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ELECTROMAGNETIC INDUCTION PUMP WITH ROTATING PERMANENT MAGNETS CAVITATION PROCESS INFLUENCE ON PRESSURE – FLOW-RATE CURVES

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Abstract

The study aims to investigate the performance of the electromagnetic induction pump with rotating permanent magnets operating at low pump inlet pressure values to determine the cavitation process's influence on the pump's pressure–flow–rate characteristics.
The experiments used the disc-type pump with rotating permanent magnets with a channel active cross-section of 20 x 70 mm and a mean diameter of 330 mm. The drive unit of the pump is a 22 kW 3-phase asynchronous electric motor. The pump's rotors have nine pole pairs of samarium-cobalt magnets. A series of experiments utilized the test loop operating with liquid sodium, equipped with two pumps and different pump interconnection possibilities, allowing series and parallel or standalone pump operation. Various values of pump inlet pressure and flow rate combinations were investigated. Pumps inlet pressure values vary from 0,01 to 3.2 bar absolute pressure. A severe flow rate decrease at low inlet pressures was observed alongside a boiling noise allowing us to judge the cavitation process occurrence in the pump. The flow rate differences at higher and lower inlet pressure values reach more than 30 %. Also, the pumps drive unit power consumption curves to identify the pump's cavitation process.

Keywords: cavitation; liquid sodium; electromagnetic pump; pressure-flow rate curves.

1. Introduction.

Electromagnetic induction pumps for liquid metals, as every type of pump, face cavitation issues when operating at low inlet pressures. It leads to flow parameters deterioration and can cause damage to the pump channel. Electromagnetic induction pumps (EMP) with rotating permanent magnets (PM) gained broader application at the end of 1990ties [1] when permanent magnets with sufficiently high magnetic fields became commercially available [2]. The operation principle relies on the Lorentz force created by a movement of the rotating permanent magnets displaced near the pump's channel [3]. Permanent magnets are placed on each rotor with varying polarity, thus creating a traveling magnetic field. The rotor is not touching the pump's channel resulting in a fully hermetical channel without any sealings. The EMPs with PM main advantages are the hermetic pump channel, relatively simple design and low costs, industrial drive unit use, and the magnetic rotor that can be easily disassembled from the pump channel [4]. Very little research has

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been done to investigate the electromagnetic induction pump with a rotating permanent magnet cavitation process. The study utilizes a purely experimental approach to determine the margins of the cavitation process for the EMP with rotating PM. The experimental investigation used the disc-type pump installed in the loop operating with liquid sodium to understand the limitations of cavitation occurrence. The cavitation process should not be neglected during the pump operation due to the danger of damage to the pump channel [5]. Test results reveal that the pump's performance is strongly influenced by inlet pressure, varying from 0,01 to 3,2 bar absolute pressure. The decrease in the flow rate reaches almost a factor of two.

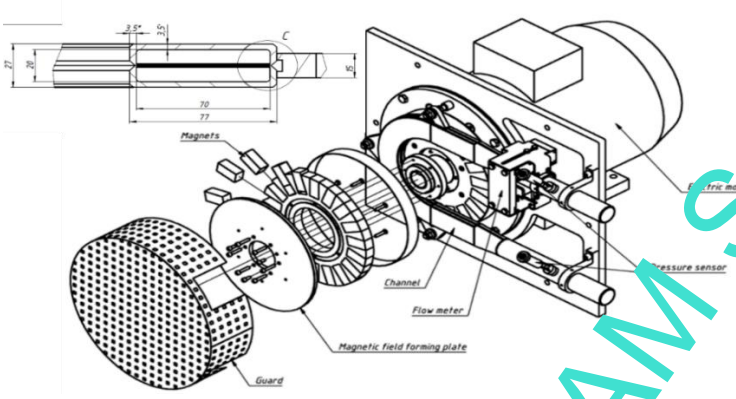

Fig. 1. Disc-type pump used for tests in the loop and its channel cross-section dimensions

2. Experimental setup and conditions.

The investigated pump and its channel cross-section are shown in figure 1. Its inner cross-section is 20 x 70 mm. The loop represented in figure 2 is from AISI 316L stainless steel. It is a closed circulation loop, using a 60,3 mm outer diameter tube with a wall thickness of 3 mm to connect all loop elements. Each pump has a conduction flow meter for the flow rate measurements, and the loop has another two flow meters for integral flow rate measurements. Loops hydraulic resistance is measured at the outlet of the investigated pump by pressure sensor 3.2 and adjusted using the valveVmD1.

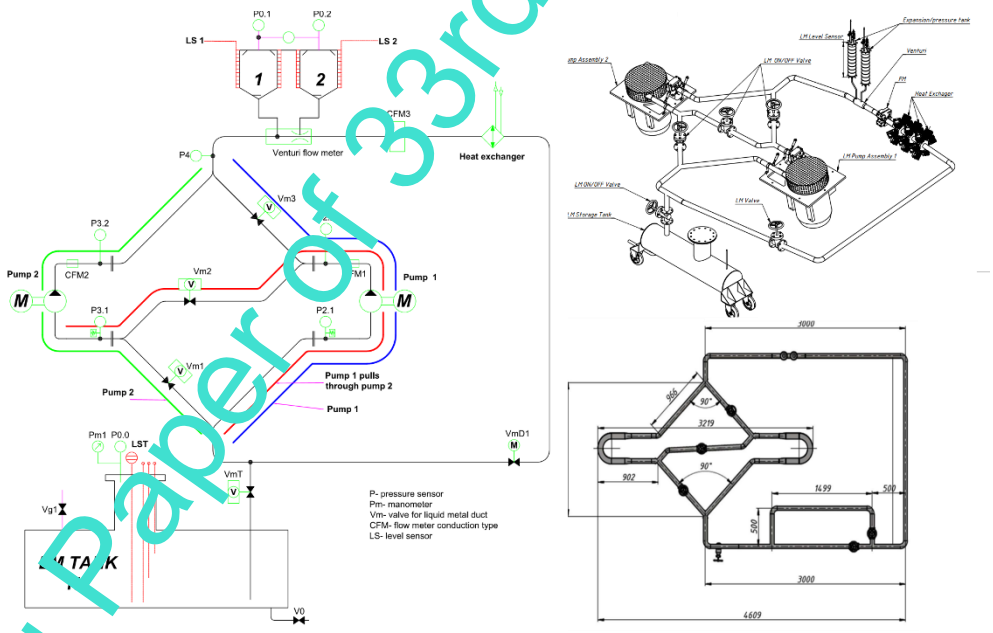

Fig. 2. Experimental loop principal scheme. The sodium flow path is drawn with a black line. The green alongside the sodium path marks the flow path "pump two." The brown line alongside the sodium path marks the flow path "pump one pulls through pump two." The blue line shows the flow path "pump one."

Pumps developed pressure is a difference between pressure measurements at sensors P2.1. and P2.2. further referred to as P_{in} and P_{out}. Loop also has two expansion tanks, 1. and 2. with continuous level meters LS1 and LS2. The pressure in the expansion tanks 1. and 2. forms the initial pressure P_{start}, measured by pressure sensors P01 and P02 when the pumps are entirely stopped. The pressure in the expansion tanks was measured using two Walfront LEPAZA60119 pressure

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sensors placed at the top of the expansion tanks. Four flow meters are installed in the loop. One of them is shown in figure 3, where the EMP with PM is delivered separately and within the sodium loop. Conduction flow meters are placed at each pump, and another for integral flow measurements. An additional Venturi flow meter is utilized for the reference flow measurement.
Our team performed several measurements, and a counterclockwise flow direction was chosen as the most appropriate for these experiments. The measurements were carried out with a fully open valve VmD1 to get the lowest loop hydraulic resistance value and highest flow rate.

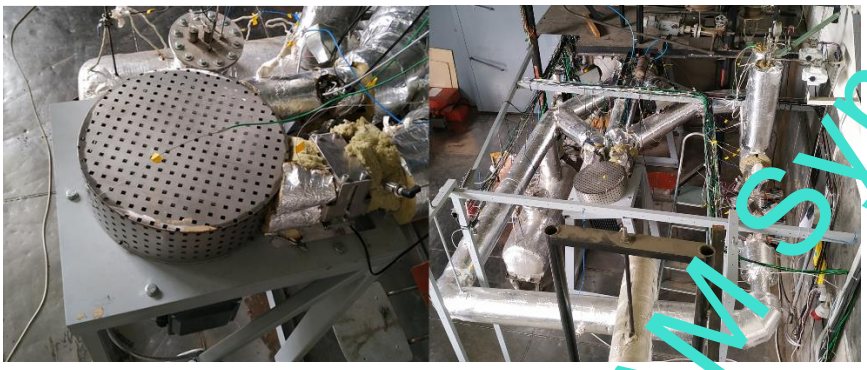

Fig. 3. Permanent magnet pump view from the top (on the left) and experimental loop.

The P_{start} value was set of 0,3;1; 1,5; 2; 2,5 and 3.0 bar absolute pressure. Pressure drop measurements along the flow pass in the loop utilizing BD DMP 331 pressure sensors P0.1.; P0.2.; P3.1.; P3.2. All pressure values are absolute pressure. The team investigated two LM loop flow configurations. The first is when pump one or pump two operates alone, through the route where the valve Vm3 is displaced, named "pump one" (or valve Vm1 for "pump two"). The other configuration has higher hydraulic resistance, where pump 2 pulls liquid metal (LM) through pump one and the leg with Vm2.

3. Measurement results and their interpretation.

Pressure–flow rate curves shown in figure 4 were obtained by varying the pump rotor's rotation speed. Measurements were carried out at a fully open valve VmD1.
The flow rate values for the "pump one" or "pump two" flow path can reach 11.8 l/s at the pump magnetic rotor rotation rate of 735 rpm. The P_{start} values of 2.5, 2.0, 1.5, and 1.0 bar follow the same path lowering to 11.4 l/s at 1.0 bar P_{start} value. The flow rate at the 0.3 bar P_{start} value drops to 5,9 l/s, caused by the cavitation observed by vibration measurements and sound spectrum recording. Also, the pump operation at low P_{start} values was accompanied by a strong "boiling" sound. The vibration and sound record analysis is not the scope of this paper.

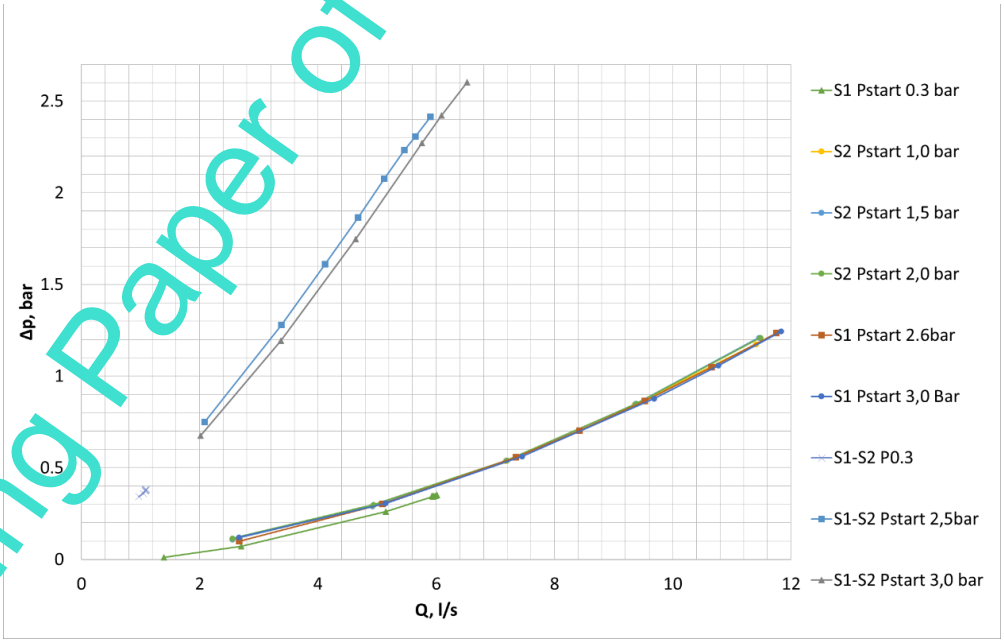

Fig. 4. Pumps developed pressure difference–flow rate (p-Q) measurement results at different flow path configurations.

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For the flow path "pump one pulls through pump two," the pump parameter deterioration is even more dramatic. The flow rate reaches only one l/s at higher P_{start} values, a clear sign of cavitation at lower inlet pressures.

The plot of the flow rate versus the pump rotor's rotation speed change is shown in figure 5. For the flow path "pump one" and "pump two," the flow rate increase is proportional to the pump magnetic rotor rotation speed increase at all initial pressure values, and the flow rate – rpm relation is a straight line. The exception is the P_{start} = 0.3 bar curve, where the line angle changes from the overall tendency at 294 rpm. The flow rate increase stops at 367,5 rpm. Further rotors rotation speed increase does not gain any flow rate increase, more so the flow rate slightly decreases at higher rotation rates. Referring to Brennen, we can consider this point a "cavitation breakdown" [6] point, where the critical combination of the inlet pressure and flow speed in the pump channel is achieved, and further magnetic field movement speed increase will not create an additional flow rate increase.

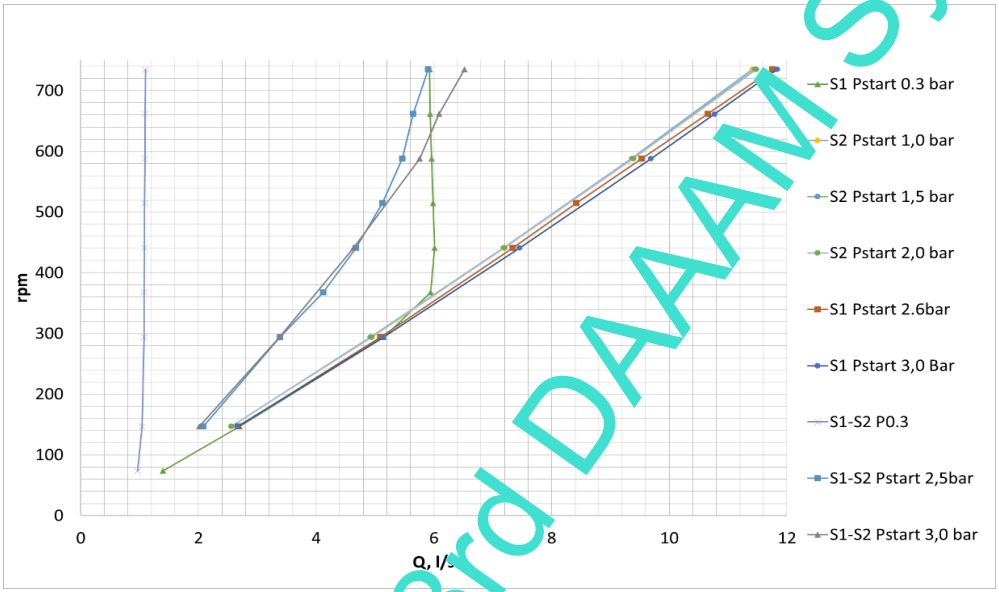

Fig. 5. Pumps developed pressure flow rates at different pump rotor rotation speed values.

For the case where "pump one pulls through pump two," the line angle is much steeper due to the higher hydraulic resistance of the loop. The deviation from the straight line starts at a 5.0 l/s flow rate even at P_{start} = 3.0 bar. At P_{start} = 2.5 bar the flow rate difference from the previous P_{start} = 3.0 bar begins from 514.5 rpm. At P_{start} = 0,3 bar, the severe cavitation starts from lower flow rates, not allowing to reach more than 1.1 l/s flow rate.

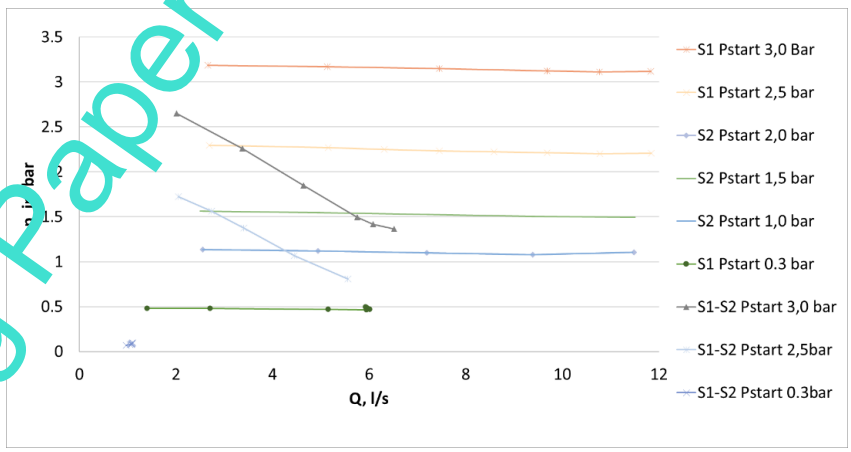

Fig. 6. Pumps developed pressure flow rates at different pump rotor rotation speed values.

Plotting the inlet pressures against the flow rate in figure 6, for the "pump one pulls through pump two" case, shows us that the inlet pressure is P2.2. drops down with the flow rate increase. This pressure drop is determined by the hydraulic

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resistance created by the Lorentz force interaction between the flowing sodium and rotor of pump two [3]. For the extreme cavitation case at P_{start} = 0,3 bar, the inlet pressure does not change much and is around 0,1 bar. As it is uncertain if the cavitation process is happening already in the channel of pump two or pump one, the case will be viewed just for reference to compare the values with the single pump operation corresponding to "pump one" and "pump two" points. For "pump one" and "pump two" cases, the inlet pressure is P2.2. or P3.2. values do not change much from the P_{start} value and are little influenced by the flow speed as we know that the pump reaches the "cavitation breakdown" point at the inlet pressure around 0,5 bar, which is determined by the combination of the inlet pressure and flow speed. This relation regarding Brennen is the cavitation number, which evaluates the probability of cavitation [5]. The cavitation number was calculated using the following formulae:

$$\sigma=2(p_1-p_v)/\rho U^2 \quad (1)$$

, where p1 is the inlet pressure P_{in}, p_v – vapor pressure [6], and U – mean flow velocity measured by the loop's flow meter. Vapor pressure varied from 2.29733E-05 Pa at 130°C to 0.00906 Pa at 227°C. A particular value of σ corresponds to the inlet pressure, P_{in}, in our case, at which cavitation occurs as the pressure is decreased, which is called the cavitation inception number and is denoted by σ_i. Cavitation number σ_a, at which the head loss is 2, 3, or 5%, often is defined as a critical cavitation number. Further reduction in the cavitation number will lead to a significant deterioration in the performance; the cavitation number at which this occurs is termed the breakdown cavitation number and is denoted by σ_b. [5]. As there were no acoustic measurements, it is impossible to determine cavitation inception and, thus, the corresponding number. Loop's tubing has an inner diameter of 54,3 mm and a cross-section of 2315,6 mm^2. Pumps channel cross-section is 1400 mm^2, which gives higher speeds at the cross-section and increases cavitation probability.
Cavitation numbers are plotted against flow speed in figure 7. For the "pump one" and "pump two" configurations, the cavitation numbers decrease with the flow speed increase for higher magnetic rotor rotation rates. At 735 rpm cavitation number varies from 9.6 at P_{start} value 3.0 bar to 3.65 at P_{start} value 1.0 bar. The P_{start} value 0,3 bar cavitation number values expectedly should follow the same path, but the situation is different – the cavitation numbers at low rotation rates drop with the flow speed increase, but the values are lower because of the lower initial inlet pressure. At 367.5 rpm, the decrease of the cavitation number stops, reaching 5.67. This s caused by the minor changes in the flow rate and, accordingly, to flow speed from 367,5 rpm to a maximal 735 rpm. Thus, we get a situation where the cavitation numbers for non-cavitating flow at P_{start} 1.0 and 1,5 bar are lower than the ones for the cavitating flow, accordingly 3.67 and 4.9 against 5.66 at P_{start} 0.3 bar at 735 rpm.

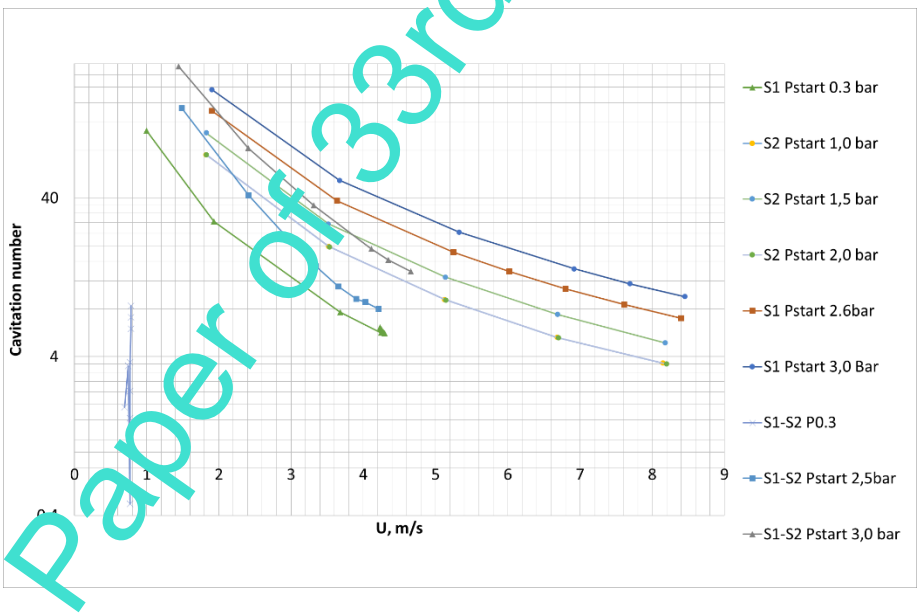

Fig. 7. Pumps flow speed at channel mean cross-section – cavitation number values at different flow path configurations.

This tendency is confirmed by plotting the cavitation number against the magnetic rotor rotation speed shown in figure 8. Here we can see the cavitation number decrease accordingly to the pump's rotor rotation speed increase for the "pump one" and "pump two" configurations for P_{start} values from 3.0 bar to 1.0 bar. The cavitation number curve for P_{start} 0.3 bar shows the change of the curve angle at 294 rpm and reaching the steady cavitation number values around 5.8 up to maximal 735 rpm.

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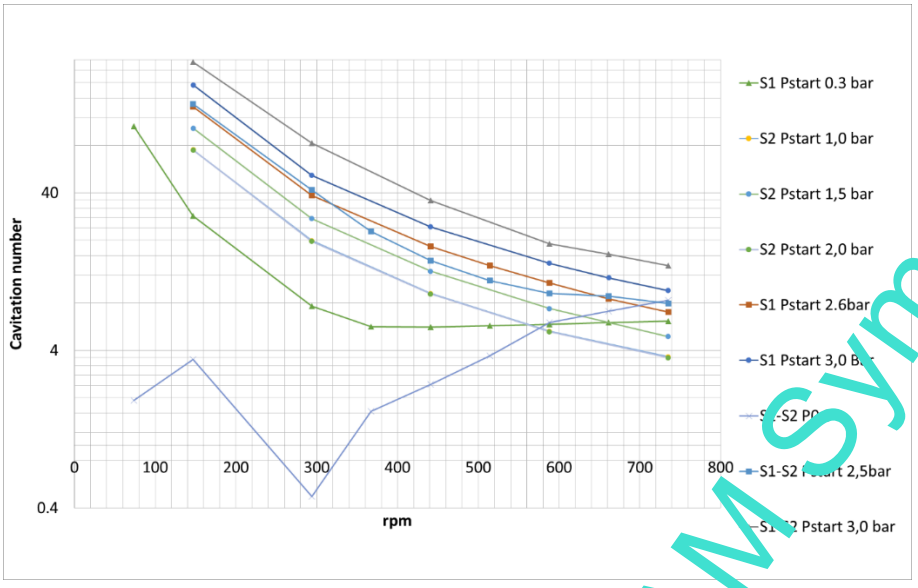

Fig. 8. Cavitation number – pumps magnetic rotor rotation rate.

The author suggests utilizing another approach for cavitation number calculation is necessary. The flow speed value is not an appropriate characteristic, which does not show the actual situation linking the electromagnetic force creating magnetic rotor movement to the conditions in the pump channel. For the centrifugal pump cavitation number calculation, the term "tip speed" is used [6]. Alternatively, the speed of the magnetic field movement would give more understanding of the "flow driving force" speed. The average radius of the pump's channel and rotation speed is used to calculate the linear speed of the magnetic rotor.

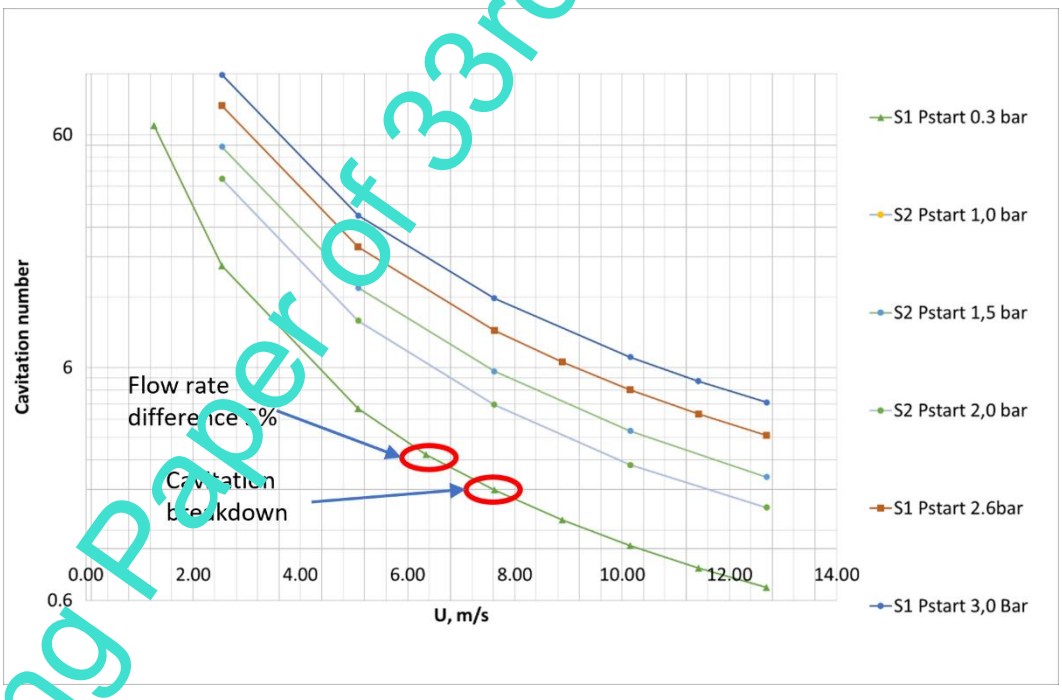

Fig. 9. Cavitation number – pumps magnetic rotor rotation rate.

The cavitation number plot against the pump's magnetic rotor rotation rate is shown in figure 9. The "pump one pulls through pump two" lines are excluded from the plot as the cavitation number values depend on the inlet pressure for P_{start} =0.3 bar giving expectedly low cavitation numbers varying from 0.57 to 0.03. For the P_{start} value, 2.5 bar cavitation

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numbers vary from 50.4 at 147 rpm to 0,88 at 735 rpm. For the P_{start} value, 3.0 bar cavitation numbers range from 87 at 147 rpm to 1,86 at 735 rpm.
The "pump one" and "pump two" configurations for P_{start} values from 3.0 bar till 1.0 bar give a stable decrease of the cavitation numbers from 38.7 till 1.5 at P_{start} 1.0 bar and corresponding values for P_{start} 3.0 bar from 108.6 till 4.3 at a magnetic rotor rotation rate from 147 till 735 rpm. The cavitation number curve for P_{start} 0.3 bar shows a similar tendency but with lower values varying from 16.4 to 0,68.
Those values gain meaning if we view them together with figure 5, where the flow rate and the pump magnetic rotor rotation rate are plotted. When the P_{start} 0.3 bar curve is compared to the P start 3.0 bar, we can see that flow rate differences of 5% start around 367,5 rpm value, corresponding to the cavitation number of 2.53. The "cavitation breakdown" for the P_{start} 0,3 bar starts at 441 rpm, corresponding to the cavitation number value of 1.8. Those numbers should also be considered considering the slip, which is always present in electromagnetic induction pumps, and for PEMDyn and Toshiba annular linear induction pumps, they are accordingly 0.172 and 0.22 [8].
Comparing the gained cavitation number values differs from literature sources for water pumps and turbines and the data on sodium pump investigation. In the work of K. Forster, for the sodium pump with a flow rate up to 150 m3/h, the cavitation inception number lies in the range of 2 to 3 for the water experiments, with slightly lower values for sodium experiments. [8]. The cavitation inception numbers for centrifugal pumps are between 0.3 and 1.4, as shown in the work of Gopalakrishnan. [10] Brennen finds the cavitation inception numbers lie around 0,8 - 1,2 and cavitation breakdown numbers for centrifugal water pumps between 0,4 and 0,5 [6]. The experimental investigation of the electromagnetic induction pump with rotating permanent magnets operating with liquid lead-bismuth eutectics (PbBi) shows the cavitation breakdown happened at the cavitation number values of 7 [11]. Although the high speed caused this in the pump inlet tubes, it is hard to compare both cases directly. The loop in the case mentioned above had a free surface, which differs from the hydraulic behavior of both loops.

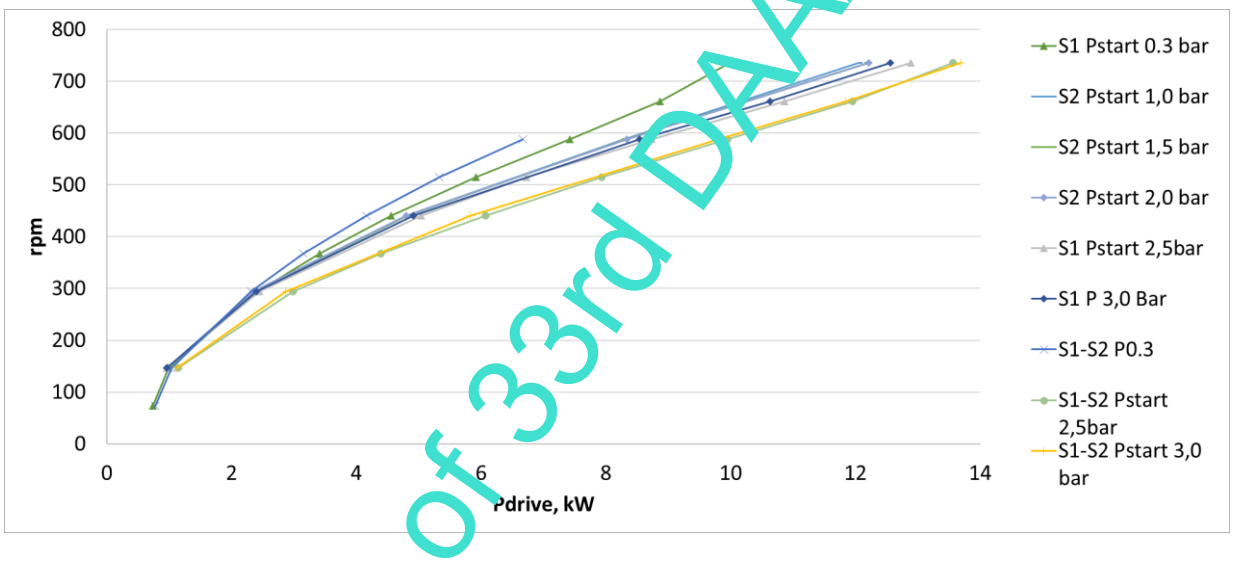

Fig. 10. Pumps drive unit consumed power – pumps magnetic rotor rotation rate for different P_{start} values.

The cavitation process can also be observed by viewing the drive unit's power consumption against the pump magnetic rotor rotation rate shown in figure 10. The 22 kW 3-phase asynchronous electric motor power supply uses an inverter with the possibility to measure the electrical power supplied to the motor. The highest power consumption rates are for the "pump one pulls through pump two" cases, reaching 13,7 kW for high P_{start} values due to increased pressure drop in the sodium loop. The case of the P_{start} 0,3 bar shows significantly less power consumption of a max of 8.88 kW, which also evidences considerable pump channel filling with cavitation bubbles.
The "pump one" and "pump two" configurations for P_{start} values from 3.0 bar to 1.0 bar curves follow a similar path with some differences at higher rotation rates reaching 12.2-12.5 kW. For the P_{start} 0.3 bar, the curve follows the way mentioned above. At higher pump rotor rotation rates, the power consumption curve becomes steeper, resulting in less consumed power of 10 kW, which links this curve to rpm – the flow rate curve plot.
4. Conclusions. Electromagnetic induction pumps with rotating permanent magnets can suffer from cavitation when operating at low inlet pressure values. A series of experiments showed the relation between the pumps developed flow rate and the inlet pressure alongside with pump magnetic rotor rotation rate. We can use the cavitation number to characterize the pump operation conditions to determine the cavitation probability. The experiment allowed us to determine the cavitation number values corresponding to cavitation breakdown and flow rate increase rate change. However, we must be cautious regarding designing EMP with PM because there is very little data on cavitation processes in those pumps. The data gained in the experiments described in the current paper does not give any

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information on cavitation inception but can provide rough initial details on the pump cavitation probability. Cavitation number values below σ = 1,8 can lead to flow increase breakdown. The pump's flow rate loss of 5% is achieved at cavitation number 2.5. Considering the slip, which is always present in electromagnetic induction pumps, those numbers should also be considered. The slip ratio should be regarded as in the cavitation number calculation, but further research is necessary.
Further, the test loop should be modified and equipped with improved acoustic measurements for the cavitation inception point location.

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6. References.

1. I. E. Bucenieks. (2000). Perspectives of using rotating permanent magnets for electromagnetic induction pump design. Magnetohydrodynamics. 2000. T36. No2. pp.181-187.
2. S. Constantinides. (2012). "The demand for rare earth materials in permanent magnets" (PDF). www.magmatllc.com. Available from: https://web.archive.org/web/20180329120806/https://www.magmatllc.com/PDF/Demand%20for%20rare%20earth%20materials%20in%20permanent%20magnets_Constantinides_120409.pdf. Accessed 2021.11.05.
3. Dubovikova N., Kolesnikov Y. and Karcher Ch. (2015). Experimental study of an electromagnetic flow meter for liquid metals based on torque measurement during pumping process. Measurement Science and Technology, Volume 26, Number 11. Pp. 1-10. DOI:10.1088/0957-0233/26/11/115304.
4. I. E. Bucenieks. (2003). High pressure and high flowrate induction pumps with permanent magnets. Magnetohydrodynamics 2003. 39, No. 4, pp.411-418, 2003. DOI: http://doi.org/10.22364/mhd.
5. Kremljak, Z[vonko] & Petkovski, M[ilan] (2020). Cavitation measurements for industrial valves, Chapter 01 in DAAAM International Scientific Book 2020, pp.001-014, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-27-3, ISSN 1726-9687, Vienna, Austria DOI: 10.2507/daaam.scibook.2020.01.
6. C. E. Brennen. Hydrodynamics of pumps. (1994). Concepts NREC and Oxford University Press .1994. Available from: https://resolver.caltech.edu/CaltechBOOK:1994.001. Accessed 2020.09.03.
7. V. Sobolev. Database of thermophysical properties of liquid metal coolants for GEN-IV. Sodium, lead, lead-bismuth eutectic (and bismuth). Scientific report of the Belgian nuclear research centre. SCK•CEN-BLG-1069. 2011. - Coolants_GEN-IV. Available from: https://inis.iaea.org/collection/NCLCollectionStore/_Public/43/095/43095088.pdf?r=1. Accessed 2021.11.05.
8. Martin-Lopez, Elena. (2018). Study of MHD instabilities in high flowrate induction electromagnetic pumps of annular linear design. Universite de Grenoble Alpes, 621 Avenue Centrale, 38400 Saint-Martin-d'Heres (France); CEA, DEN-DTN (France). PhD Thesis. 2018.
9. Foerster, K. (1985). Acoustic surveillance as a detection method for cavitation in pumps. Specialist's meeting on cavitation criteria for designing mechanisms working in sodium: Application to pumps. Summary report. International Atomic Energy Agency, International Working Group on Fast Reactors, Vienna (Austria); 289 p; 2002; p. 169-201; IAEA-IWGFR specialists' meeting on cavitation criteria for designing mechanisms working in sodium: Application to pumps; Bergisch Gladbach (Germany); 28-29 Oct 1985.
10. Gopalakrishnan, S. (1985). Modern cavitation criteria for centrifugal pumps. Proceedings of the 2nd International Pump Symposium, Texas A&M University. Available from: https://www.91metallurgist.com/blog/wp-content/uploads/2016/01/Modern-Cavitation-Criteria-for-Centrifugal-Pumps.pdf. Accessed 2021.11.10.
11. K. Kravalis, F. Boix, I. Bucenieks, et.al. (2022). Experimental cavitation investigation of the electromagnetic PbBi pump with rotating permanent magnets. Magnetohydrodynamics Vol. 58 (2022), No. 1-2, pp. 195–203 DOI: 10.22364/mhd.58.1-2.21.

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