

## Permanent magnet dipole stirrer for aluminium furnaces

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### Abstract

Use of permanent magnet systems for metallurgical applications have been proposed before. We have continued development of such systems by investigation use of single magnetic dipole which is realized as permanent magnet cylinder. Magnet is magnetized orthogonal to its axis and has been mounted to the side of the liquid metal reservoir. System first was modelled using small scale experiment with galinstan melt. Velocity distributions and flow patterns in reservoir using Ultrasound Doppler Anemometer were acquired and will be presented here. Additionally, numerical model using Comsol and Cenos modelling software were developed alongside analytical, non-dimensional estimation calculations. Experimental results were used to adjust and verify calculations. Using these calculations, industrial scale system was modelled and designed, and built. Industrial prototype was installed to 20t aluminium remelting furnace in Norway. It demonstrated that sufficient flow for efficient stirring could be achieved, while power of unit did not exceed 2kW, what is up to 30 times less than for comparable size classical EM stirrers with current windings. Besides system allows unique versatility by changing tilt angle to change flow pattern continuously allowing adaptive melting process, and costs significantly less than classical systems. By the time of the conference another prototype will be commissioned and results will be included.

**Key words :** Permanent magnet; Metal stirrer; Melt treatment; Magnetohydrodynamics; Aluminum

### Introduction

High temperature and aggressive properties of aluminum alloys make it complicated to use different mechanical devices to solve technological problems, such as liquid metal transportation, dosing and stirring. Therefore, even more importance and topicality are contactless electromagnetic methods for processing of molten metals. Along with the traditional electric heating devices in furnaces and mixers, electromagnetic devices for liquid metal transportation, pouring and stirring are being widely applied [1-3]. Liquid metal induction pumps already are used in nuclear applications for reactor cooling systems. Classical electromagnetic (EM) pump with current windings are easy to operate as they are made without moving parts and low service needs. Main disadvantages for these pumps are high energy consumption and necessity for large and powerful transformers. Most of the power consumed by the three-phase induction pumps is spent on the creation of a required induction value of the magnetic field by a set of coils. For more possible applications in metallurgical technologies, the permanent magnet pumps were not effective due to the high temperature of melts ( $\geq 700$  °C) and due to the need to produce channels with rather thick walls (200-300 mm) from ceramic refractory materials. As a result, the nonmagnetic gap becomes very big and, hence, the magnetic field strength in the liquid metal zone becomes rather low, not providing sufficient efficiency of the pump.

Nowadays, new technologies for the production of permanent magnets have made them cheaper and available in large quantities. Permanent magnets can be used as magnetic field source instead of current windings [4]. The same as permanent magnet pumps can become competitive in metallurgy as they are already used for low melting temperature metals in nuclear industry and research applications. It is demonstrated that the travelling magnetic field in the induction pump could be generated by a system of permanent magnets with alternating polarity fixed on a rotating ferrous base cylinder or disc [5,6]. Moreover, in permanent magnet systems the only power consumption is needed to rotate magnet along the axis.

In this work we present laboratory scale permanent magnet stirrer and its industrial scale prototype which is built and tested on 20t aluminium remelting furnace. Practical experience is obtained in work with previous permanent magnet pump studies. [7-9]

### Experimental setup

Experimental laboratory setup is made as a model to simulate aluminium furnace. Stirrer is single permanent magnet cylinder 50mm in diameter and with height 100mm, magnetized orthogonal to its axis. Magnet is positioned on the side of liquid metal reservoir. For these experiments galinstan melt is used, as it is in liquid state in room temperature and the electrical conductivity is high enough to be used. Permanent magnet rotates around its symmetry axis. The tilt of the stirrer is adjustable so it can be set on horizontal, vertical and tilted (45 degree angle) positions, see Fig. 1. For stirring application use of magnet dipole is more effective than multipole permanent magnet assembly as dipole magnetic field intensity is higher, but rotation frequency has to be low anyway to avoid influence from skin



depth and complicated technical challenges. Even with 5 to 10 Hz skin effect is significant (3-4 cm) which is comparable to size of liquid metal pool. This sets the maximum operating frequencies both in laboratory and industrial scale stirrer since at that point increase in rotational frequency will not give increase in integral flow.

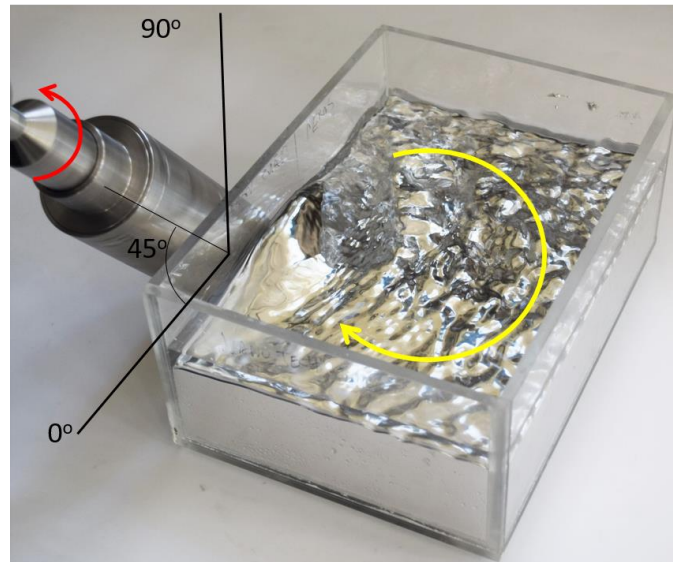


Fig. 1: Laboratory scale setup - permanent magnet stirrer with adjustable tilt position. Magnet creates intense flows and surface deformations in the melt; Yellow arrow shows melt flow direction, red - magnet rotation direction.

Metal flow velocities depending on magnet position and rotation frequency is measured by Ultrasound Doppler Anemometer. Fig. 2 shows comparison of flow characteristic velocities and velocity fluctuation interval close to the reservoir wall with stirrer on a side and on opposite side of the reservoir. Horizontal magnet position showed highest metal surface deformations, but lower characteristic velocities than other configurations, also can be detected with high fluctuation interval. Highest flow intensity in metal volume is reached with magnet tilted in 45 degree angle. In vertical and tilted configuration metal creates 1 vortex instead of 2 or many, as it is in horizontal magnet position. In this setup 1 vortex leads to better steering in whole volume - velocity measurements on opposite side of reservoir are higher.

In these measurements melt depth is 32mm. This value is derived scaling down metal furnace minimum melt depth as simulates the worst case scenario for side stirrer. Even at this level, stirring can be achieved by tilting the magnet. The technology supports the tilt adjustments during operation, which means optimal tilt can be set for varying melt levels during stirring cycle.

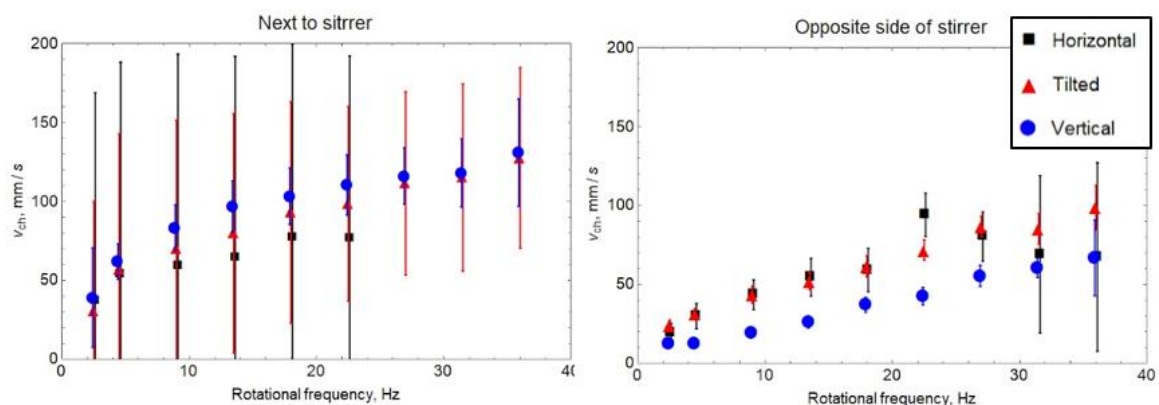


Fig. 2: Liquid metal characteristic velocities and velocity fluctuation interval in various magnet positions: horizontal, vertical and tilted in 45 degree angle. Melt depth is 32mm.

In case of normal melt depth - 52 mm, changing tilt affects the flow type, however, the characteristic velocities are similar. With shallow depth ratio of melt depth and magnet rotor vertical height is too low for effective utilization of magnet flux which affects magnitude of induced current. This reduction of effectiveness is seen Fig. 3, where lower metal depth corresponds to lower velocities on both sides of reservoir. However this effect can be negated by tilting. Our observation and measurements indicate at such low level a 45 degree tilt provide both azimuthal and radial velocity in bath.

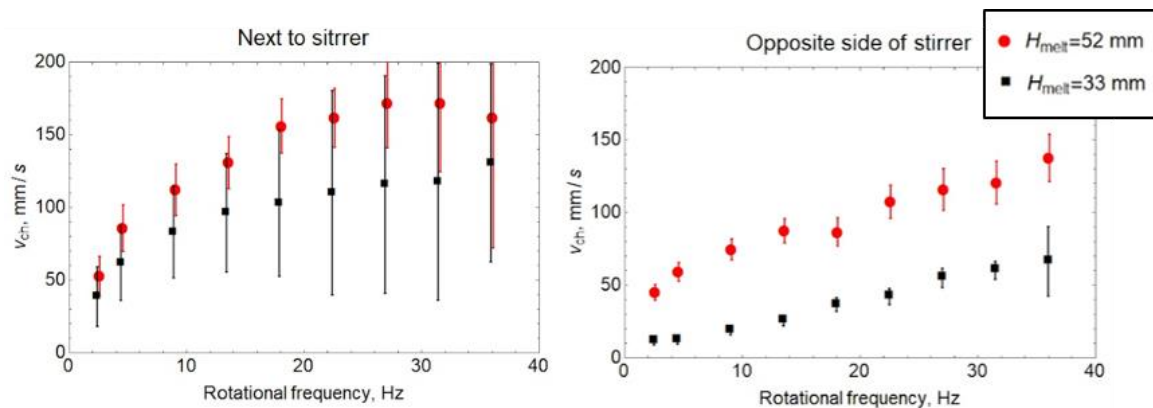


Fig. 3: Liquid metal characteristic velocities on both sides of the reservoir while stirred low and medium depth melt.

### Results and discussion

Liquid metal oscillations are detected even with very low magnet rotation frequencies - 1 to 2 Hz. Horizontal magnet position for metal stirring seems to be not as effective since metal flows are not intense in whole metal volume. In model experiment there is little increase of stirring intensity when magnet rotation frequency reach around 25 Hz because of skin effect. Scaling that to industrial sizes, gives us optimal frequency of 0.7 Hz. During experiments the most intense stirring is detected in case when magnet is tilted in 45 degree angle, even sharp surface deformations shows up.

For aluminium alloy homogenization purposes industrial scale stirrer is built and tested in industrial environment, see Fig.4. As scaling factors to use symmetry of process conditions we use the same approach as in our previous article [8]. Aluminium furnace for tests is located in Norway, its capacity is 20 tonnes and typical aluminium depth is 80cm. Stirrer is designed to create 22 L/s flow in normal conditions.

This magnet assembly is made from 16 permanent magnet discs, Fig. 4.a. Each disc consists of 12 smaller magnets and is surrounded by stainless steel cover. Steel rods are used to compress the magnet discs in a cylinder. Overall, magnet rotor is 80cm high and 30 cm in diameter. Typical wall thickness for aluminium furnace is 30cm, assembled magnet magnetic field is 40mT on opposite side of the wall. Magnet is built to reach rotation frequency up to 6 Hz but the optimal frequency for the particular furnace geometry is 1-2 Hz.

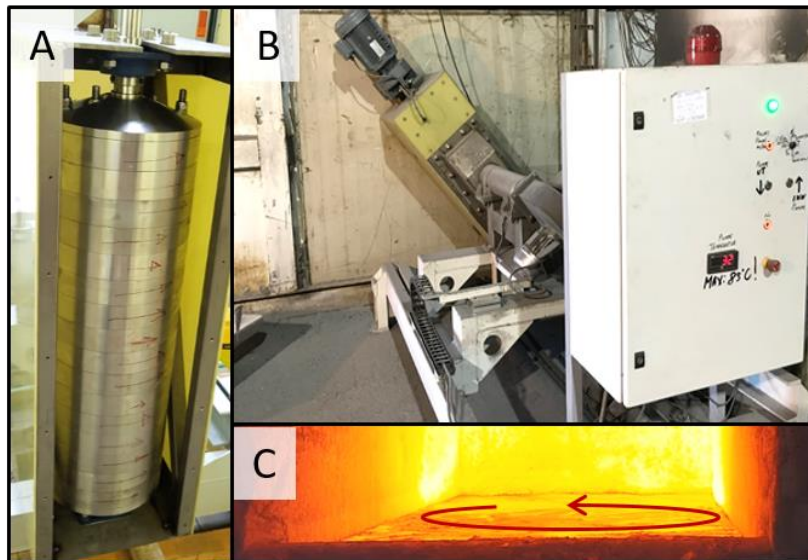


Fig. 4: Industrial scale stirrer for 20t aluminium furnace: A) Permanent magnet assembly; B) Stirrer located next to 20t aluminium furnace wall. Magnet is tilted in 45 degree angle. C) Aluminium furnace is stirred by magnet. Recognizable metal flow on metal surface is detected.

Presented industrial stirrer allows changes of the magnet tilt angle, what results with wide range of flow patterns depending on processes in furnace. Stirrer demonstrated sufficient flow while power unit did not exceed 2kW, what is about 30 times (!) more effective than equivalent EM stirrer with current windings.

### Conclusions

This study showed that permanent magnet pumps and stirrers can be used in large scale devices for industrial purposes and have many advantages comparing to other alternative methods - easy operation, low energy consumption, easy to adjust for various low melting temperature alloy furnaces and flow patterns. Model experiments yield high enough velocities throughout whole volume of metal even in shallow depth. The tilt adjustability of magnet allows real-time adaptation during melting cycle for optimal stirring regime. As of now 40 cm rotor is under construction designed for 12t aluminum furnace.

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