ASSESSMENT OF LINEAR PERMANENT MAGNET LIQUID METAL DISPENSER

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Abstract: A new type of a liquid metal pump has been developed for efficient contactless dispensing out of industrial metal furnaces. The concept consists of two opposing arrays of cylindrical diametrically magnetized synchronously rotating permanent magnets (Fig.1). The magnetization directions of the magnets are phase-shifted in respect to each other to maximize magnetic field strength and reduce oscillating forces between the magnets and overall torque. Numerical modelling for magnetic fields, resulting forces and torques was done with Comsol in 3D. A numerical model was built in order to verify the analytical model, where it was possible. It was found that there exist 3 minimums for the sum of the torques. These calculations gave the mechanical constraints needed to construct such a device.

Keywords: liquid metal, pump, permanent magnets, phase shift, torque

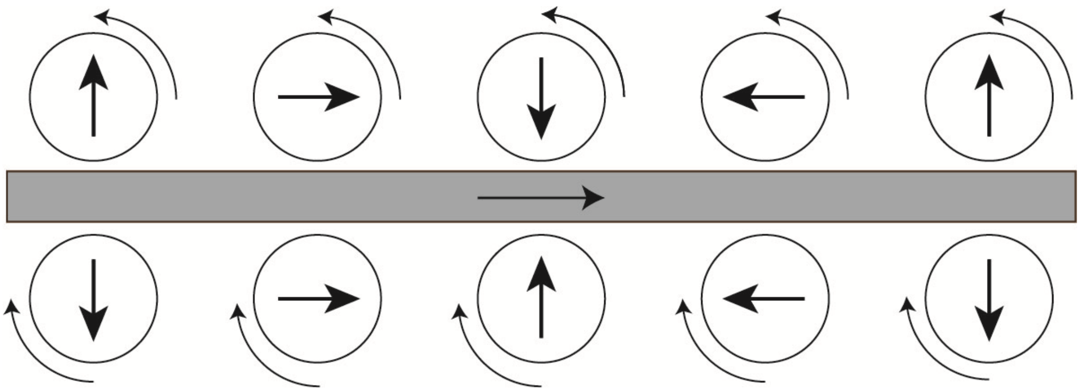

Figure 1. Cylindrical magnets with a linear liquid metal channel

1. Introduction It has been proven that permanent magnet systems can create industrially relevant liquid metal flows. [1,2,3] The goal of this study was to find the best configuration of magnets in order to achieve a minimum torque needed to power the magnet system. When the magnets are all magnetized in the same direction, the torque necessary to rotate them is very high in the beginning and changes its sign when passing a quarter of a rotation. This results in a heavily oscillating system when the system is driven. Such a system would be impractical because of the high stresses in the driving mechanism. Because the application of this pump would be for metallurgy, its reliability is very important. It is known that using permanent magnets in a Halbach array increases the magnetic field strength on one side and decreases on the other side. [4] This principle is used as a guideline for this study in order to achieve maximum magnetic field strength between the two rows.

2. Theoretical model A permanent magnet can be viewed mathematically as the sum of loops of electric current. Each loop has a magnetic moment expressed by:

$$\mu = \frac{1}{2} r \times j, \tag{1}$$

where μ is the magnetic moment, r is the position vector and j is the electric current density. In order to calculate the torque acting on a magnet, this formula is used:

$$\tau = \mu \times B, \tag{2}$$

where τ is the torque acting on the magnet and B is the external magnetic field. The angle between the magnetization directions of two consecutive magnets is defined as θ (see Fig.2).

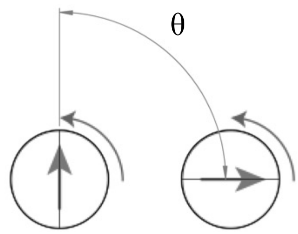

Figure 2. The angle θ

By integrating all of the electrical current loops, the external magnetic field can be calculated. Then the external magnetic field is applied to one of the magnets (which is not included in the external field) and the torque is calculated. Then the same is done for one full rotation of the magnet so the sum value is known. This was done for each of the magnets and finally, the sum of torques is calculated and plotted with respect to the phase angle between them (see Fig.3). All of these calculations were done using Mathcad 15.0.

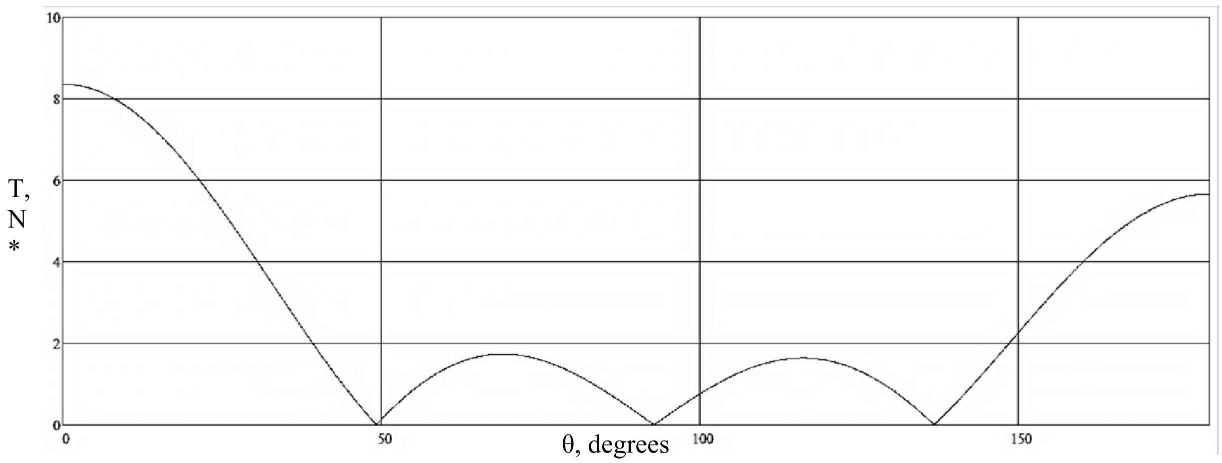

Figure 3. Torque sum vs phase angle θ for 1 row

The torque sum minimums were found when θ=49,1; 92,8; 136,8. It was also calculated that the sum of torques for both rows results in a constant value of T=2,2x10e-15 $N \cdot m$ over the range of θ.

3. Experimental setup The experimental device (Fig.4) was built with 10 cylindrical NdFeB magnets (D50mmx200mm), 5 in each row in a stainless steel frame coupled together with a system of gears, sprockets and chains. The remanent magnetization of the magnets is 1,42 T. The distance between magnet axis in one row is 88 mm and the distance between the two rows is 115 mm. A 11 kW three-phase motor was used as the drive.

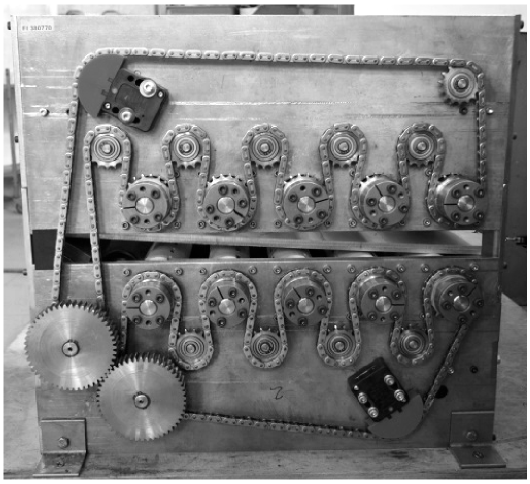

Figure 4. Experimental device – front

An experiment was made where the pushing power of this pump was tested. A sheet of aluminium alloy 5754 with sizes 12x180x600 mm was put in between the two rows of magnets and using luggage scales, the force exerted on the sheet was measured as a function of the rotational frequency of magnets (Fig.5).

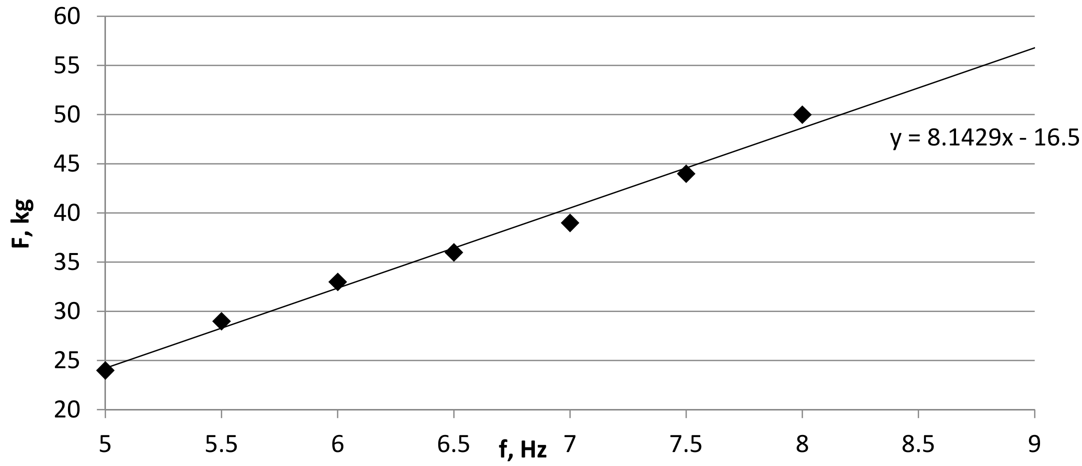

Figure 5. Force exerted on an aluminium sheet vs rotational frequency

During the experiments it was noted that the aluminium sheet was warming up and at the same time the force measured was dropping. The warming up is caused by Joule heating when the magnets induce currents and this effect is dependent upon the rotational frequency. Furthermore, when the temperature increases in the aluminium, it’s conductivity decreases, so the resulting electromagnetic force decreases.

An estimate for the pressure head of liquid aluminium can be done. The pressure created is calculated as P=2,27 bar at 8 Hz. Thus the pressure head is

$$h = \frac{P}{\rho \cdot g} = \frac{F}{S \cdot \rho \cdot g} = 9{,}75m$$

4. Numerical model A 3D stationary study was done in COMSOL Multiphysics 5.0 calculating magnetic fields and forces using a parametric sweep. The two parameters used for the sweep were θ – an angular shift parameter and a t parameter for time. The time parameter is only symbolic as the study is stationary; t is only used to evaluate the system when it has been shifted as if it would be turning. θ is defined as the angle of phase shift of magnetization between two consecutive magnets. The sweep for θ used values between 0 and 180 degrees with the step size of 0,5 degrees. The sweep for t used values between 0 and 4,5 with step size of 0,5 s. In the model the rotational frequency was set to 0,1Hz, so this gave the values for the first half turn. An air region of 8x8x8 m was chosen around the magnets in order to minimise the end effects. Then the model calculated the sum of all torques created by the magnetic field interactions over the range of θ and integrated over the range of t (Fig.6). The graph is plotted only for θ between 0 and 180 degrees because the geometry is symmetrical.

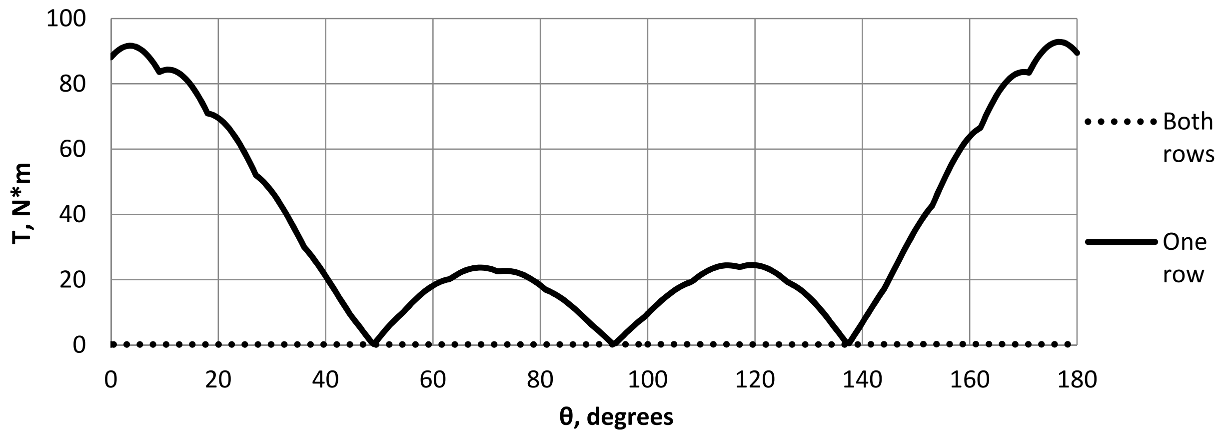

Figure 6. Torque sum vs phase angle θ

The torque sum minimums were found for θ=49; 93,5; 138. At these points, the value of the torque sum is around $T \approx 0{,}3\ N \cdot m$. When calculating the torque sum over both rows, the resulting values show no minimums and the absolute values are very low (around $0{,}15\ N \cdot m$) compared to the one row situation.

5. Results and discussion The numerical and analytical analysis shows that there exist three minimums for the sum of torques of 5 magnets in one row. Thus, one of these three angles θ should be used in order to minimise the issues encountered with the mechanical drive of such a device. It is suspected that of these three θ, the one closest to 90 degrees should be used because this configuration is the closest to a Halbach array and preliminary estimate shows that this angle produces the best pumping parameters. The θ values for both analyses show a good agreement because the difference between them is less than 1%.

It should be noted that it was calculated that the sum of torques for both rows is constant and approaches 0 whatever the angle θ, however, each individual magnet is subjected to varying torques over the rotational period. This can be explained by the symmetry of the system – the configuration in one row is mirrored to the other row thus the forces cancel out each other. Furthermore, the ability to set the angle θ for each magnet has a limited precision thus the sum of torques is not constant in reality.

6. Conclusions An analytical analysis calculating the sum of torques for a 10 cylindrical permanent magnet liquid metal pump was performed with success. A numerical analysis was done to verify the analytical solutions.

Another analysis should be made to find out the most optimal phase angle with regard to the effectiveness of the liquid metal pumping capabilities (pressure, flowrate). It was found that the overall torque needed for powering the system is very small, so if the mechanical drive can be made very rigid, the phase angle should be optimized for maximum pump effectiveness.

REFERENCES

[1] A.Bojarevics et al. (2015) Arrays of Rotating Permanent Magnet Dipoles for Stirring and Pumping of Liquid Metals

[2] A.Bojarevics et al. (2014) Experimental Model Tests of a Permanent Magnet Stirrer for Aluminium Furnaces

[3] A. Bojarevics, T. Beinerts, (2010) Experiments on Liquid Metal Flow Induced by Rotating Magnetic Dipole Moment

[4] K.Halbach (1980), Design of Permanent Multipole Magnets with Oriented Rare Earth Cobalt Materials