A SIMPLIFIED MODEL OF CENTRIFUGAL ELECTROMAGNETIC INDUCTION PUMP WITH ROTATING PERMANENT MAGNETS

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Abstract: In this work authors discuss main physical phenomena and present simplified axisymmetric analytical model of centrifugal electromagnetic induction pump (CEMIP). Obtained results are slightly modified for real geometry of CEMIP and compared with experimental data. In the end the comparison with linear electromagnetic induction pump (LEMIP) is performed. Possible advantages and optimization of CEMIP are discussed.

Introduction

Investigations of centrifugal electromagnetic pumps for liquid metal applications have been performed already in 1980ies [1]. Due to rather complicated construction and no significant superiority shown over traditional methods of liquid metal transport, such design has not gained wide appreciation and more common linear pumps are used.

The advantages electromagnetic induction pumps (EMIP) with rotating permanent magnets over inductor based ones have been demonstrated in [2]. Centrifugal EMIP or CEMIP with rotating permanent magnets was investigated analytically in regime of zero flowrate also providing experimental data in [3], but leaving some questions unanswered. The lack of analytical models, which could be used for integral characteristic estimation, does not allow correctly analyze CEMIP and compare with linear EMIP or LEMIP.

1. Presentation of the problem

We consider conducting cylinder (fig. 1), the height of cylinder b is relatively small compared to radius in cylindrical coordinate system. Rotating permanent magnet system creates a magnetic field in form of travelling wave moving over azimuth and interacts with conductive cylinder from radius R_1 to R_2. For simplicity, in this radial region external magnetic field is considered constant over height and has only z component:

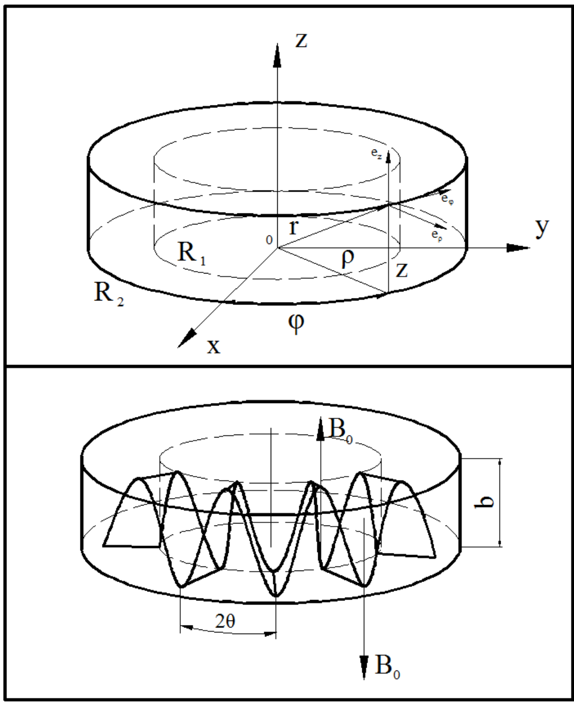
$$\boldsymbol{B_e}(\varphi, t) = Re\left[B_0 e^{iM(\omega_B t - \varphi)}\right]\boldsymbol{e_z} \quad (1)$$

Such travelling field will induce EM forces and generate azimuthal motion of conductive media in direction of travelling field. By neglecting effects over height, it is convenient to use 2D polar coordinate system. Schematic of CEMIP is shown in (fig. 2). One can divide the flow volume into two regions:

1. $R_i < \rho < R_1$ - inactive or radial transition region, where flow is determined by radial velocity component v_ρ and in case of non-zero flowrate azimuthal component v_φ is neglected.
2. $R_1 < \rho < R_2$ - active or magnetic field interaction and pressure development region, where flow is mainly determined by azimuthal velocity component v_φ, but radial component v_ρ

also has significant impact because of inertial braking force, which appears due to radial (transverse) motion of fluid.

Developed pressure is determined by processes in active or magnetic field interaction region $R_1 < \rho < R_2$, therefore only this region is mainly considered in the simplified analytical model.



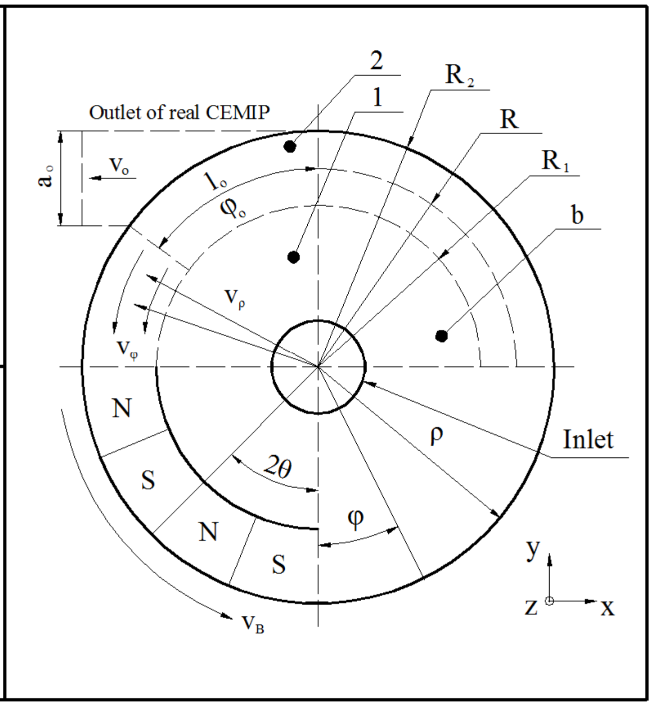


Fig. 1. Cylindrical coordinate system with conductive liquid and travelling magnetic field.

Fig. 2. Principal schematic of CEMIP. 1 – inactive region, 2 – active region.

Several assumptions have been made to simplify the model. First of all, azimuthal and radial velocities have axi-symmetric forms to satisfy continuity:

Secondly, active parts mean radius is big enough to neglect curvature of cylindrical system and magnetic Reynolds number multiplied by slip is significantly less than unity:

In case of (5), the averaged EM force can be expressed in rather simple form (6). Frictional losses are taken into account by semi-empirical formulation [4] of friction factor λ.

As λ is also function of velocity solution method requires initial guess and iterative approach. After inserting (6, 7) in Navier - Stokes equation we have 2 equation system of 2 unknown parameters - v_φ and p:

$$\begin{cases} \rho_m\left(\frac{v_\rho^2}{\rho}+\frac{v_\varphi^2}{\rho}\right)-\frac{\sigma B_0^2}{2}v_\rho=\frac{\partial p}{\partial \rho} & (8) \\ \frac{\lambda}{D_h}\cdot\frac{\rho_m v_\varphi^2}{2}+2\rho_m\frac{v_\varphi v_\rho}{\rho}-\frac{\sigma B_0^2 k_v}{2}\left(v_B-v_\varphi\right)=0 & (9) \end{cases}$$

After radially averaging second term in (9) with (10) and introducing rations of forces K - inertial – friction; N_λ - electromagnetic – friction (11, 12):

$$2\rho_m\frac{v_\varphi v_\rho}{\rho}\approx\frac{\rho_m Q}{\pi b R^2}v_\varphi \quad (10); \quad K=\frac{2QD_h}{\lambda v_B \pi b R^2} \quad (11); \quad N_\lambda=\frac{\sigma B_0^2 k_v D_h}{\lambda \rho_m v_B} \quad (12);$$

Equation (9) is transformed to quadratic algebraic equation solution of which is:

$$v_\varphi=\frac{v_B}{2}(K+N_\lambda)\left[\sqrt{1+\frac{4N_\lambda}{(K+N_\lambda)^2}}-1\right] \quad (13)$$

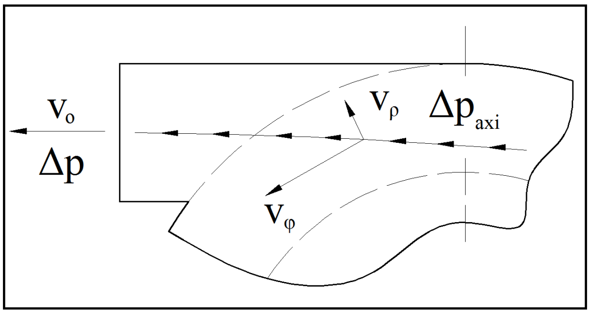


Fig. 3. Some mean streamline in the outlet.

Using (3, 13) in integration of (8) solution for axi-symmetric case is obtained. However, for real geometry (fig. 3) Bernoulli's law is used on some mean streamline with coefficients (14, 15) and using axi-symmetric solution. Finally, using (4) and introducing (16) developed pressure of CEMIP can be calculated (17) or in case of zero flowrate Q using (18).

$$k_\varphi=\left(\frac{1}{\varphi_o}\int_0^{\varphi_o} cos(\varphi)\,d\varphi\right)^2 \quad (14); \quad k_\rho=\left(\frac{1}{\varphi_o}\int_0^{\varphi_o} sin(\varphi)\,d\varphi\right)^2 \quad (15); \quad v_R=\frac{Q}{2\pi R b} \quad (16)$$

$$\Delta p=\rho_m\cdot\frac{\Delta R}{R}\cdot\left(v_\varphi^2+v_R^2\right)-\frac{\sigma B_0^2 v_R R}{2}\cdot ln\left(\frac{R_2}{R_1}\right)+\frac{\rho_m}{2}\cdot\left(k_\varphi v_\varphi^2+k_\rho v_R^2-v_o^2\right)+\delta p_i \quad (17)$$

$$\Delta p|_{Q=0}=\frac{\rho_m v_\varphi^2}{2}\cdot\left[2\frac{\Delta R}{R}+k_\varphi\right] \quad (18);$$

2. Comparison with experimental results

Experimental loop (fig. 4) consisted of electromotor (1.) and rotor of magnetic system (2.). It was possible to change air gap (*d*) using bolt mechanism. Channel of pump with liquid metal (4) was placed into open vessel (3.) externally cooled by the water. In-Ga-Sn eutectic was used to be able operate in room temperature and without external heating. Valve (5.) and EM conduction flow meter (6.) were used to regulate and measure flowrate of CEMIP. Single differential gas-liquid manometer (7.) was used to estimate developed pressure difference between inlet and outlet. It was possible due to the fact that diameter of expansion tank (9.) was much larger than diameter of manometer and changes of base level were so minor that they could be neglected. Before filling the loop from supply tank (10.) it was for-vacuumed with mechanical vacuum pump (8.). Experimental loop parameters are collected in (table. 1).

Table. 1. Parameters and their values of experimental setup.

CEMIP dimensions				Other parameters		B field parameters	
Radius, m		Dimensions, m				d, mm	B_0,T
R_2	0.15	b	0.01	σ, S/m	3. 46 e6	5	0.27
R	0.125	a_o	0.06	ρ_m, kg/m^3	6.44 e3	10	0.18
R_1	0.1			μ, Pa/s	2.4 e-3	15	0.13
R_i	0.02			Poles	16	20	0.09

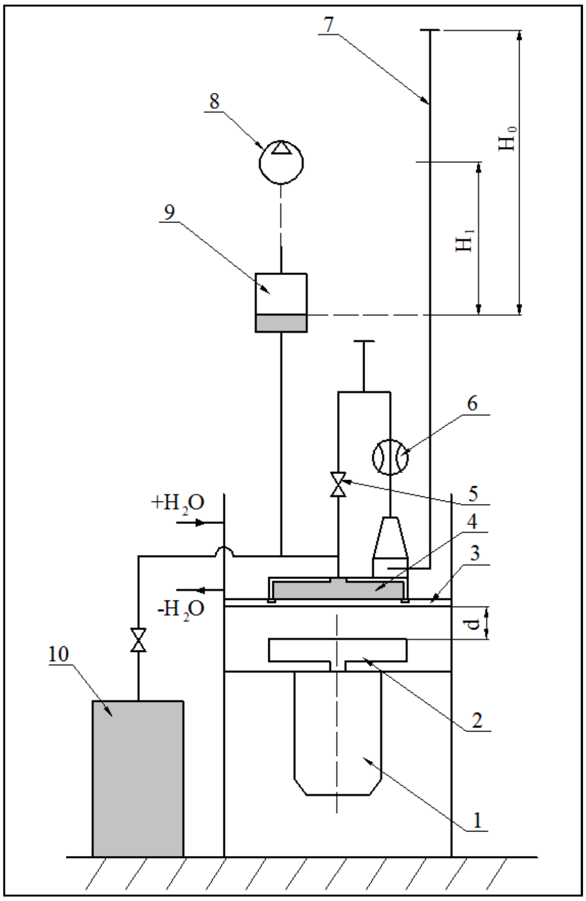


Fig. 4. Experimental loop of CEMIP.

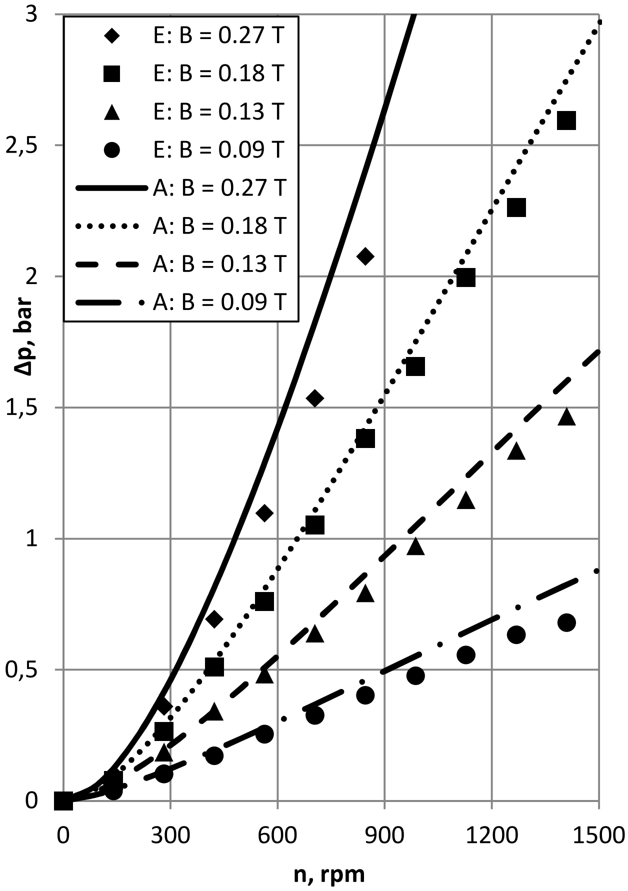


Fig. 5. Developed pressure as function of magnetic systems rotation speed. Q = 0 [l/s].

Comparison of maximum developed pressure with different amplitude of magnetic field B_0 is shown in (fig. 5), where E – experimental data and A – analytical solution (18). It can be observed, that in all cases analytical results correspond to experiment fairly well. In the case of high N (high B_0 and low v_B), developed pressure increases as quadratic function of rotation, while for smaller values it increases almost linearly.

In (Fig. 6 – 9.) E - experimental data and A – analytical solution (17) of Δp – Q curves with fixed rotation speed n and magnetic field amplitude B_0 are compared. Theoretical model qualitatively corresponds to experimental data. However, better agreement is achieved with lower B_0 (N) (fig. 8, 9). It could be explained by smaller influence of friction factor λ, which is estimated approximately, in calculation of v_φ and therefore developed pressure.

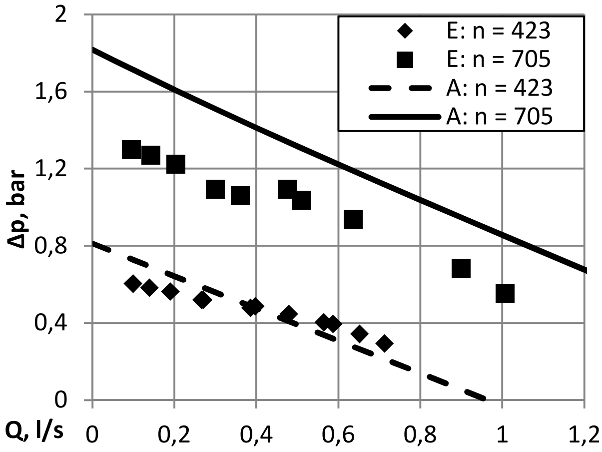


Fig. 6. $\Delta p - Q$ curves, $B_0 = 0.27$ [T].

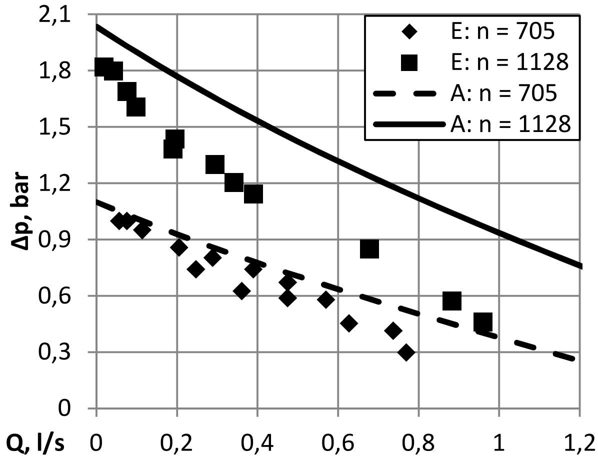


Fig. 7. $\Delta p - Q$ curves, $B_0 = 0.18$ [T].

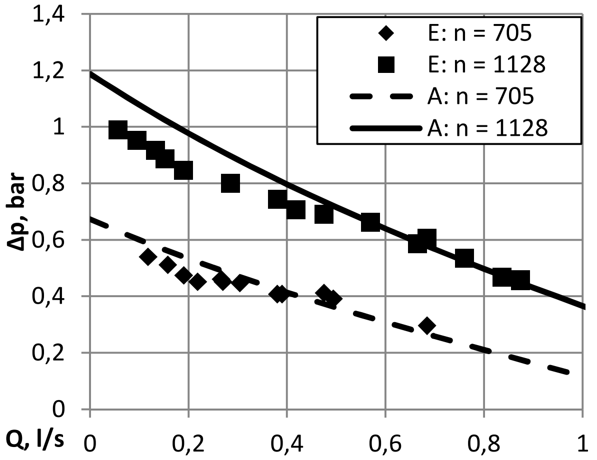


Fig. 8. $\Delta p - Q$ curves, $B_0 = 0.13$ [T].

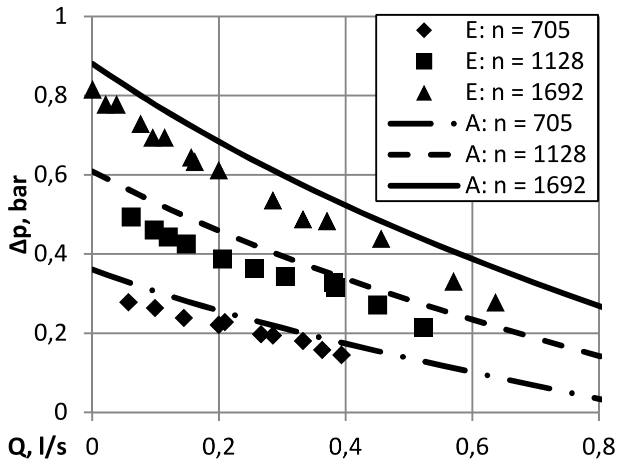


Fig. 9. $\Delta p - Q$ curves, $B_0 = 0.09$ [T].

3. Conclusion

The simplified estimations (17, 18) derived in this work shows qualitative agreement with experimental data (fig. 5 – 9) and can be used for estimation of integral parameters of CEMIP. Due to principally different physical mechanism of pressure development from LEMIP, such device might have advantage in application where mixing of conductive media is required and low values of N_λ are only possible. Expanded and detailed version of this study can be found in [5].

4. References

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