Analytical design of the Direct Current magnetohydrodynamic pump

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New reactor concepts and safety analyses for the Polish Nuclear Energy Program

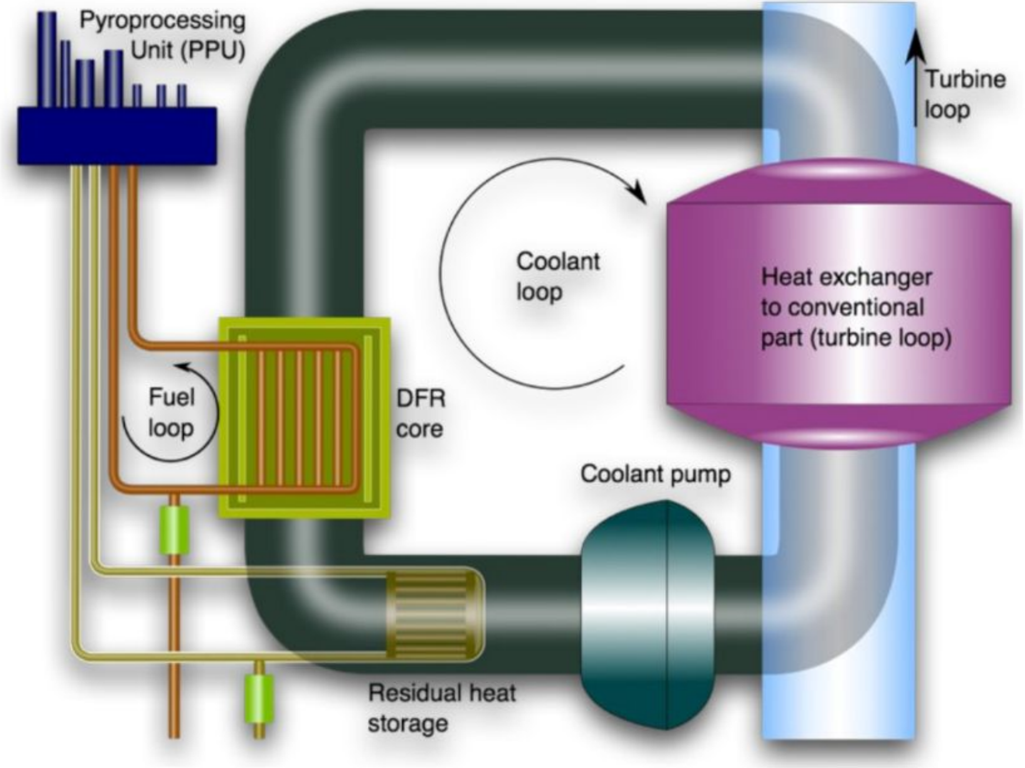
POWR.03.02.00-00.I005/17

Agenda

- Introduction
- DC conduction pumps
- Equivalent circuit for DC conduction pump
- Equivalent circuit - equations
- Analytical equations
- Total pressure generated by the DC pump
- Example of calculation from articles
- Calculation for Uranium - Chromium eutectic

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



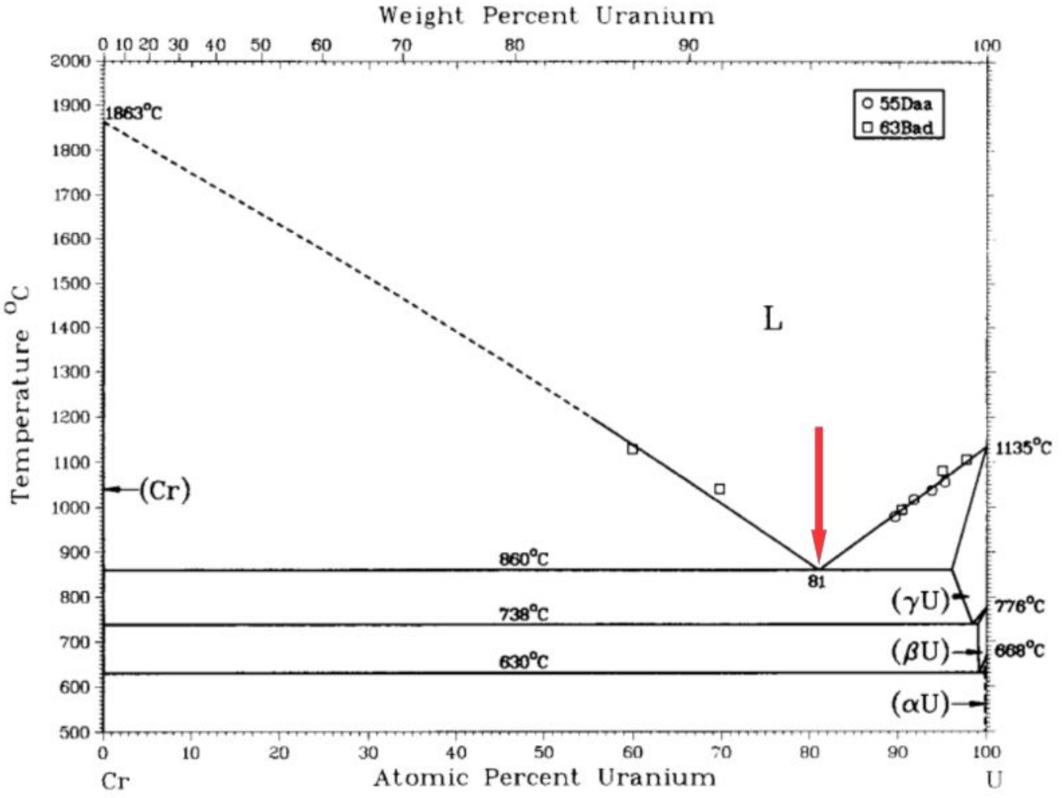
Dual Fluid Reactor [1]

Uranium - Chromium eutectic

FUEL MIXTURE:

- Cr – 4.78%
- ^{235}U – 12.80%
- ^{238}U – 82.42%

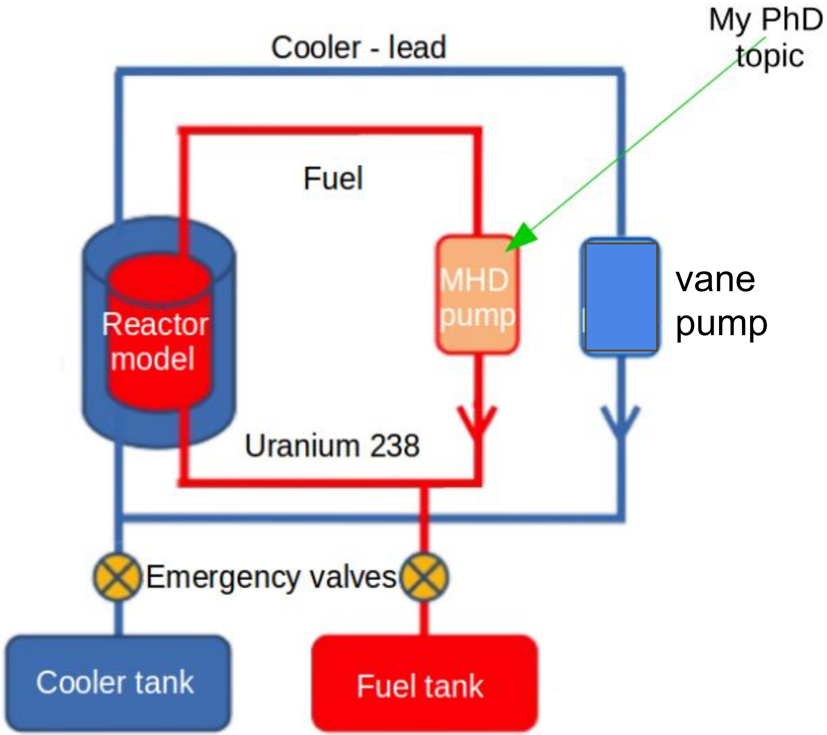
- The lowest melting point temperature



U-Cr phase diagram [Venkatraman M. Neuman J.P., Peterson D.,E, 1985]

Minidemonstrator

- Two loops – fuel and coolant
- Two pumps: MHD and Vane pump
- Fuel - Uranium 238
- Cooler - lead



Mini-demonstrator scheme[1]

Electromagnetic (MHD) pumps

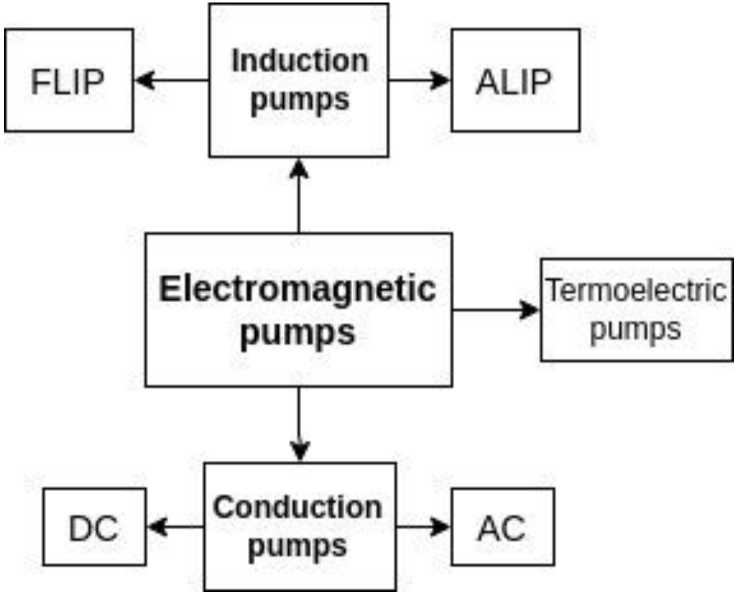
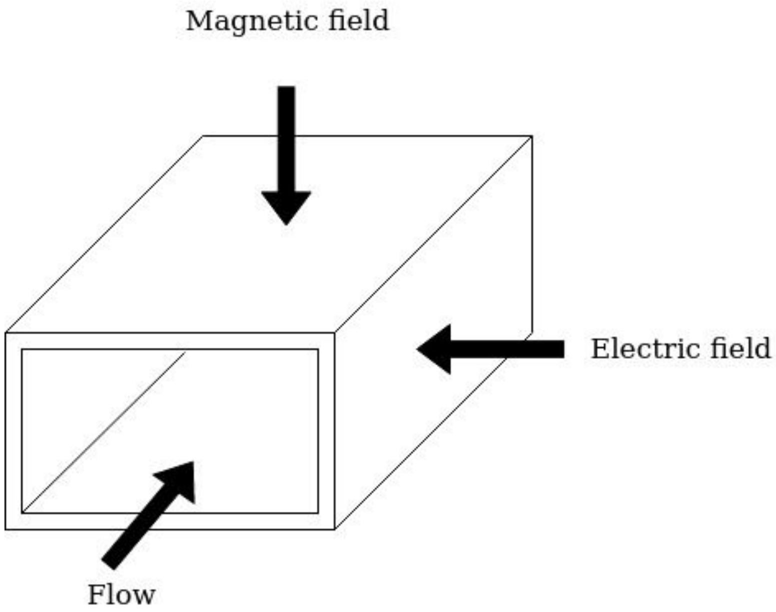
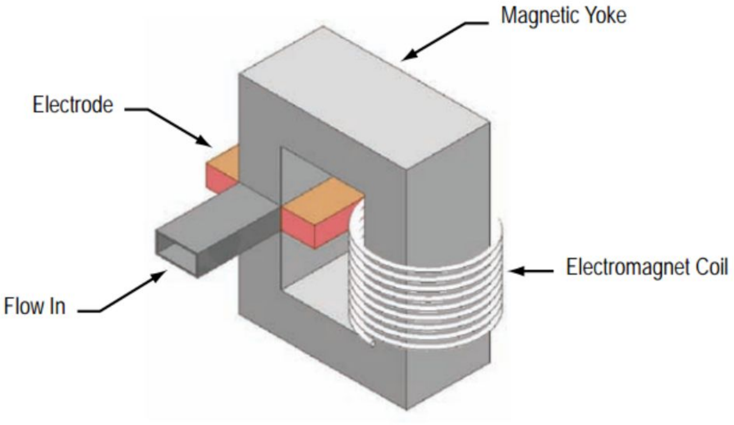


Diagram of the division of mhd pumps

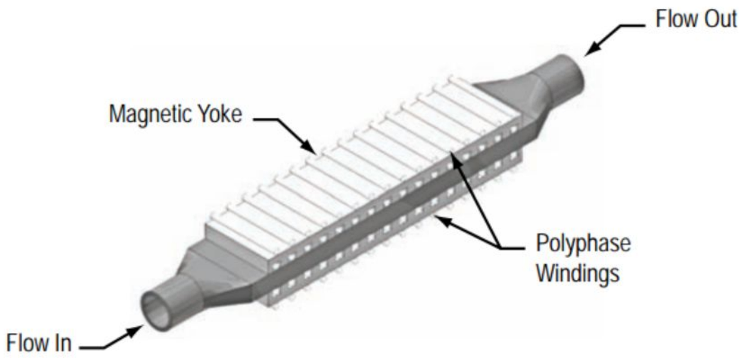


Magnetohydrodynamics pump scheme

Conduction and induction pumps



Schematic representation of a DC conduction pump [3]



Schematic representation of a FLIP induction pump[3]

- It has a magnet to produce a magnetic field and an electrode to produce an electric field
- Simple and compact design
- Continuous flow of liquid metal

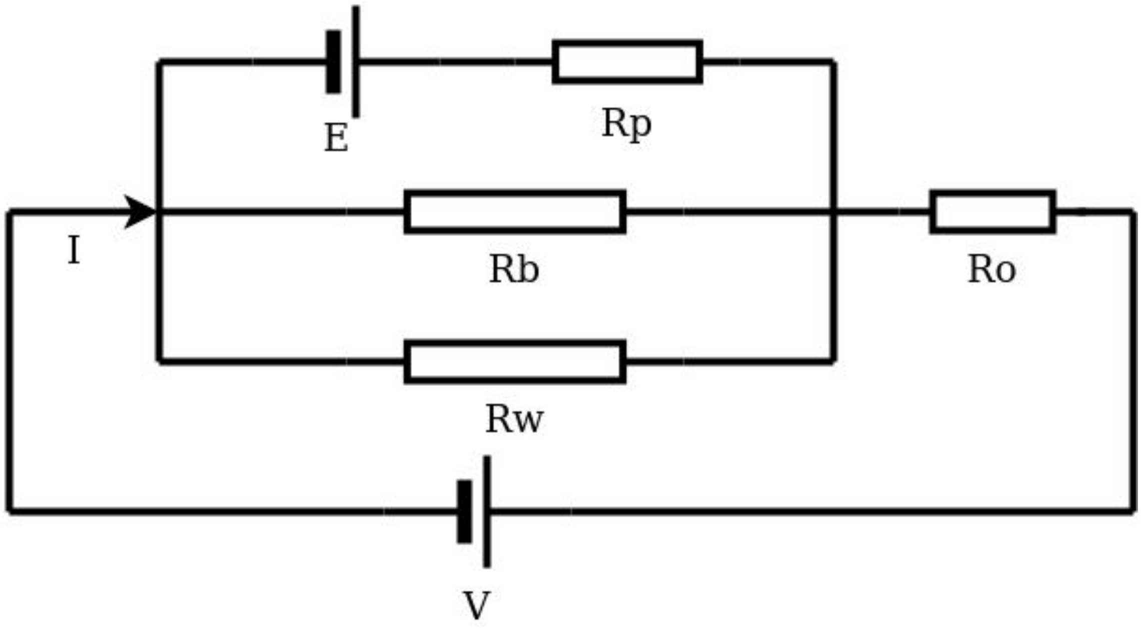
- It has a magnet to produce a magnetic field (electric field is induced by a magnetic field)
- Needs transformers to work
- Pulsed liquid metal flow

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

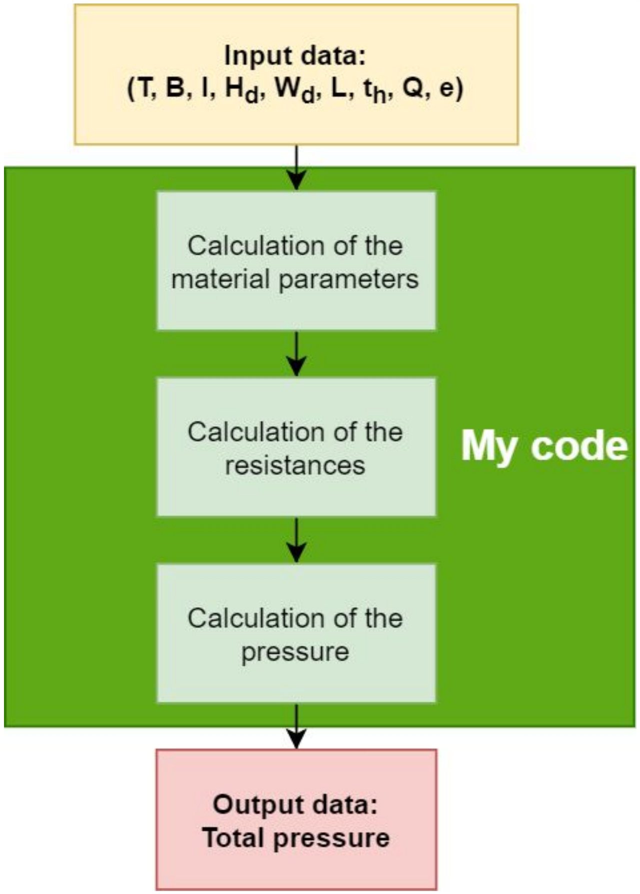
- I - current
- V - voltage
- E - electromotive
- Rp - liquid metal resistance
- Rb - resistance of the bypass
- Rw - resistance of the wall
- Ro - outer resistance



Electric equivalent scheme of DC MHD pump

Program block diagram

- Import data:
  - Temperature (T)
  - Magnetic induction (B)
  - Input current (I_t)
  - Height of duct (H_d)
  - Width of duct (W_d)
  - Length of duct (L)
  - Thickness (t_h)
  - Flow rate (Q)
  - Roughness (e)



Equivalent circuit - equations

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)

```
Rp = sigma*Wd/(Hd*L)
Rs = sigma2*Wd/(2*th*L)
Rf = sigma /(K2*Hd)
Rver = Rs*Rf/(Rs+Rf)
```

$$R_p = \frac{\rho_{LM} W_d}{H_d L}$$

$$R_w = \frac{\rho_w W_d}{2 t_h L}$$

$$R_b = \frac{\rho_{LM}}{K_2 L}$$

Analytical equations

$$F = \boxed{B\,I\,W_d}$$

$$\Delta P = \frac{F}{H_d W_d}$$

$$R_{ver} = \frac{R_w R_b}{R_w + R_b}$$

$$\Delta P = \frac{B\,\boxed{I}}{H_d} \rightarrow I = \frac{\boxed{R_{ver}}\, i_t - \boxed{B\,W_d\,v}}{R_p + R_{ver}} \rightarrow E_p$$

- B - magnetic induction
- I - current
- F - Lorentz force
- E_p - Electromotive force
- v - velocity of liquid metal
- i_t - input current
- R_{ver} - Substitute resistance

Total pressure generated by the DC pump

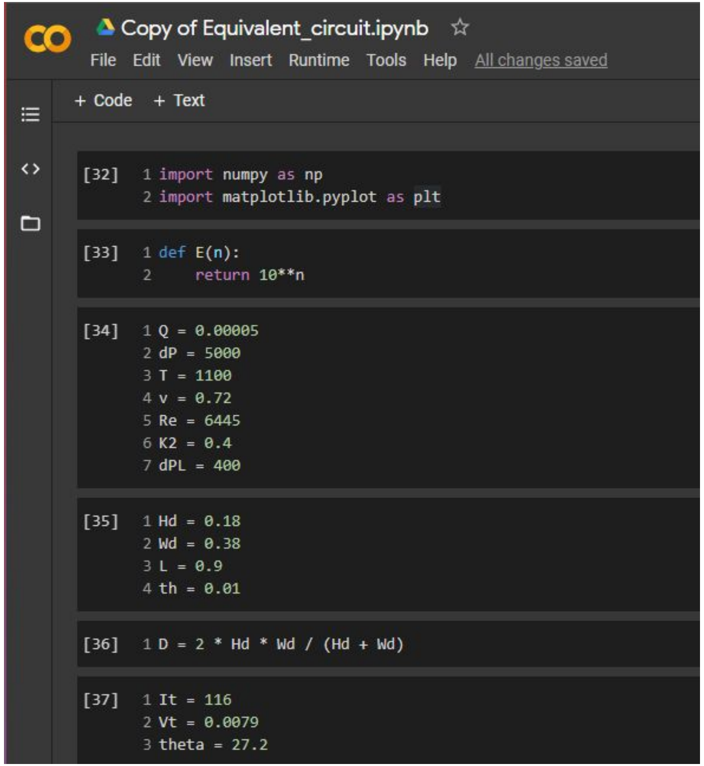
$$\Delta P = \frac{B i_t R_{ver}}{(R_{ver}+R_p) H_d} - \frac{B^2 Q}{(R_{ver}+R_p) H_d^{\,2}} - \frac{f_d \rho_{LM} L Q^2 (W_d + H_d)}{4 (W_d H_d)^3}$$

Pressure development

Pressure loss due electromotive force

Hydraulic pressure loss

Google colaboratory



Fragment from Google Colaboratory

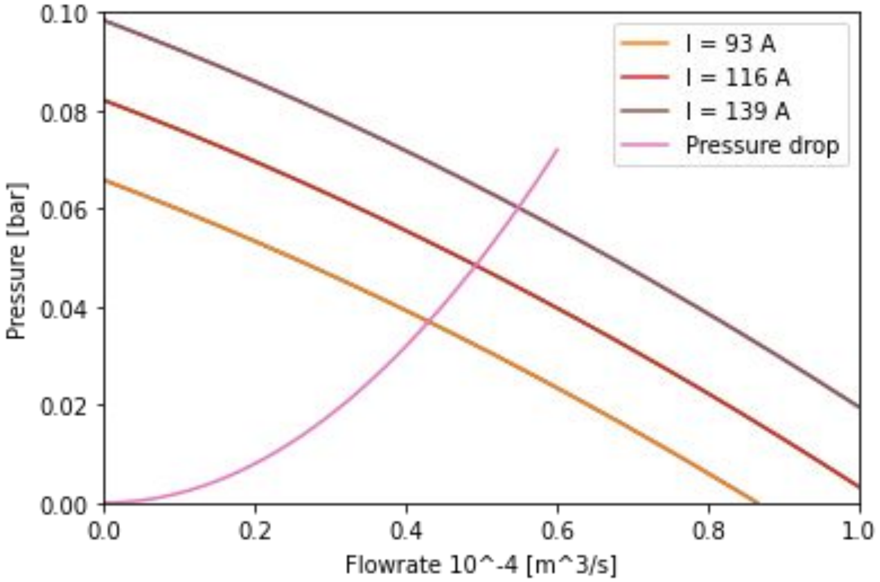
The ability to work on the code on any device without installing special software.

Google's provision of computing power and 12 GB of RAM for calculations

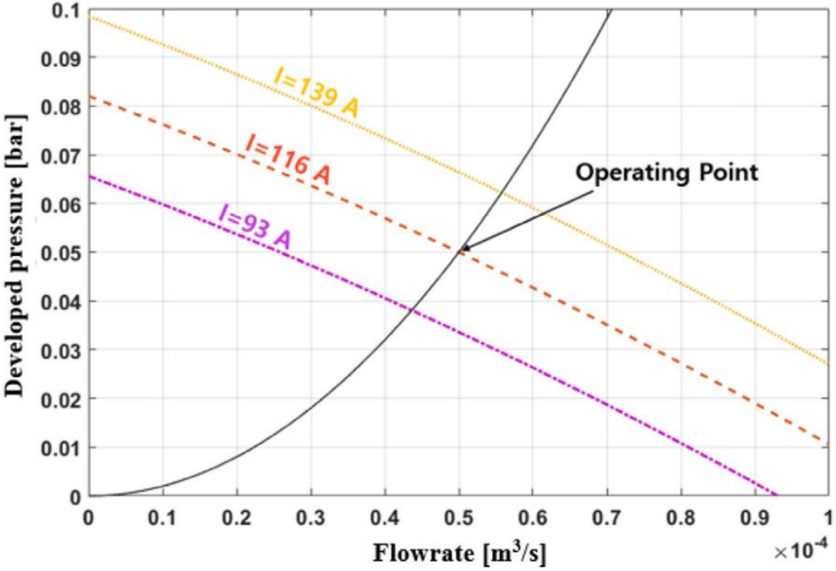
No need to install libraries, just need to import them

easy file sharing with code from a Google drive

Calculations for Sodium liquid metal

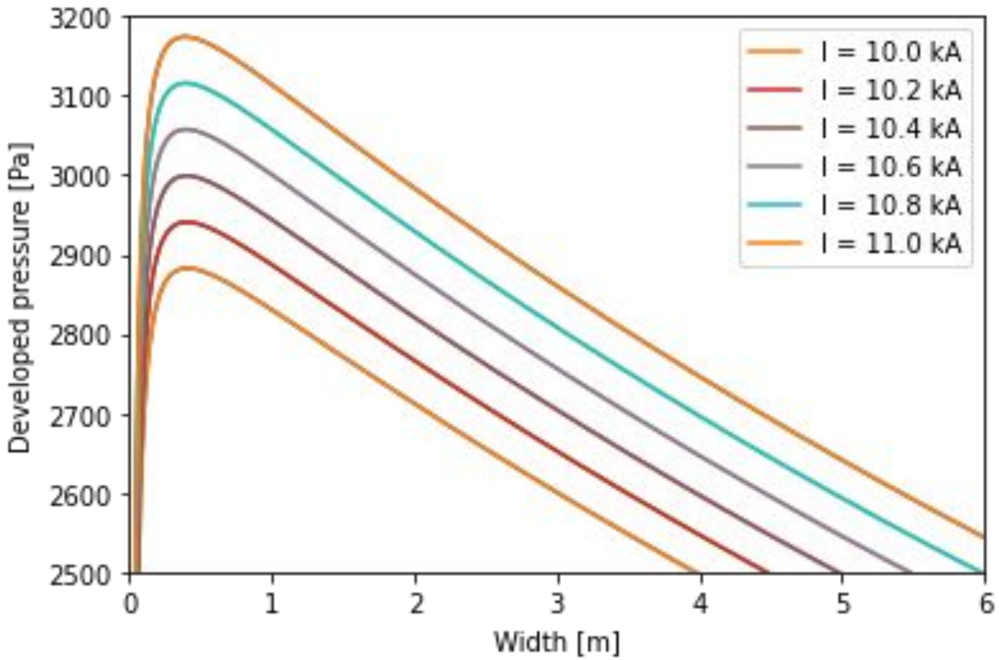


The diagram of the pressure dependence on the flowrate



The example diagram of the pressure dependence on the flowrate [5]

Calculations for Uranium-Chromium liquid metal

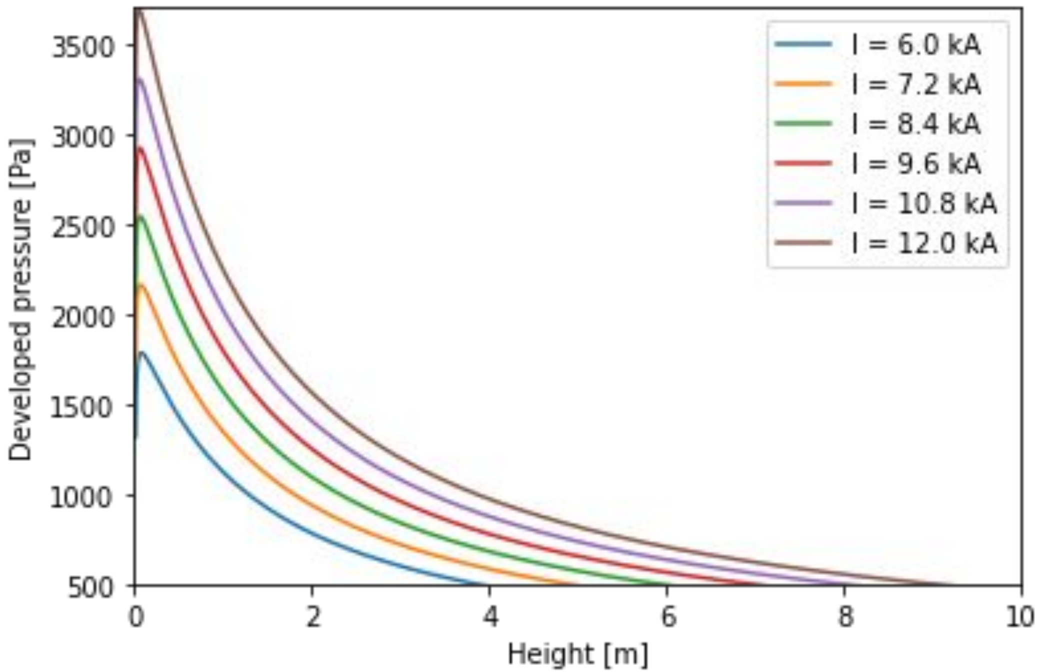



```
I = []
X = []
wynik = []
for i in range(10000,11200,200):
    X = []
    wynik = []
    for x in np.linspace(0.01,10,10000):
        Rp = sigma*x/(Hd*L)
        Rs = sigma2*x/(2*th*L)
        Rf = sigma /(K2*Hd)
        Rver = Rs*Rf/(Rs+Rf)
        D = 2 * Hd * x / (Hd + x)
        part1 = -1.8*((6.9/Re)+np.power((e/(3.7*D)),1.11))
        f = np.power((1/part1),2)
        dP1 = B*i*Rver/((Rver + Rp)*Hd)
        dP2 = B*B*Q/((Rver+Rp)*(Hd*Hd))
        dP3 = ((f*rho*L*Q*Q*(x+Hd))/(4*np.power((x*Hd),3)))
        dPtot = dP1-dP2-dP3
        if dPtot < 0:
            pass
        else:
            X.append(x)
            wynik.append(dPtot)
    plt.plot(X,wynik)
```

The diagram of the pressure dependence on the width

Code made to generate the calculation

Calculations for Uranium-Chromium liquid metal

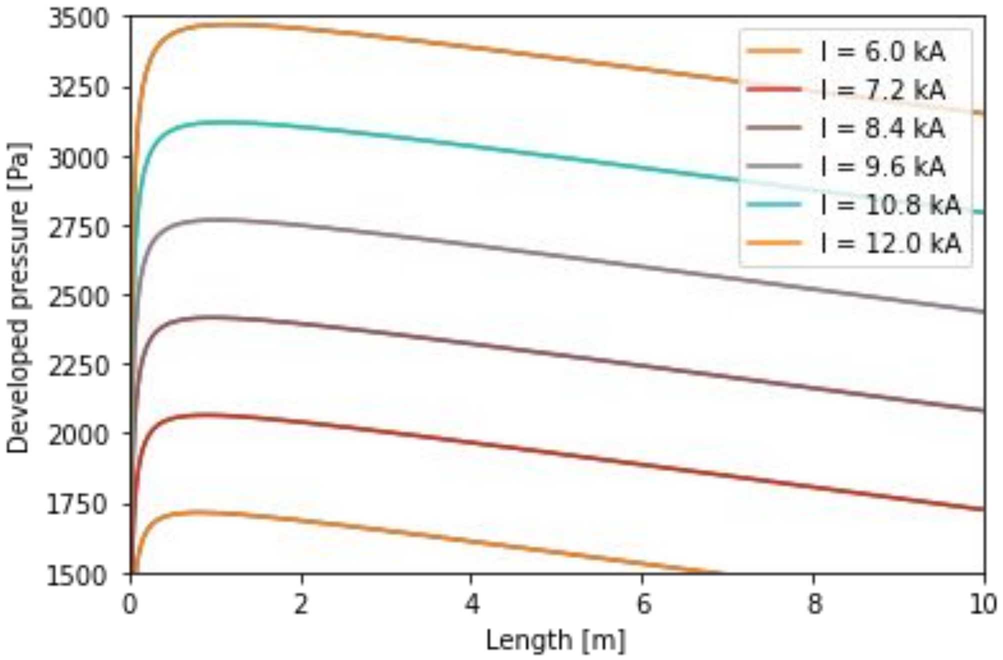


The diagram of the pressure dependence on the height

```
I = []
X = []
wynik = []
for i in range(6000,13200,1200):
    I.append(i)
    X = []
    wynik = []
    for x in np.linspace(0.01,10,10000):
        Rp = sigma*Wd/(x*L)
        Rs = sigma2*Wd/(2*th*L)
        Rf = sigma /(K2*x)
        Rver = Rs*Rf/(Rs+Rf)
        D = 2 * x * Wd / (x + Wd)
        part1 = -1.8*((6.9/Re)+np.power((e/(3.7*D)),1.11))
        f = np.power((1/part1),2)
        dP1 = B*i*Rver/((Rver + Rp)*x)
        dP2 = B*B*Q/((Rver+Rp)*(x*x))
        dP3 = ((f*rho*L*Q*Q*(Wd+x))/(4*np.power((Wd*x),3)))
        dPtot = dP1-dP2-dP3
        if dPtot < 0:
            pass
        else:
            X.append(x)
            wynik.append(dPtot)
```

Code made to generate the calculation

Calculations for Uranium-Chromium liquid metal



Graph of the pressure dependence on length

```
I = []
X = []
wynik = []
for i in range(6000,13200,1200):
    X = []
    wynik = []
    for x in np.linspace(0.01,10,10000):
        Rp = sigma*Wd/(Hd*x)
        Rs = sigma2*Wd/(2*th*x)
        Rf = sigma /(K2*Hd)
        Rver = Rs*Rf/(Rs+Rf)
        D = 2 * Hd * Wd / (Hd + Wd)
        part1 = -1.8*((6.9/Re)+np.power((e/(3.7*D)),1.11))
        f = np.power((1/part1),2)
        dP1 = B*i*Rver/((Rver + Rp)*Hd)
        dP2 = B*B*Q/((Rver+Rp)*(Hd*Hd))
        dP3 = ((f*rho*x*Q*Q*(Wd+Hd))/(4*np.power((Wd*Hd),3)))
        dPtot = dP1-dP2-dP3
        if dPtot < 0:
            pass
        else:
            X.append(x)
            wynik.append(dPtot)
    plt.plot(X,wynik)
```

Code made to generate the calculation

Conclusion and next steps

- The Equivalent Circuit Method is one of the popular design methods for MHD pumps
- With the equivalent electrical circuit method, the parameters of the pump can be determined, but the velocity profile of the pump cannot be determined.
- The calculation for larger pumps should be tested and the results compared with the experiment
- A program has been developed that can be used to design a magnetohydrodynamic pump using the equivalent electrical circuit method
- I plan to modify the program to calculate the current instead of calculating the pressure, because the lowest possible current is important for economic and construction reasons
- It is also planned to simulate CFDs and compare the results with those obtained by the analytical method

Literature

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.

2. Venkatraman M., Neumann J. P., The Cr-U (Chromium-Uranium) System, Bulletin of Alloy Phase Diagrams, Vol. 6, No. 5, 1985.

3. Polzin, K.A.,"Liquid metal pump technologies for nuclear surface power,"American Nuclear Society Space Nuclear Conference, Paper 2002, June 2007.

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5. Lee G.H., Kim H.R., *Design analysis of DC electromagnetic pump for liquid sodium-*CO_2 *reaction experimental characterization*, Annals of Nuclear Energy 109, 490-497, 2017.

Thank you for attention

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Analytical equations 2

$$\Delta P = \frac{B i_t R_{ver}}{(R_{ver}+R_p) H_d} - \frac{B^2 Q}{(R_{ver}+R_p) H_d^{\,2}} - \frac{f_d \rho_{LM} L Q^2 (W_d + H_d)}{4 (W_d H_d)^3}$$

$$i_t = \left(\Delta P + \frac{B^2 Q}{(R_{ver}+R_p) H_d^{\,2}} + \frac{f_d \rho_{LM} L Q^2 (W_d + H_d)}{4 (W_d H_d)^3} \right) \frac{(R_{ver}+R_p)}{R_{ver}} \frac{H_d}{B}$$

$$\left(K_1 + \frac{f_d \rho_{LM} L (W_d + H_d)}{4 (W_d H_d)^3} \right) Q^2 + \left(\frac{B^2}{(R_{ver}+R_p) H_d^{\,2}} \right) Q - \frac{B i_t R_{ver}}{(R_{ver}+R_p) Hd} = 0$$