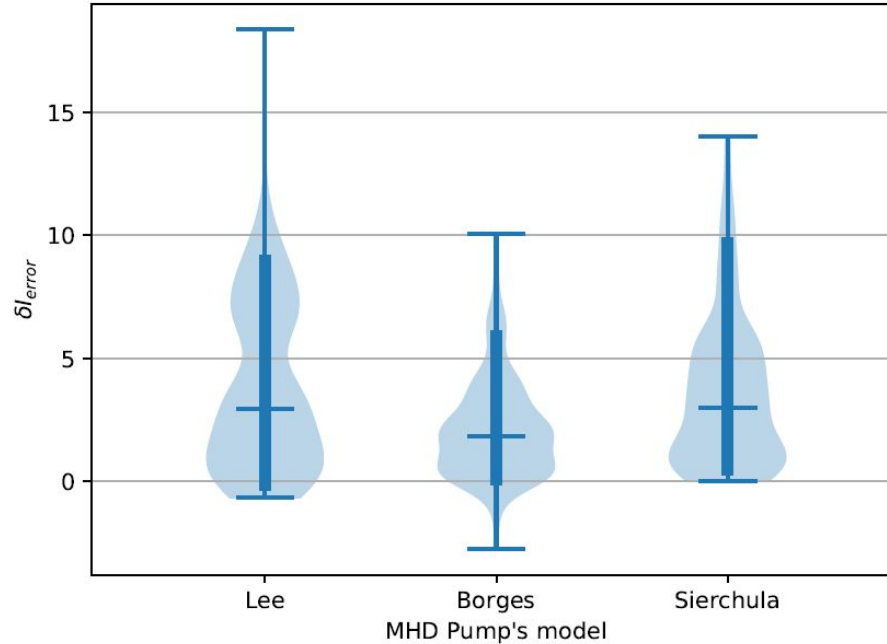
		Medium	T [$^{\circ}C$]	$\Delta P [Pa]$	A [m^2]	v [$\frac{m}{s}$]	B [T]
Lee and Kim (2017)	1024	Na	240-360	4000-6000	$(5.6-8.3) \cdot 10^{-6}$	0.58-0.86	0.14-0.21
Borges et al. (2010)	1024	Pb	400-600	27680-41520	$(0.24-0.36) \cdot 10^{-3}$	0.32-0.48	0.72-1.09
Sierchuła et al. (2019)	1024	UCr	880-1320	12000-18000	0.064-0.096	1.6 - 2.4	0.8-1.2

Range 3 - T $\pm 20\%$, all -20% +50%

		Medium	T [$^{\circ}C$]	$\Delta P [Pa]$	A [m^2]	v [$\frac{m}{s}$]	B [T]
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Borges et al. (2010)	1024	Pb	400-600	27680-51900	$(0.24-0.45) \cdot 10^{-3}$	0.32-0.6	0.72-1.35
Sierchuła et al. (2019)	1024	UCr	880-1320	12000-22500	0.064-0.120	1.6 - 3	0.8-1.5

Violin plots of relative error of minimum current

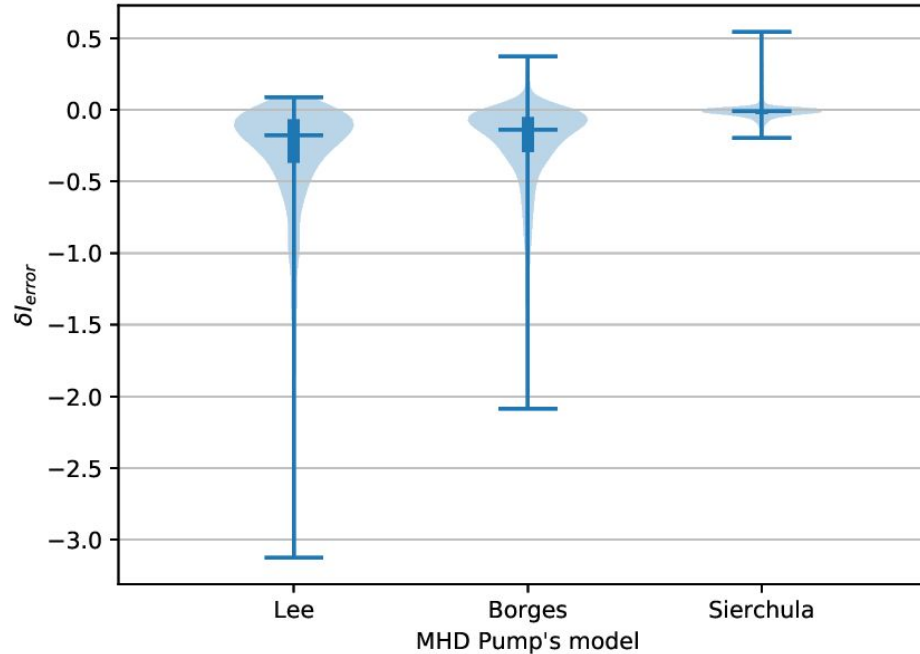
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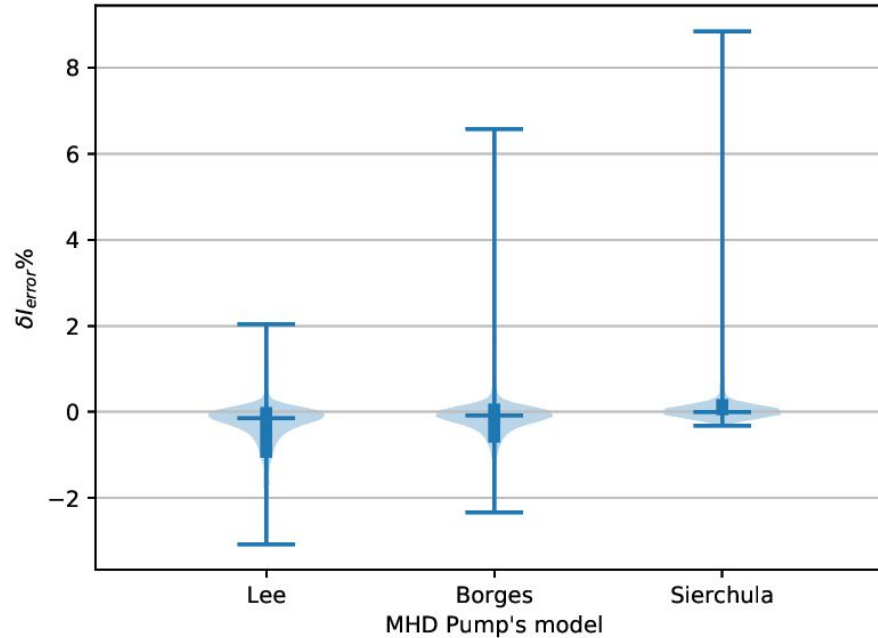
Range 2 - $\pm 20\%$



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Violin plots of relative error of minimum current

Range 3 - $T \pm 20\%$,
all -20% +50%



	Medium	T [$^{\circ}C$]	$\Delta P [Pa]$	A [m^2]	v [$\frac{m}{s}$]	B [T]
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Summary and conclusions

- Validation of calculations using the Equivalent Circuit Method were performed
- Metaheuristic optimization of pump channel geometry using simulated annealing were performed
- After applying approximation and regression, formulas for pump design were proposed.
- The ECM is a simplified model and needs to be developed



Optimization of the DC magnetohydrodynamic pump for the Dual Fluid Reactor

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Abstract

The Dual Fluid Reactor (DFR) is a new nuclear reactor concept in which the medium in both circuits — fuel and coolant — is liquid. It is an innovative design that is expected to have high operating economy due to its high operating temperature. This paper discusses a magnetohydrodynamic pump for a two-fluid reactor in which both loops contain liquid metals. Since the fuel loop of the reactor uses Uranium - Chromium (U-Cr) eutectic, whose temperature can reach 1300 °C, a pump that can withstand high temperatures, corrosion and erosion must be used. Such a device is the magnetohydrodynamic pump, which forces the flow of liquid metal by means of a current and an electromagnetic field. The authors of this paper focused on the modeling of a direct current conducting magnetohydrodynamic pump using the analytical Equivalent Circuit Method (ECM). This method was originally developed in a study of an experimental MHD pump to propose a model by which the pressure rise generated on the pump can be calculated. It is also possible to use the ECM method to calculate other parameters of the MHD pump at a given pressure drop, which has been done in this work.

The works of Lee and Kim (2017) and Borges et al. (2010) were used to validate the author's implementation of the ECM method while data from Sierchuła et al. (2019) was taken to provide information on an example DFR reactor for which an MHD pump was designed. Moreover, using metaheuristic methods, the above magnetohydrodynamic pumps were optimized to minimize the magnitude of the feed current. During that process, the key effects of current flux and pump length on the optimal pump geometry were observed. It turns out that for certain fluids there are critical values that can serve as design values for specific MHD pump applications.

Finally, in order to propose more universal pump design models, a space of 1024 input points was generated based on reference values of the above articles such as temperature, pressure drop, cross section, fluid velocity, and magnetic induction. For this space, a metaheuristic analysis was performed to obtain a set of 1024 pumps with optimized geometries for minimum input current. Finally, by applying the multi-element regression method, linear models were obtained that allow estimating the MHD pump dimensions from the input parameters.

The current values achieved for the pumps created from the regression models in 95% of the cases are greater by up to 5% of the current values from the geometries obtained from simulation annealing for all pumps.

Keywords: MHD, DFR, pump, optimization

1. Introduction

With the development of civilization, the amount of electricity needed to meet human needs has been continuously increasing. In today's situation of highly developed and densely populated countries, the existing conventional methods of producing electricity are slowly becoming insufficient. The main limiting factors are the finite supply of fossil fuels and climate warming caused by emissions. Nuclear power addresses these problems by offering more production capacity with virtually zero greenhouse gas emissions. A nuclear reactor is a device in which controlled radioactive decays are carried out to produce heat and electricity. First generation nuclear reactors included

the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR). These devices were developed up to the third generation. However, increasing attention has been paid to the safety and efficiency of light-water reactor-based nuclear power. For this reason, a fourth generation of reactors based on less conventional coolants was started.

This has resulted in reactor designs that use liquid salts (Molten Salt Reactor - MSR Serp et al. (2014), Uhlir (2007)), liquid metals (Lead-cooled Fast Reactor - LFR Smith et al. (2008), Alamberti et al. (2014)) or noble gases (Gas Cooled Fast Reactor - GFR van Rooijen (2009), Hejzlar et al. (2005)) as the coolants.

In addition to the above-mentioned solutions, an additional nuclear reactor concept, called Dual Fluid Reactor (DFR) Hake et al. (2015) was developed. This reactor consists of two loops — a cooling loop and a fuel loop. Molten metals are present in both loops, while molten salts may also be present in the fuel loop. DFR reactors in which the

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Thank you for attention



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