MHD pumps: Annular Linear Induction Pump (ALIP)

Linards Goldšteins - Institute of Physics of University of Latvia
(Linards.Goldsteins@lu.lv)
Emmanuel Lo Pinto - CEA Cadarache
(emmanuel.lopinto@cea.fr)
Summary

1. Basics of MHD pumping
2. Some applications of MHD pumping
3. Types of MHD pumps
4. Elements of design of an ALIP
5. Equivalent circuit model
6. Ideal ALIP model
7. Role of the slip magnetic Reynolds number in ALIP
8. Stalling instability in ALIP
9. MHD instability in ALIP
10. Experimental and numerical studies on TESLA-EMP loop (IPUL)
11. Experimental and numerical studies on PEMDYN loop (CEA)
1. Basics of MHD pumping

Example of a conducting fluid in a channel

- EM force on an elementary volume of fluid: \( \overrightarrow{f_{EM}} = j_y B_z \overrightarrow{u_x} \)
- Total EM force in the channel:
  \[
  F_{EM} = \iiint_V j_y(x, y, z)B_z(x, y, z)\,dx\,dy\,dz
  \]
- Developed pressure:
  \[
  p_{EM} = F_{EM}/S
  \]
2. Some applications of MHD pumping

- Conducting fluids
- Reliability / service time is key
  - no sealing required
  - no moving parts in direct contact with fluid

- Space industry
  - SNAP 10 pump for space reactor

- Nuclear industry
  - Concentrated Solar Power
  - JHR reactor CALIPSO device prototype pump

- Computer hardware
  - LM-10 pump for CPU cooling

- Alkali & non-alkali metal production

Reliability / service time is key, as it is crucial for the longevity of the system. MHD pumps lack sealing requirements and have no moving parts in direct contact with the fluid, offering advantages in terms of reliability and ease of maintenance. These pumps are particularly useful in high-temperature processes, such as in the nuclear and space industries. They can be used in a variety of applications, including concentrated solar power, computer hardware cooling, and specialized metal production processes.
3. Types of MHD pumps

- **Conduction pumps**
  - DC conduction
  - AC conduction
  - Current directly supplied to the fluid
  - Magnetic field from permanent magnets (DC type pump) or electromagnet

- **Induction pumps**
  - Moving inductor
  - Static inductor
  - Travelling magnetic wave
    - Moving permanent magnets
    - Arrangement of coils (static)
  - Current induced in the fluid channel thanks to the time-varying magnetic flux (Lenz’s law)
3. Types of MHD pumps

- DC conduction pump
  - Common operating range:
    - Low flowrate (0 – 10 m3/h)
    - Low pressure rise (0 – 1 bar)
  - Assets:
    - Simple design & optimisation
    - Cheap production
    - No moving part
  - Drawbacks:
    - Very high current required
    - DC power supply needed
2. Types of MHD pumps

➢ Permanent magnet pump (radial air gap type)

• Common operating range:
  o Low to medium flow rate (up to $10^2$ l/s)
  o Low to high developed pressure
    (0 – 10 bars & more)

• Assets:
  o Higher efficiency (compared to other EM pumps)
  o Relatively cheap production (use of commercial motor)
  o Relatively small size (for high developed pressure)
  o Simple construction (no coils...)

• Drawbacks:
  o Rotating magnetic disks
  o Flow channel has a complex geometry
3. Types of MHD pumps

- **Annular Linear Induction Pump (ALIP)**

  - **Common operating range:**
    - Medium to high flowrate (up to $10^3$ m$^3$/h)
    - Low to high developed pressure (0 – 10 bars)
  
  - **Assets:**
    - No finite width effect
    - Very high mechanical resistance
    - No moving parts
  
  - **Drawbacks:**
    - More expensive than other EM pumps
    - High developed pressure means higher currents or longer pump

Drawing of ALIP design with external inductor
4. Elements of design of an ALIP

1. Origin: asynchronous motor
   - Magnetic circuit
   - Rotor

2. Intermediate step: flat linear induction pump
   - Polyphase inductor
   - Annular liquid metal channel
   - Ferromagnetic core

3. Final step: the ALIP
   - Symmetry axis
   - Liquid metal
   - Conducting side bar
   - Polyphase inductor
   - Conducting side bar

MHD pumps: Annular Linear Induction Pumps (ALIP)
4. Elements of design of an ALIP

- Longitudinal cross section
4. Elements of design of an ALIP

➢ Transverse cross section
4. Elements of design of an ALIP

• Generation of a “sinusoidal” travelling wave
  ➢ 3 phases & 2 slot/pole/phase case

Wavelength \( \lambda = \frac{2\pi}{k} \)

\[
i_2(t) = I_0 \cos \left( \omega t - \frac{2\pi}{3} \right)
\]

\[
i_1(t) = I_0 \cos(\omega t)
\]

\[
i_3(t) = I_0 \cos \left( \omega t - \frac{4\pi}{3} \right)
\]

\[\vec{j} = j_0 e^{j(\omega t - k z - \psi)} \vec{u}_\phi\]

Actual current wave produced by the coils

Pole pitch \( \tau = \frac{\lambda}{2} \)

Ideal applied current wave
5. Equivalent circuit model

- ALIP (external inductor) seen as an Single-sided Linear Induction Machine (SLIM)
  - Short primary: inductor
  - Long secondary: liquid metal

![Diagram of ALIP with primary core, liquid metal, and back iron](image-url)
5. Equivalent circuit model

• SLIM equivalent circuit for one phase referred to primary phase
  - $V_1$: input voltage / $I_1$: input current
  - $R_1$: resistance of primary winding
  - $X_1$: stator leakage reactance
  - $X_m$: magnetization reactance
  - $X'_2$: secondary leakage reactance referred to primary side ($X'_2 \approx 0$ for liquid secondary sheet)
  - $R'_2$: liquid metal annulus resistance referred to primary side
  - $s = \frac{v_s - v_f}{v_s}$: slip
  - $v_s = \lambda f = 2\pi f$: magnetic field velocity
  - $v_f$: liquid metal velocity
  - Iron losses neglected
5. Equivalent circuit model

- Expression of circuit parameters (3-phase ALIP): $R_1$

$$R_1 = \text{resistivity of conductor} \times \frac{\text{length of conductor}}{\text{cross section of conductor}} \approx r_{cu} \frac{W_1 \pi D_0}{0.6wh} = r_{cu} \frac{2pq\pi D_0 W_1^2}{0.6wh}$$

- $r_{cu}$: electrical resistivity of conductor (ex. copper)
- $W_1$: number of coil turns per phase
- $D_0$: average diameter of a coil turn
- $p$: number of pole pairs
- $q$: number of slot/pole/phase
- $w$: slot width
- $h$: slot depth
- Hypothesis: 60% of the coil cross section is made of conductor
5. Equivalent circuit model

• Expression of circuit parameters (3-phase ALIP): $X_1$

$$X_1 = 2\pi f L_1 \approx \frac{2\pi f}{pq} \left[2\mu_0 W_1^2 \pi D_0 \left(\frac{h - d}{3w} + \frac{d}{w}\right)\right]$$

- $W_1$: number of coil turns per phase
- $D_0$: average diameter of one turn of coil
- $p$: number of pole pairs
- $q$: number of slot/pole/phase
- $w$: slot width
- $h$: slot depth
- $d$: slot depression depth
- Hypothesis: rectangular slots of constant width
5. Equivalent circuit model

• Expression of circuit parameters (3-phase ALIP): \( R'_2 \) & \( X_m \)

\[
R'_2 \approx r_{lm} \frac{6\pi D_c W_1^2}{p\tau d_c}
\]

\[
X_m = 2\pi f L_m \approx 2\pi f \frac{6\mu_0\pi D_c \tau W_1^2}{\pi^2 p g_e}
\]

• \( r_{lm} \): electrical resistivity of liquid metal
• \( W_1 \): number of coil turns per phase
• \( D_c \): average diameter of liquid metal annulus
• \( p \): number of pole pairs
• \( \tau \): pole pitch

• \( g_e \): effective air gap \( (g_e = K_c \times g) \)
• \( g \): air gap
• \( K_c \): Carter’s coefficient
• \( d_c \): annulus thickness
• Hypothesis: single layer winding, 1 phase/slot (winding factor \( k_w \approx 1 \))
5. Equivalent circuit model

- Computation of pressure rise (3-phase ALIP):
  
  ➢ Useless output power: \( P_U = 3R'_2 \frac{(1-s)}{s} (I'_{2\text{rms}})^2 = (\Delta P_{EM} Q) \)
  
  ➢ Pressure from EM force: \( \Delta P_{EM} = 3 \frac{C I'_{1\text{rms}}^2}{Q} \frac{R'_2(1-s)}{s \left( \frac{(R'_2)^2}{\chi_m s^2+1} \right)} \)
  
  ➢ Finite length effect coefficient: \( C = \frac{2p-1}{2p+1} \)
  
  ➢ Pressure loss (fluid viscosity): \( \Delta P_{loss} = \frac{1}{2 \rho \lambda (2d_c)} \frac{V_f^2}{2\rho \tau} \)
  
  ➢ Available pressure: \( \Delta P = \Delta P_{EM} - \Delta P_{loss} \)
6. Ideal ALIP model

1. Consider two, infinitely long perfect ferromagnetic cylinders
2. Sheet layer of external linear current density is spread on surface of external cylinder
3. Cylindrical layer of liquid metal with conductivity \( \sigma \), height \( d_h \) and mean radius \( R \) is moving axially with velocity \( v \) in the annular nonmagnetic gap with height \( d_m \).
6. Ideal ALIP model

From Amperes law follows boundary condition: \[ B_z \bigg|_{r=r_o} = \mu_0 I_{lin} \]

Induction equation (r component) to solve in the gap:

\[
\frac{\partial^2 (rB_r)}{\partial r^2} + \frac{\partial^2 B_r}{\partial z^2} - \mu_0 \sigma \left( \frac{d_n}{d_m} \right) \left[ \frac{\partial B_r}{\partial t} + \nu \frac{\partial B_r}{\partial z} \right] = 0
\]
6. Ideal ALIP model

\[
\frac{\partial^2 (r B_r)}{\partial r^2} + \frac{\partial^2 B_r}{\partial z^2} - \mu_0 \sigma \left( \frac{d_h}{d_m} \right) \left[ \frac{\partial B_r}{\partial t} + v \frac{\partial B_r}{\partial z} \right] = 0
\]

Let us height-average induction equation (otherwise solve for vector potential \( A \)):

\[
\frac{1}{d_m} \cdot \frac{\partial (r B_r)}{\partial r} \bigg|_{r=r_i}^{r=r_o} + \frac{\partial^2 B_r}{\partial z^2} - \mu_0 \sigma \left( \frac{d_h}{d_m} \right) \left[ \frac{\partial B_r}{\partial t} + v_z \frac{\partial B_r}{\partial z} \right] = 0
\]

Using divergence of \( B \) and boundary conditions, height-averaged form is obtained:

\[
\frac{\partial (r B_r)}{\partial r} = - \frac{\partial B_z}{\partial z} \quad \Rightarrow \quad \frac{\partial^2 B_r}{\partial z^2} - \mu_0 \sigma \left( \frac{d_h}{d_m} \right) \left[ \frac{\partial B_r}{\partial t} + v \frac{\partial B_r}{\partial z} \right] = i \alpha \mu_0 \frac{\sqrt{2A}}{d_m}
\]
6. Ideal ALIP model

\[ \frac{\partial^2 B_r}{\partial z^2} - \mu_0 \sigma \left( \frac{d_h}{d_m} \right) \left[ \frac{\partial B_r}{\partial t} + \nu \frac{\partial B_r}{\partial z} \right] = i \alpha \mu_0 \frac{\sqrt{2A}}{d_m} \]

Looking for solution in form:

\[ B_r = B \cdot e^{i(\alpha z - \omega t)} \]

Complex amplitude of magnetic field is obtained:

\[ B = \frac{B_0}{i + Rm_s} \]

Where external field has been introduced:

\[ B_0 = \frac{\mu_0 \sqrt{2A}}{d_m \alpha} \]
6. Ideal ALIP model

\[ B = \frac{B_0}{i + Rm_s} \]

Slip magnetic Reynolds number:

\[ Rm_s = Rm \cdot s \]

Magnetic Reynolds number:

\[ Rm = \frac{\mu_0 \sigma v_B}{\alpha} \left( \frac{d_n}{d_m} \right) \]

Slip:

\[ s = 1 - \frac{v}{v_B} \]

Velocity of magnetic field:

\[ v_B = \frac{\omega}{\alpha} = 2 \tau f \]
6. Ideal ALIP model

Height averaged induced current density follows from Ampere's law:

\[
\bar{j} = j \cdot e^{i(\alpha z - \omega t)} e_\phi = \left[ \frac{1}{\mu_0} \frac{\partial B_r}{\partial z} - \frac{I_{\text{lin}}}{d_m} \right] e_\phi = -\frac{Rm_s}{i + Rm_s} \frac{\sqrt{2}A}{d_m} \cdot e^{i(\alpha z - \omega t)} e_\phi
\]

Quasi-stationary developed pressure can be found using complex amplitudes:

\[
\Delta p = \text{Re} \left[ \frac{jB^*}{2} \right] \cdot \frac{V}{S} \cdot \frac{e_\phi \times e_r}{e_z}
\]

It leads to a relatively simple formula widely used in EMP design:

\[
\Delta p = \frac{\sigma B_0^2 v_B L}{2} \cdot \frac{s}{1 + Rm_s^2}
\]
7. Role of the slip magnetic Reynolds number in ALIP

What is slip magnetic Reynolds number?

Slip magnetic Reynolds number:

\[ Rm_s = Rm \cdot s \]

Magnetic Reynolds number:

\[ Rm = \frac{\mu_0 \sigma v_B}{\alpha} \left( \frac{d_n}{d_m} \right) \]

Slip:

\[ s = 1 - \frac{v}{v_B} \]

Velocity of magnetic field:

\[ v_B = \frac{\omega}{\alpha} = 2\pi f \]

What does it characterize???
7. Role of the slip magnetic Reynolds number in ALIP

**What does it characterize?**

One definition can be: ratio of magnetic field convection and diffusion.

In context of ALIP: ratio of induced and full magnetic fields.

\[ Rm_s = \frac{\mu_0 \sigma (v_B - v) \tau}{d_h} \]

- **Electrical conductivity**
- **Relative motion of magnetic field**
- **Characteristic size (pole length)**
7. Role of the slip magnetic Reynolds number in ALIP

Distribution of height averaged external magnetic field in ALIP

\[ \nu_B = 2\pi f \]
7. Role of the slip magnetic Reynolds number in ALIP

Developed EM pressure in Ideal ALIP is function of $Rm_s$:

$$\Delta p = \frac{\sigma B_0^2 v_B L}{2} \cdot \frac{s}{1 + Rm_s^2} \sim \frac{Rm_s}{1 + Rm_s^2}$$

![Graph showing the relationship between EM pressure/force and slip magnetic Reynolds number (Rms). The graph illustrates the maximum EM pressure/force at various flowrates. High and low flowrates are indicated on the x-axis, with Rms values ranging from 0 to 2.5. The graph also shows the trend as Rms approaches 0 and infinity.](image)
7. Role of the slip magnetic Reynolds number in ALIP

Demagnetization - Lenz Law – Skin effect – Magnetic field expulsion

Induced and full field as function of $Rm_s$.

Phase of induced field as function of $Rm_s$. 
7. Role of the slip magnetic Reynolds number in ALIP

Developed EM pressure in Ideal ALIP is function of $Rm_s$:

$$\Delta p = \frac{\sigma B_0^2 v_B L}{2} \cdot \frac{s}{1 + Rm_s^2} \sim \frac{Rm_s}{1 + Rm_s^2}$$

![Graph showing the relationship between pressure and slip magnetic Reynolds number. The graph is divided into stable and unstable regions. The x-axis represents Rms, and the y-axis represents pressure. There are three curves: one for Rms -> 0, one for Rms -> inf, and another for Rms/(1+Rms^2). The stable region is shaded green, and the unstable region is shaded red.](image)
8. Stalling instability in ALIP

Operating point of ALIP is defined by pressure – flowrate characteristics of pump and hydraulic load (loop).

\[ \Delta p = \Delta p_{EM} + \Delta p_L \]

\[ Rm_s = 1 \]
8. Stalling instability in ALIP

In experimentally reported behaviour of a large ALIP for SFR by Ota et al. three principal operating areas were identified and summarized:

2. Transient, instability. Operation is impossible in this area.
3. MHD instability. Inhomogeneous flow, large fluctuation of flowrate and pressure. Undesirable operation regime.
8. Stalling instability in ALIP

Stalling condition:

\[
\frac{\partial (\Delta p_{EM})}{\partial Q} > \frac{\partial (\Delta p_L)}{\partial Q}
\]

No stalling!
8. Stalling instability in ALIP
8. Stalling instability in ALIP
9. MHD instability in ALIP

Why stalling and transition to unstable region (3) is undesirable?

Stalling in context of ALIP is uncontrolled transient from stable region (1) to unstable (3).

Region (3) is characterized by **MHD instability**. Behaviour of ALIP is very different. E.g. steady flow assumption *falls apart.*
9. MHD instability in ALIP

\[ Rm_s = \frac{\mu_0 \sigma (v_B - v_z) d_h}{\alpha d_m} \approx 1 \]

A: \( v_z \uparrow f_z \downarrow \) or \( v_z \downarrow f_z \uparrow \)

Stable velocity profile

B: \( v_z \uparrow f_z \uparrow \) or \( v_z \downarrow f_z \downarrow \)

Instable velocity profile

1. Cut!
2. Unfold!

\[ \Delta r \ll R \]

INLET

OUTLET

Periodic boundaries

MHD pumps: Annular Linear Induction Pumps (ALIP)
9. MHD instability in ALIP

1. Amplifications of azimuthal unhomogenities
2. Low frequency pressure pulsations
3. Vibrations
4. Strongly vortical flow
5. Decrease of efficiency

Gailītis et al. (1975)
MHD instability threshold

Kirillov et al. (1980)
Ota et al. (2004)
Araseki et al. (2004)
Experimental evidence

Kirillov et al. (1980)
Ota et al. (2004)
Araseki et al. (2004)

Araseki et al. (2004)
2D φ-z model of ALIP

MHD pumps: Annular Linear Induction Pumps (ALIP)
10. Experimental and numerical studies on TESLA-EMP loop (IPUL)

Experimental pump

Integral measurements:
- Pressure
- Flowrate
- Temperature
- Voltage
- Current
- Pressure pulsations

Technological pump
10. Experimental and numerical studies on TESLA-EMP loop (IPUL)

144 point magnetic field measurements fixed on inductor (grid y-z: 50 x 60 mm)
10. Experimental and numerical studies on TESLA-EMP loop (IPUL)

Controlled parameters:
• Applied current $I$ to FLIP ($N$)
• Flowrate $Q$ in the loop ($R_{ms}$)

Power supply of $f = 50$ Hz was used.

Operating regimes:

\[ I = 220 \ [A] \quad N = 0.67 \]
\[ Q = 0 \ldots 42 \ [L/s] = 0 \ldots 151 \ [m^3/h] \quad R_{ms} = 4.8 \ldots 3.43 \]
10. Experimental and numerical studies on TESLA-EMP loop (IPUL)

\[ Rm_s = 3.43 \quad (Q = 40 \text{ L/s}) \]

- **Development of M-shape**d flow profile
- **Steady distribution** of \(|B_x|\)
- **Qualitative agreement**
  
  spatial resolution: 50 x 60 [mm]
  temporal: 0.05 [s]
10. Experimental and numerical studies on TESLA-EMP loop (IPUL)

\[ Rm_s = 3.82 \quad (Q = 30 \text{ L/s}) \]

- Pronounced M-shaped flow profile.
- Negative velocity in centre of outlet
- Small oscillation of \(|B_x|\) in the outlet
- Agreement maintained
10. Experimental and numerical studies on TESLA-EMP loop (IPUL)

$Rm_s = 4.15$  
$(Q = 20 \text{ L/s})$

- Transition to **vortical flow**
- **Periodic oscillations** of $v_z$ and $|B_x|$
- Strong **recirculation in centre**
  - Loss of symmetry
- **Oscillations confirmed experimentally**
10. Experimental and numerical studies on TESLA-EMP loop (IPUL)

\[ Rm_s = 4.47 \quad (Q = 10 \text{ L/s}) \]

- Flow **strongly vortical** all-over the channel
- **Irregular oscillations** of \( v_z \) and \( |B_x| \)
- Qualitative agreement maintained

\[ R_m s = 4.47 \quad (Q = 10 \text{ L/s}) \]
11. Experimental and numerical studies on PEMDYN loop (CEA)

<table>
<thead>
<tr>
<th>PEM specification</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Liquid sodium</td>
</tr>
<tr>
<td>Flowrate</td>
<td>0 - 1500 m³/h</td>
</tr>
<tr>
<td>Temperature</td>
<td>115 - 200°C</td>
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<tr>
<td>Input current</td>
<td>0 – 550 A</td>
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<tr>
<td>Supply frequency</td>
<td>5 – 20 Hz</td>
</tr>
<tr>
<td>Max power input</td>
<td>325 kW</td>
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<tr>
<td>Phases</td>
<td>3</td>
</tr>
<tr>
<td>Pole pairs</td>
<td>3</td>
</tr>
<tr>
<td>Slots/pole/phase</td>
<td>2</td>
</tr>
<tr>
<td>Stator length</td>
<td>2 m</td>
</tr>
</tbody>
</table>

MHD pumps: Annular Linear Induction Pumps (ALIP)
11. Experimental and numerical studies on PEMDYN loop (CEA)

- Accuracy of numerical models in support of pump design: performance curves

  ➢ Discrete inductor model

  ➢ Current sheet model

  ![Diagram of MHD pumps: Annular Linear Induction Pumps (ALIP)]

  ![Performance curve: 5Hz 400A]

Linards Goldšteins / Emmanuel Lo Pinto

MHD pumps: Annular Linear Induction Pumps (ALIP)
11. Experimental and numerical studies on PEMDYN loop (CEA)

- Accuracy of numerical models in support of pump design: DSF amplitude estimate

![Graphs showing time and frequency plots with Rms values]

Rms > 4

Rms < 1
Useful resources

• General EM pumps design guidelines and feedback
  • Baker & Tessier – Handbook of electromagnetic pump technology

• Induction machines design
  • Nasar & Boldea – The induction machines design handbook (2nd Edition)

• MHD instabilities
  • E. Martin Lopez - Study of MHD instabilities in high flowrate induction electromagnetic pumps of annular linear design (PhD thesis)
  • L. Goldšteins – Experimental and numerical analysis of behavior of electromagnetic annular linear induction pump
Thank you for your attention!

Any questions?