

## Article

# Permanent Magnet Pump for Aluminum Transport in a Linear Channel

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**Abstract:** Electromagnetic systems designed for liquid metal transportation offer a wide range of promising applications within the metallurgical industry. Among these systems, permanent magnet pumps stand out due to their remarkable advantages in processing liquid aluminum. These pumps enable the generation of a vigorous flow of liquid metal, all while maintaining a non-contact approach by bypassing the insulating walls. In this study, we investigate the flow of liquid metal in a rectangular cross-section channel created by a permanent magnet pump. To comprehensively analyze the flow characteristics and assess the technology's scalability, we employ order of magnitude evaluations alongside an experimental model. Ultrasound Doppler velocimetry is utilized to measure the velocity distribution, which reveals an intriguingly asymmetric flow pattern. Furthermore, additional measurements are conducted to determine the integral flow rate and pressure difference. Remarkably, the numerical simulations align closely with the experimental results, demonstrating good agreement in the p-Q curves. These findings provide substantial evidence supporting the remarkable potential of this technology in various applications, such as aluminum degassing, particle agglomerate dispersion, and efficient transportation.

**Keywords:** liquid metal transport; permanent magnet; travelling magnetic field; MHD; aluminium metallurgy



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## 1. Introduction

In the field of metallurgy, the processing of liquid metals, including tasks such as transport, dosing, and stirring, presents significant challenges due to the extreme temperatures and corrosive nature of the molten metal. While mechanical methods have been traditionally employed for liquid aluminum processing, they suffer from drawbacks such as contamination of the melt, heat losses, and safety risks. In contrast, electromagnetic techniques offer the ability to generate similar flows in a contactless manner, eliminating the need for moving parts within the melt and ensuring a safe working distance.

Currently, electromagnetic (EM) methods are widely used in the industry for tasks such as stirring and heating of the molten metal. Electromagnetic conduction pump is classical approach to generate Lorentz force and melt flow in the channel by using direct current through the melt by electrodes and applied external magnetic field [1,2]. Main challenges of EM conduction pumps in metallurgy are to ensure good electrical contact between electrodes and the melt as the electrodes tend to degrade in the aggressive environment. To avoid direct contact with the melt, typically EM induction for heating and flow generation applications is used. An alternating magnetic field is generated using inductor systems [3–5]. Nowadays, permanent magnets have become more available and can be used as an alternative to inductor systems. This approach involves utilizing rotating permanent magnet systems to produce the required alternating magnetic field for liquid metal transfer [6,7]. This method offers significant energy efficiency advantages as it avoids the Joule heat losses associated with inductor coils.

Permanent magnet pumps were initially developed for transporting low melting temperature alloys in channels, primarily for scientific and nuclear applications [8,9]. These pioneering devices utilized multi-pole permanent magnet rotors, which exhibit high efficiency when the separation between the magnet and the melt is small. However, their performance deteriorates rapidly as the wall thickness increases. In contrast, the magnetic dipole configuration performs significantly better for thick walls commonly found in aluminum foundries [10,11]. This can be attributed to the slower decay of the dipole field with distance compared to the multi-pole field. Additionally, the induced electromagnetic force is proportional to the square of the magnetic induction, further enhancing the performance of the magnetic dipole configuration. The authors of this study are among the pioneers in utilizing such permanent magnet technologies in aluminum metallurgy.

The present study focuses on investigating the flow of liquid metal in a rectangular channel driven by a rotating permanent magnet. This geometry closely approximates the conditions often encountered in aluminum foundries. Moreover, the rectangular channel cross-section ensures an equal distance between the melt and the magnet along the magnet-facing wall. Consequently, a larger volume of melt is exposed to the strongest magnetic field, in comparison to alternative configurations such as a round tube.

The study considers two distinct modes of operation. In the pump mode, the channel ends are open, and the electromagnetic force drives the flow of liquid metal through the channel. This mode is beneficial for transporting liquid metal from one production phase to another. It offers advantages such as improved flow control and greater flexibility in construction, compared to gravity-driven transport alone.

On the other hand, in the stirrer mode, the channel ends are closed, and turbulent recirculation of the liquid metal is generated. This regime finds utility in aluminum degassing processes [12] or in the dispersion particle agglomerates into metal matrix composites (MMCs) [13,14]. The formation of particle agglomerates poses a fundamental challenge in MMC production. It is hypothesized that a strongly turbulent flow can help mitigate these agglomerates through local viscous shear or pressure fluctuation. Similarly, the stirrer mode can be employed to break up argon bubbles injected into the aluminum melt for the purpose of hydrogen removal (degassing) [15]. The conventional approach involves using rapidly rotating graphite injectors [16], which suffer from erosion caused by the aggressive environment and typically last only around six weeks. In contrast, a rotating permanent magnet can offer comparable local flow properties in a contactless manner, eliminating the erosion concerns associated with graphite injectors.

In a previous study [17], the experimental investigation of a turbulent and recirculating liquid metal flow in a closed rectangular cavity driven by a rotating permanent magnet was conducted. In the current study, we complement these experimental findings with numerical modeling using open-source software, along with additional laboratory experiments.

An important aspect of the current study is the inclusion of the pump regime, which was not previously explored. By considering both the stirrer and pump modes, we aim to provide comprehensive data that can be used to evaluate the suitability of rotating permanent magnet devices for various applications in aluminum foundries, as described earlier.

Through this combined experimental and numerical approach, our study aims to contribute valuable insights and data that can aid in assessing the potential of rotating permanent magnet systems in meeting the requirements of aluminum foundry applications, including improved flow control, effective aluminum degassing, dispersion of secondary phases in MMC production, and efficient transport of liquid metal between production phases.

## 2. Theoretical Background

### 2.1. Order of Magnitude Estimations

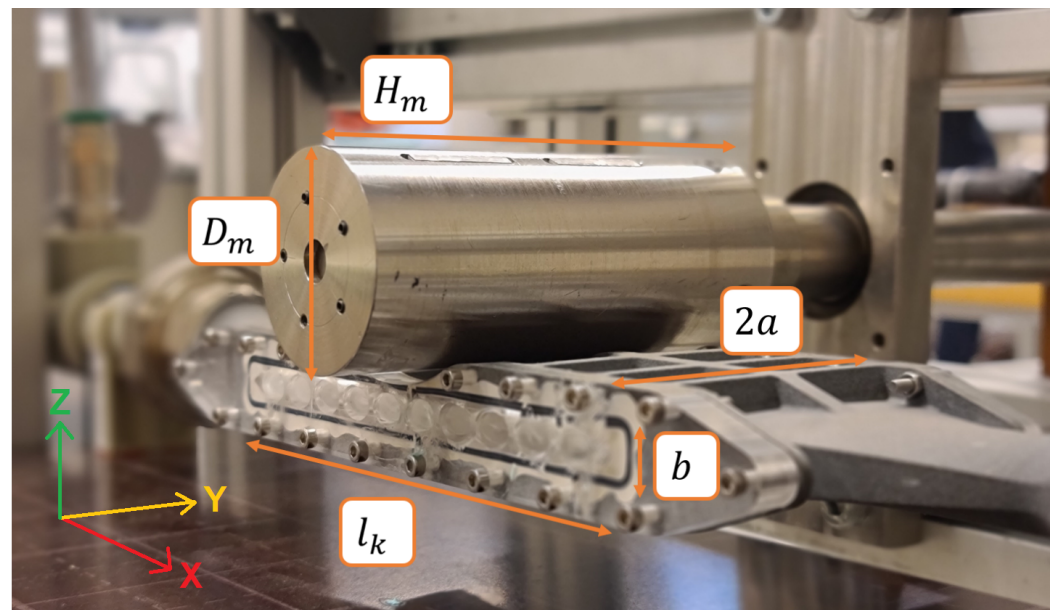
In order to determine the geometry of the system, order of magnitude estimations are performed for the pressure and velocity in a linear rectangular duct. The force responsible for the motion is generated by a cylindrical permanent magnet rotor that is radially magnetized. It is assumed that the flow of liquid metal in the x-axis direction is solely caused by



the interaction between the z-component of the magnetic field and the y-component of the induced current, see Figure 1.

The dominant induced current circuit lies in the x-y plane and is primarily induced by the change in the z-component of the magnetic field, which is strongest directly above the rotor. The y-component of the current circuits can be utilized for liquid metal transport, while the x and z components within the volume contribute to additional stirring.

The model system consists of liquid metal with constant physical properties such as electrical conductivity ( $\sigma$ ), viscosity ( $\nu$ ), and density ( $\rho$ ). Although these parameters are typically temperature-dependent, for the purposes of our model system, we assume them to be constant. The liquid conductor is confined within a rectangular volume with a remanent magnetization of  $B_r$ , and it rotates uniformly at a frequency of  $f$ .



**Figure 1.** Close-up of the linear part of the experimental apparatus denoting the position of the permanent magnet rotor and the linear channel, where  $H$ —rotor height,  $D$ —rotor diameter,  $2a$  is the channel width in y-axis direction,  $b$  channel height in z-axis direction,  $l$  channel linear part length in x-axis direction.

Nondimensional frequency or the shielding factor can be determined using

$$\Omega = 2 \left( \frac{b}{\delta} \right)^2 = \mu_0 \sigma \omega b^2, \quad (1)$$

where  $b$  is the height of the liquid metal channel,  $\delta$  the skin depth with  $\mu_0$  being the vacuum permeability and  $\omega = 2\pi f$  the angular frequency. If  $\Omega \ll 1$ , the induced magnetic field is negligible when compared to the external magnetic field. Definitions of all dimensionless parameters used in this study are listed in Table 1.

To estimate the induced current, we can utilize the order of magnitude estimations for Maxwell's equation, specifically, the equation  $\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$ . This equation describes the relationship between the electric field intensity  $E = |\mathbf{E}|$  (where  $j = \sigma \mathbf{E}$ ) and the magnetic field induction  $B = |\mathbf{B}|$ .

**Table 1.** Dimensionless parameters.  $B_0$  is the maximum magnetic flux density inside the container,  $\mu_0$  is the magnetic permeability of vacuum,  $\mathbf{u}$  is the liquid velocity,  $\tau$  is the distance in which magnetic field changes sign and  $||$  denotes the absolute value.

| Quantity                              | Symbol      | Definition                     |
|---------------------------------------|-------------|--------------------------------|
| Reynolds number                       | $Re$        | $\max \mathbf{u} b/\nu$        |
| Reynolds number of the magnetic field | $Re_\omega$ | $\omega\tau^2/\nu$             |
| Magnetic Reynolds number              | $Re_m$      | $\max \mathbf{u} b\mu_0\sigma$ |
| Dimensionless frequency               | $\Omega$    | $\mu_0\sigma\omega b^2$        |
| Hartmann number                       | $Ha$        | $B_0\tau\sqrt{\sigma/\nu\rho}$ |
| Stuart number of the magnetic field   | $N_\omega$  | $Ha^2/Re_\omega$               |

By considering the equation  $\nabla j \approx j_x/\tau + j_y/(2a) = 0$ , where  $\tau$  represents the half length of the magnetic field in the x-direction and  $2a$  is the width of the channel in the y-direction, we can deduce that  $f_x = -(\tau/2a)j_y$ . Substituting this expression into Maxwell's equation leads us to Equation (2).

$$\frac{j_y}{\tau} - \frac{j_x}{2a} = \frac{j_y}{\tau} \left( 1 + \left( \frac{\tau}{2a} \right)^2 \right) = B_z \omega \sigma \quad (2)$$

By expressing  $j_y$ , we obtain (3). A geometric relation of  $1 + (\tau/2a)^2$  is present, indicating that the maximum current in y-direction can be achieved if  $\tau \ll 2a$ .

$$j_y = \frac{\sigma \omega \tau}{1 + \left( \frac{\tau}{2a} \right)^2} B_z \quad (3)$$

The electromagnetic volume force can be estimated using  $f_x = j_y B_z$ , leading to Equation (4). The developed pressure can then be estimated by multiplying this force by the volume of the channel in the active region, denoted as  $V = 2ab\tau$ , and dividing it by the cross-sectional area  $S = 2ab$ , as shown in Equation (5).

It is worth noting that the pressure can be increased if certain conditions are met, such as having a channel width much smaller than the half length of the magnetic field ( $b \ll \tau$ ) and a channel width much smaller than twice the channel height ( $b \ll 2a$ ). Additionally, higher values of rotational frequency ( $\Omega$ ) and magnetic field induction ( $B_z$ ) can also contribute to increased pressure.

$$f_x = \frac{\sigma \omega \tau}{1 + \left( \frac{\tau}{2a} \right)^2} B_z^2 \quad (4)$$

$$\begin{aligned} p_x &= \frac{\sigma \omega \tau}{1 + \left( \frac{\tau}{2a} \right)^2} B_z^2 \frac{2ab\tau}{2ab} = \frac{\sigma \omega \tau^2}{1 + \left( \frac{\tau}{2a} \right)^2} B_z^2 = \\ &= \frac{1}{1 + \left( \frac{\tau}{2a} \right)^2} \left( \frac{\tau}{b} \right)^2 \Omega B_z^2 = \frac{1}{\left( \frac{b}{\tau} \right)^2 + \left( \frac{b}{2a} \right)^2} \frac{1}{\mu_0} \Omega B_z^2 \end{aligned} \quad (5)$$

Pressure estimate can be used in the velocity estimate as (6):

$$v_x = \sqrt{\frac{p_x}{\rho}} = B_z \sqrt{\frac{\Omega}{\rho \mu_0}} \left( \left( \frac{b}{\tau} \right)^2 + \left( \frac{b}{2a} \right)^2 \right)^{-0.5} \quad (6)$$

To estimate the pressure, it is necessary to determine the effective magnetic field induction. In this case, the rotor can be approximated as a cylindrical dipole with a height  $H$  and a diameter  $D$ . The rotational frequency of the rotor is denoted as  $\omega$ . When  $2a \leq 0.7 H$ , an approximation of an infinitely long magnet can be used, as the variation of the magnetic field induction across the channel width is below 10.

To derive the formula for the magnetic field generated by an infinite cylinder with permanent magnetization  $B_r$  in cylindrical coordinates  $(r, \varphi)$  and transform it to Cartesian coordinates  $(x, z)$ , we can arrive at Equation (8). The magnet occupies the space where  $r$  ranges from 0 to  $D/2$ , and  $y$  ranges from  $-D$  to  $D$ .

$$B = (B_\rho, B_\varphi, B_y) = \frac{B_r}{2} \left( \frac{D}{2r} \right)^2 (\cos \varphi, \sin \varphi, 0) \quad (7)$$

$$\begin{aligned} B_z &= B_\rho \sin \varphi + B_\varphi \cos \varphi = \frac{B_r}{4} \left( \frac{D}{r} \right)^2 \sin \varphi \cos \varphi \\ &= \frac{B_r}{4} \left( \frac{D}{x^2 + z^2} \right)^2 \sin \left( \arctan \frac{z}{x} \right) \cos \left( \arctan \frac{z}{x} \right) \end{aligned} \quad (8)$$

From (8) we can calculate the effective

$$B_{z,eff} = \frac{1}{\tau\sqrt{2}} \int_{-\tau/2}^{\tau/2} B_z(x, D) dx = 0.17T \quad (9)$$

To ensure a low non-dimensional frequency (1) and a high liquid metal velocity (6), the height of the channel should be significantly smaller than both its width and half the length of the magnetic field. In the study, a ratio of 1:8.5 for  $b:2a$  has been investigated, with a specific value of  $b = 0.05$  m.

In order to apply the formula for an infinite permanent magnet (8), the height of the magnet is set to  $2a = 0.7$  H, where H represents the height of the channel. For simplicity, it is assumed that H is twice the diameter of the magnet, denoted as D.

## 2.2. Scaling

The proposed concept of a permanent magnet pump is being studied with the aim of developing a technology that can be applied on an industrial scale. Therefore, it is crucial to evaluate the scaling process to determine if it is feasible to scale up the concept. In order to create a scaled model that accurately represents the studied physics, both geometric and kinematic (flow similarity) as well as dynamic (force similarity) criteria must be maintained.

Geometric similitude is achieved by selecting a scale of 1:6 (as shown in Table 2), which means that the experimental apparatus is six times smaller than the industrial one. However, it is important to note that due to limitations in available degrees of freedom, specifically only having control over the rotational frequency, not all non-dimensional criteria can be satisfied in the scaled model.

Despite the inability to satisfy all non-dimensional criteria, the scaled model still allows for valuable insights and assessments of the technology's performance in a more manageable experimental setup.

**Table 2.** Geometrical parameters for the experimental GaInSn model and industrial Al model, where  $\tau$  is evaluated at the closest surface to the magnet.

|         | Channel's Height $b$ , mm | Channel's Width $2a$ , mm | Channel's Length $l$ , mm | Nonmagnetic Distance $d$ , mm | Magnet's Height $H$ , mm | Magnet's Diameter $D$ , mm | Characteristic Length $\tau$ , mm |
|---------|---------------------------|---------------------------|---------------------------|-------------------------------|--------------------------|----------------------------|-----------------------------------|
| GaInSn  | 8                         | 70                        | 150                       | 5                             | 100                      | 50                         | 72.5                              |
| Al melt | 48                        | 420                       | 900                       | 30                            | 600                      | 300                        | 435                               |

The choice of characteristic scales in a system can result in different leading dimensionless parameters. Notably, the selection of the time scale has a significant impact on the formulation of the Navier-Stokes equation. There are two options to consider: using the viscous time scale  $\tau^2/\nu$  or the rotational frequency  $1/\omega$  as the time scale.

When using the viscous time scale, the Lorentz force is proportional to  $Ta = Ha^2 Re_\omega$ . Conversely, if the rotational frequency is chosen as the time scale, the Lorentz force becomes proportional to  $N = Ha^2 / Re_\omega$ . This discrepancy can introduce ambiguity in the system's formulation.

To avoid this ambiguity, it is important to maintain consistency in the value of  $Re_\omega$  between the laboratory setup and the proposed scaled device. This requirement leads to Equation (10), ensuring the proper scaling and equivalence between the two systems.

$$\omega_{Al} = \left( \frac{\tau_G}{\tau_{Al}} \right)^2 \frac{v_{Al}}{v_G} \omega_G = \frac{\omega_G}{12} \quad (10)$$

With the fixed value of  $Re_\omega$ , the dimensionless frequency  $\Omega_{Al}$  increases to  $2.6 \Omega_G$  in the scaled-up setup. However, it is important to note that even in the scaled-up system, the assumption  $\Omega \ll 1$  still holds. While the increase in  $\Omega$  itself may not be significant, Equation (6) suggests that the velocity could increase by a factor of 2.6, considering the simultaneous decrease in density by the same factor ( $\Omega_G = 2.6 \Omega_{Al}$ ).

It is worth mentioning that it is possible to maintain the magnitude of the relevant magnetic field  $B_z$  in the scaled-up setup. This is due to the fact that not only the nonmagnetic distance is increased, but also the radius of the magnet is increased by the same factor. It has been shown that the magnetic field around a cylindrical permanent magnet remains invariant when the radius of the magnet is used as the distance scale [18].

The increase in velocity in the scaled-up setup is supported by the increase in the interaction parameter  $N_{Al}$ , which is 25 times larger than  $N_G$ . According to Equation (10), this suggests that stronger forcing is achieved with smaller rotation frequencies in the scaled-up system. Additionally, the increase in  $N$  implies that the oscillatory component of the force, which has not been considered in the calculations, becomes more important in the scaled-up setup.

Indeed, while the estimation for scaling up the setup shows promise, it is important to acknowledge the low confidence in the absolute value of the estimated velocity. Experimental measurements are necessary to validate and accurately determine the velocity in the scaled-up setup. Only through experiments can the actual velocity magnitude be reliably determined.

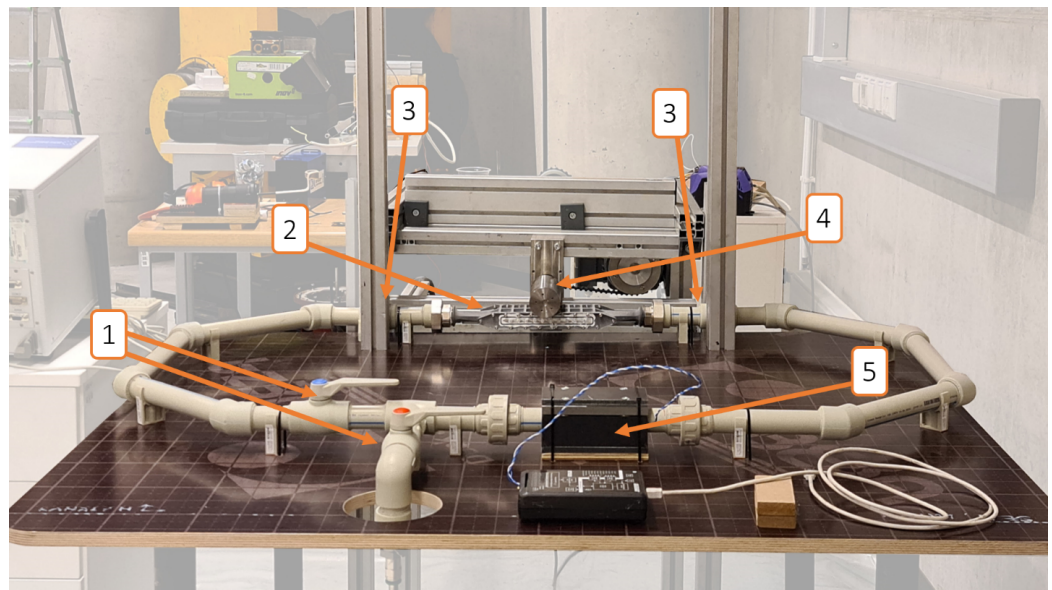
Furthermore, the estimation does not take into account the potential impact of force oscillations on the velocity magnitude. In the scaled-up setup, where force oscillations are expected to be more significant, these oscillations may have an effect on the velocity magnitude. This highlights the importance of experimental measurements to capture the full dynamics and understand the complete behavior of the system.

In summary, while the estimations provide some insight into the scaling process, experimental measurements are crucial to validate the results, determine the actual velocity, and assess the impact of force oscillations on the system's behavior.

### 3. Experimental Apparatus

A scaled table-top model has been developed in the laboratory to investigate the pressure, flow rate, and flow structure in the linear part of the channel, which has a rectangular cross section. The scaled model is designed as a closed loop system due to limitations in the availability of metal for the experiment and to minimize the risks of leakage and metal oxidation. An image of the experimental system can be seen in Figure 2. The system is divided into two parts: the active (central) part and the peripheral part of the channel.

The active part consists of the linear channel, which represents the desired geometry for the laboratory experiment, and the permanent magnet rotor that drives the flow. This section is made of PA12 material using 3D printing technology, ensuring a hermetic and safe environment for the experiment. Pressure measurements are taken using atmospheric pressure gauges placed at a distance of 100 mm from both ends of the linear part to measure the pressure drop across the pumping region.



**Figure 2.** Experimental model: Full view, where 1—valve, 2—3D-printed linear part, 3—manometer location, 4—permanent magnet rotor, 5—flow meter; squares on the plate are  $10 \times 10$  cm.

The permanent magnet rotor includes a cylindrical permanent magnet, a shaft, gears, a timing belt for rotating the magnet, a motor driven by a frequency converter, and aluminum x-profiles to adjust the position of the magnet. To minimize vibrations, the rotor and its drive system are isolated from the table on which the liquid metal channel is mounted. This isolation helps reduce the transmission of vibrations to the experimental setup.

Overall, the table-top model provides a controlled and safe environment to investigate the desired flow parameters and characteristics in the linear part of the channel using the scaled-down system.

The rotor in the experimental setup is a cylindrical dipole with a diameter of  $D = 50$  mm and a height of  $H = 100$  mm. It consists of an NdFeB permanent magnet with a remanence of  $B_r = 1.4$  T. The magnetization is perpendicular to the axis of the cylinder. To provide additional protection and support, the magnet is placed inside a 1 mm thick stainless steel shell. The rotor is positioned symmetrically in the width of the linear part of the channel, with its axis coinciding with the center of the linear part.

To reduce the distance between the magnet and the liquid metal, the magnet is placed in a bend of the linear channel wall. The non-magnetic distance between the magnet and the liquid metal is approximately  $d = 5.2$  mm. A small rotational eccentricity of the magnet, with an amplitude of less than 0.2 mm, is observed at rotational frequencies below 25 Hz. At higher frequencies, the eccentricity decreases, but mechanical vibrations of the machine increase, posing a risk to the precise positioning of the magnet so close to the channel.

The magnetic flow meter used in the setup is custom-made and utilizes ferrite permanent magnets enclosed in a steel frame. It produces a voltage on two electrodes in contact with the liquid metal, allowing for flow measurement. The flow meter has been calibrated in a dedicated device and incorporates a high-resolution USB data acquisition module to measure the signal accurately.

The peripheral part of the system is constructed using PPR fusible pipes and connections with an internal diameter of  $D_p = 23$  mm. This choice of material ensures both the strength and tightness of the duct, chemical inertness, and ease of assembly. The peripheral part includes valves for flow control, as well as metal inlet and outlet points. A conduction flow meter is also integrated into the system.

The total volume of the channel, including both the active and peripheral parts, is approximately 1.5 L. Filling the channel with liquid metal is carried out using a specially designed stainless-steel vessel. The metal is pushed into the channel using argon gas, ensuring a known volume of metal inside the channel and protecting it from oxidation.



The linear part of the experimental channel is designed to meet several criteria. Firstly, it has a rectangular cross-section with a height of  $b$  and a width of  $2a$ . The channel is linear along its length  $l$ , as depicted in Figure 1. This design allows for convenient connection with manometers and facilitates velocity measurements of the liquid metal flow.

The material chosen for the linear part of the channel is PA12, which is a 3D-printed plastic material. This material provides the necessary hermeticity, rigidity, and chemical inertness to ensure it does not react with the GaInSn liquid metal used in the experiment. Additionally, the material lacks electrical conductivity, simulating the behavior of a ceramic shell in an industrial setting.

To achieve the desired shape, the channel was 3D-printed using PA12 material with a powder technique. Prior to this experiment, tests were conducted to determine the suitability of different materials, ultimately leading to the selection of PA12. The transition from the rectangular cross-section of the channel to a circular cross-section was designed to resemble the connection to an industrial pipe. In an actual industrial setup, the channel would be connected to a large volume furnace. However, due to the limited supply of liquid Galinstan, the channel is connected to a larger diameter pipe to replicate the increased volume outside of the channel.

To enable velocity measurements from the sides of the channel, 6 mm thick plexiglass plates with gaskets were attached using M3 stainless-steel screws. These plates, along with the 3D-printed part, can be seen in Figure 1, providing a clear view of the channel and facilitating the measurement of velocity profiles.

The experimental setup utilizes GaInSn eutectic alloy as the working fluid. This alloy is composed of 68% gallium, 22% indium, and 10% tin by weight. It remains in a liquid state at room temperature, with a melting point of approximately 10 °C. GaInSn is considered non-toxic [19].

The physical properties of GaInSn are summarized and compared with those of liquid aluminum in Table 3. One notable property is that as the temperature increases, the electrical conductivity of GaInSn decreases [20]. The experimental system is not actively cooled, and temperature measurements in direct contact with the liquid metal are not planned. Therefore, the system is allowed to cool naturally between experimental runs.

**Table 3.** Comparison of physical properties between GaInSn [20] and aluminium alloys.

|         | $\rho$ , kg/m <sup>3</sup> | $\sigma$ , MS/m | $\nu$ , $\mu\text{m}^2/\text{s}$ | $f$ , rev/s | $Re_\omega$ | $\Omega$ | $N$  |
|---------|----------------------------|-----------------|----------------------------------|-------------|-------------|----------|------|
| GaInSn  | 6400                       | 3.27            | 0.335                            | 8.3         | 1.56e6      | 0.014    | 0.27 |
| Al melt | 2600                       | 2.8             | 1.0                              | 0.7         | 1.56e6      | 0.035    | 6.75 |

To address the issue of leakage, it is important to note that the channel volume is considered closed. However, prolonged and intense mixing can adversely affect the quality of velocity measurements. Therefore, long series of experiments are not desirable.

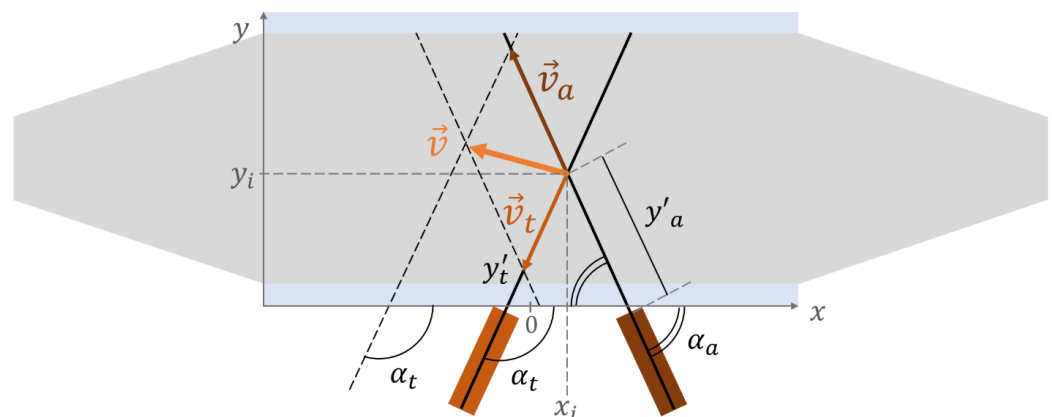
To improve the quality of the GaInSn, the metal underwent purification processes, including filtration and heating in an argon atmosphere. These processes aimed to remove oxides and dissolved gases that may have entered the metal from previous experiments.

Velocity measurements were performed using the Signal Processing anemometer DOP2000 v2125, employing the pulsed ultrasonic Doppler velocity method (PUDV). The device consists of a probe that integrates a receiver, a transmitter, and a computer for signal analysis. Only one probe can be used for measurements at a time. The transmitter generates short ultrasonic pulses, while the receiver continuously captures the reflected signal. In PUDV, the analysis focuses on the pulse shift in the received signal, which correlates with flow and particle velocities [21]. The probe can measure velocities parallel to the ultrasound beam, providing information about the spatial distribution of velocities. However, it has limitations in terms of maximum velocity and measurable distance, which depend on parameters such as the pulse repetition frequency  $f_{prf}$ , speed of sound in the environment  $c$ , and transmitter frequency  $f_e$ .

The chosen probes for velocity measurements have a transmitter frequency  $f_e$  of 2 MHz and a pulse repetition frequency  $f_{prf}$  of 4672 Hz. The time between subsequent measurements is 31.8 ms, which limits the ability to study finer flow structures. The maximum measured velocity modulus is  $v_{max} = 1.6$  m/s, and the measuring depth is  $x_{max} = 0.29$  m, which is significantly greater than the channel width  $2a = 0.07$  m. The transmitter power is set to medium, and the receiver has a spatial resolution of 4.39 mm. A constant gain of 46 dB is applied to the signal.

Velocity measurements are performed within the angle range  $|\alpha| \in [65^\circ, 70^\circ]$  from the x-axis. Attempts were made to measure velocities perpendicular to the side of the channel ( $\alpha = 90^\circ$ ) within the range  $x \in [-65, 0]$  mm, but the data obtained showed only chaotic noise. Measurements at lower angles ( $|\alpha| < 50^\circ$  and  $|\alpha| > 130^\circ$ ) were challenging due to poor sound contact, possibly because the gel layer was too thick for a part of the ultrasound beam. At higher angles ( $85^\circ < |\alpha| < 95^\circ$ ), the obtained velocity profiles contained mostly noise, likely because most of the ultrasound beam reflected off the opposite wall of the channel and immediately returned to the transmitter.

To reconstruct the flow rate, data from two measurements were used in a time-averaged manner, as simultaneous measurements were not possible. Time averaging was performed over 1000 measurements, covering a duration of slightly over 30 s. This interval was chosen as optimal for characterizing the flow and generating a sufficient amount of data. A Python script was developed for flow rate reconstruction using vector summation in a non-orthogonal coordinate system. A geometric representation of the reconstruction, including global coordinates  $x$  and  $y$ , as well as  $y'$ , which is parallel to each beam, is presented in Figure 3.



**Figure 3.** Velocity field reconstruction using two velocity component measurements:  $\alpha_a = 65^\circ$ ;  $\alpha_t = 115^\circ$ .

In the script, to utilize as many data points as possible, adjacent measurement points are shifted by 3 to 4 mm, considering the spatial resolution of 4.39 mm. The beams are considered intersected if the difference in data coordinates falls within the range of  $\Delta x = \pm 1$  mm and  $\Delta y = \pm 1$  mm. However, the script does not take into account beam divergence or refraction caused by changes in the environments of plexiglass-metal and gel-plexiglass.

There are limitations to the measurement range. Measurements cannot be made beyond  $|x| > 65$  mm, and on the  $y = 82$  mm side, measurements in the  $x = 0$  mm region are challenging due to the mounting of the permanent magnet rotor. Figure 3 illustrates that in the first 30 mm near the probe, there are dead regions where no measurement could be obtained due to an oversaturated signal. The dead region exceeds the theoretical near-field length and varies for different measurements, indicating possible issues with the sound signal despite careful handling.

#### 4. Numerical Simulation

Governing electromagnetic equations of our model system are Ampere's law and Ohm's law

$$\begin{cases} \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + B_r \nabla \times \mathbf{m} \\ \mathbf{J} = -\sigma \nabla \phi - i\omega \sigma \mathbf{A} + \sigma \mathbf{u} \times \mathbf{B} \end{cases} \quad (11)$$

in harmonic formulation, where  $\phi$  is electric scalar potential,  $\mathbf{A}$  is magnetic vector potential,  $\mu_0$  is magnetic permeability of vacuum,  $i$  is the imaginary unit and  $\omega = 2\pi f$  is the angular frequency of the magnet. Additionally, the complex magnetization unit vector  $\mathbf{m} = (\mathbf{e}_x - i\mathbf{e}_y)$  inside the volume of the magnet and  $\mathbf{m} = 0$  outside. The real part of the magnetization represents the rotation angle when magnet poles are present in the x-direction and the imaginary part represents the rotation when magnet poles are present in the y-direction. Then, the curl of magnetic vector potential  $\mathbf{B} = \nabla \times \mathbf{A}$  is used to calculate magnetic flux density and the time-averaged volume force  $\mathbf{F} = 0.5\mathcal{R}(\mathbf{J} \times \mathbf{B}^*)$ , where  $\mathcal{R}$  represents the real part of the complex number and  $*$  represents the complex conjugate.

The time-averaged volume force is inserted in the incompressible Navier-Stokes equation

$$\frac{\partial \mathbf{u}}{\partial t} + (\nabla \times \mathbf{u}) \times \mathbf{u} = -\nabla \left( \frac{p}{\rho} \right) + \nu \nabla^2 \mathbf{u} + \frac{\mathbf{F}}{\rho}, \quad (12)$$

where  $\partial \mathbf{u} / \partial t = 0$  for steady-state calculations.

Although the induced body force also exhibits an oscillatory component, our investigation assumes that the term  $B_0^2 \sigma / \rho \omega \ll 1$  holds true. This assumption stems from the fluid's inertia, where  $\rho \mathbf{u} \cdot \nabla \mathbf{u} \sim \rho \omega^2 \tau$  is sufficiently large to disregard the oscillatory contribution of the force, estimated as  $\sim B_0^2 \sigma \omega \tau$ . Therefore, within our model system, the flow is solely generated by the time-averaged volume force. This approach has demonstrated favorable agreement between numerical simulations and experimental observations in the context of a swirling flow generated by a rotating permanent magnet [22].

Hydrodynamic calculations were conducted using a customized finite volume solver developed within the open-source software OpenFOAM v2206 (Available at <https://openfoam.org/>, accessed on 1 September 2022). For transient simulations, the PIMPLE algorithm was employed to solve Equation (12), while the SIMPLE algorithm was utilized for steady-state simulations. At the container walls, the velocity boundary conditions were specified as “no-slip”.

The volume force, denoted as  $\mathbf{F}$ , was computed using a finite element solver implemented in the Elmer version 9.0 open-source software (Available at <http://www.elmerfem.org/>, accessed on 1 September 2022). Within Elmer, the built-in time-harmonic solver known as “WhitneyAVHarmonicSolver” was employed to determine the current density  $\mathbf{J}$  and magnetic vector potential  $\mathbf{A}$ , following the equation system (11).

The force solution obtained from Elmer was then transferred to OpenFOAM and incorporated into Equation (12). Conversely, the velocity distribution computed by OpenFOAM was sent back to Elmer to recalculate the Lorentz force for the subsequent time step. The communication between the solvers was facilitated by the EOF-Library [23], an open-source software package designed for this purpose.

##### 4.1. Reynolds-Averaged Simulation

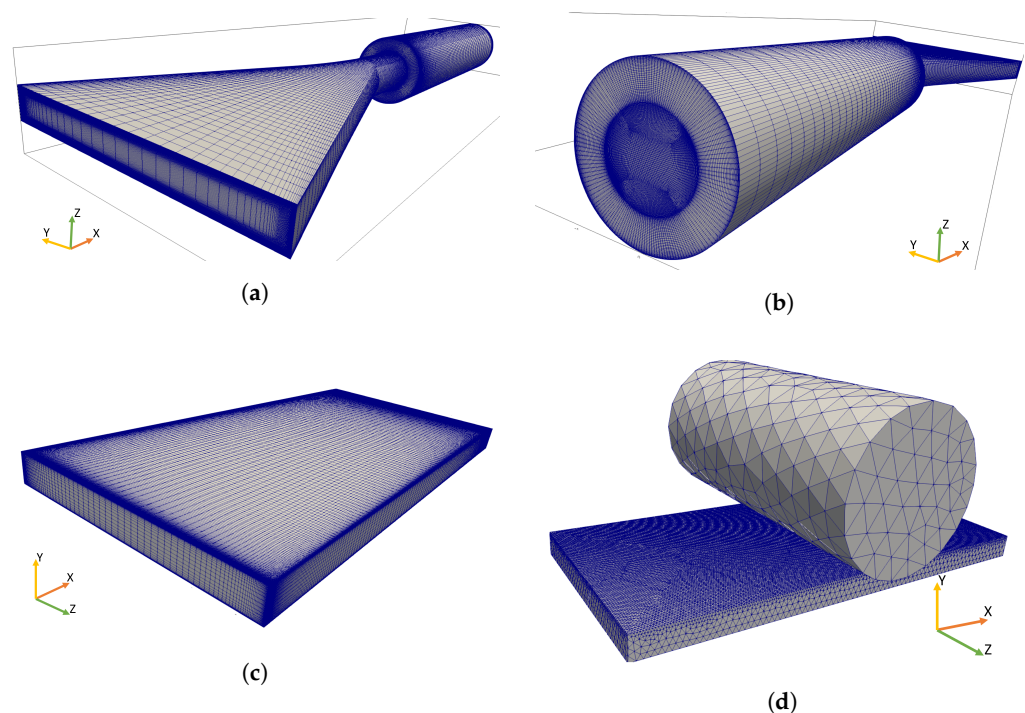
The initial steady-state and transient solutions were obtained using the  $k\text{-}\omega$ SST turbulence model, which facilitated the parametric study of the system without requiring significant computational resources. For the steady-state flow solution, the SIMPLE algorithm was employed, while the PIMPLE algorithm was utilized for transient calculations. The  $k\text{-}\omega$ SST turbulence model is classified under the Reynolds-averaged simulation (RAS) models and is specifically designed for highly turbulent flows within enclosed volumes [24]. Consequently, it was chosen as the preferred turbulence model over alternatives such as the Spalart-Allmaras,  $k\text{-}\varepsilon$ , and  $k\text{-}\omega$  models.

A notable challenge arose in accurately determining the pressure drop across the linear (rectangular) section of the channel. This difficulty stemmed from the transition through

the confuser/difuser regions, necessitating the inclusion of flow simulations through the diffuser and confuser sections to obtain p-Q characteristics that could be compared with the experimental setup.

For the hydrodynamic calculations, a structured, hexahedral mesh was generated using the Gmsh 4.10.5 software (Available at <http://gmsh.info/>, accessed on 1 September 2022). The mesh for the individual rectangular section comprised 875 thousand cells, while the more complex geometry of the diffuser/confuser required 1.95 million cells. Mesh is shown in Figure 4. The combined geometry, including the confuser, rectangular section, and diffuser, was meshed with 4.4 million cells. The mesh in the boundary layers was refined to maintain a wall parameter  $y^+ = 33$ , which falls within the lower end of the supported range for the  $k-\omega SST$  model. The first cell size near the boundary was determined as  $l_y = \nu y^+ / u_\tau$ , with a rough estimation of the friction velocity  $u_\tau = \omega(d + D/2)$  based on the magnetic field velocity on the nearest surface to the magnet.

Regarding electromagnetic calculations, the mesh was generated using the SALOME 9.6.0 software (Available at <https://www.salome-platform.org/>, accessed on 1 September 2022) and consisted of approximately 580 thousand tetrahedral elements.



**Figure 4.** Mesh: (a) confuser; (b) diffuser; (c) rectangular region; (d) elmer mesh.

#### 4.2. Large Eddy Simulation

The mesh for the Large Eddy Simulation (LES) consisted of 2.38 million cells, as shown in Figure 5c. Although this is a significantly larger number of cells compared to the  $k-\omega SST$  simulation, the distribution of cells was such that the mesh was finer in the bulk of the container. Consequently, the cell size near boundaries and corners was similar, as depicted in Figure 5a,b.

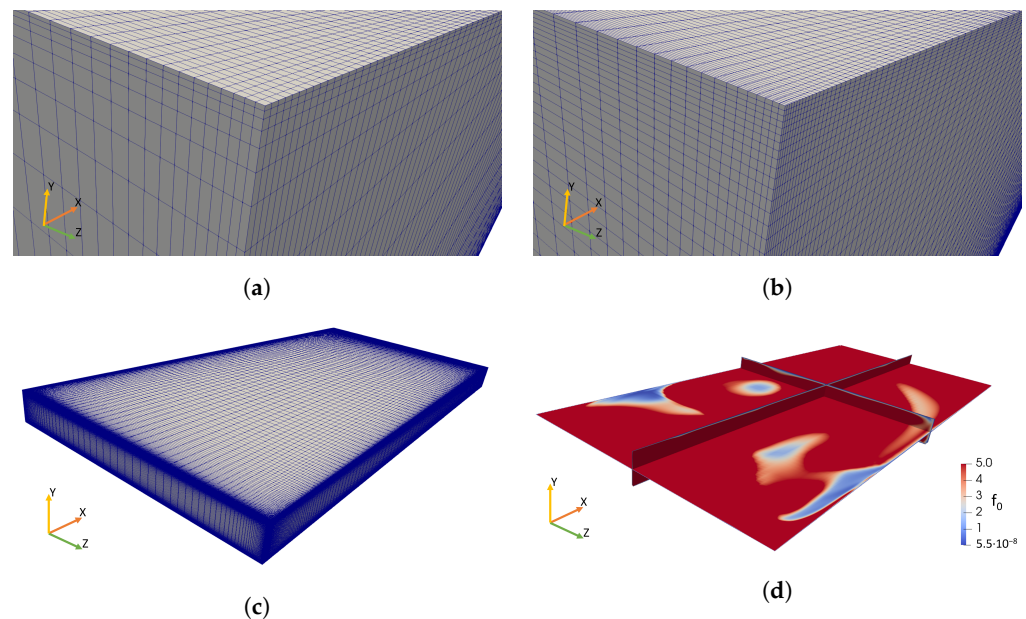
Before conducting the LES, it is recommended to prepare a sufficiently fine mesh to resolve at least 80% of the turbulent eddies [25]. The quality of the mesh can be estimated based on a previous Reynolds-averaged simulation (RAS). In the simulation using the  $k-\omega SST$  turbulence model, the characteristic turbulent length scale can be calculated as  $l_{\text{turb}} = \sqrt{k} / (C_\mu \omega_t)$ , where  $k$  represents the turbulent kinetic energy,  $\omega_t$  is the specific rate of dissipation, and  $C_\mu = 0.09$  is a turbulence model-specific coefficient.

For the LES model, we have opted for the Smagorinsky model with the Van Driest damping function near boundaries [26]. This model calculates the characteristic length scale as

$$l_{res} = \min\left(\frac{\kappa y}{C_s} \left(1 - \exp\left(\frac{-y^+}{A^+}\right)\right), V^{1/3}\right), \quad (13)$$

where  $y$  and  $y^+$  are dimensional and dimensionless distance from wall, respectively,  $V$  is a volume of a cell and  $\kappa = 0.41$ ,  $C_s = 0.158$ ,  $A^+ = 26$  are coefficients. Essentially  $l_{res}$  is calculated as the cube-root of a cell volume in the bulk of the container, whereas near boundaries Van Driest damping function is used to avoid necessity of extremely fine mesh near walls.

The mesh quality is estimated as  $f_0 = l_{turb}/l_{res}$ , where  $f > 5$  should correspond to >80% resolved eddies [25]. Our calculated  $f_0$  over slices in the rectangular section of duct shows that there are parts, where  $f_0 < 5$ , but most part of the mesh is sufficiently resolved (Figure 5d).



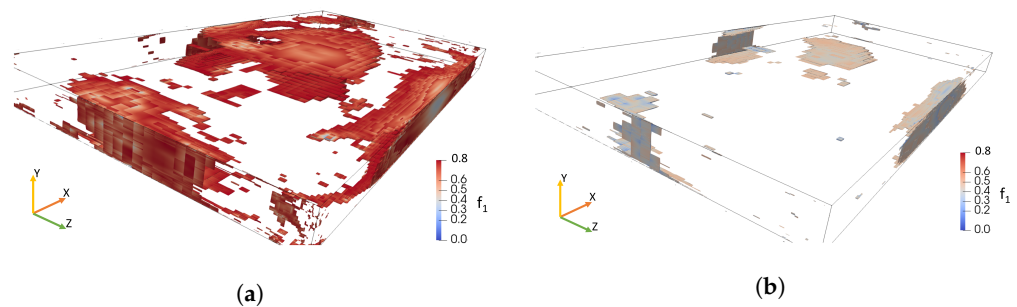
**Figure 5.** Mesh: (a) for  $k-\omega$ SST (shown at a corner); (b) for LES (shown at a corner); (c) for LES; (d) quality for LES simulation.

After LES simulation is completed, the resolved kinetic energy can be weighed against the total kinetic energy as

$$\begin{cases} f_1 = \frac{k_{res}}{k_{res} + k_{LES}} \\ k_{res} = \frac{1}{2} \left( \langle \tilde{u}_x^2 \rangle + \langle \tilde{u}_y^2 \rangle + \langle \tilde{u}_z^2 \rangle \right); & \tilde{u} = u - \langle u \rangle, \\ k_{LES} = \left( \frac{\nu_t}{C_k l_{res}} \right)^2 \end{cases} \quad (14)$$

where  $k_{res}$  is resolved kinetic energy,  $k_{LES}$  is sub-grid or modelled kinetic energy,  $\langle u \rangle$  denotes time average and  $C_k = 0.094$  is a model coefficient. From calculated  $f_1$  we can see that there are many cells near walls that have smaller value than 0.8 (Figure 6a), corresponding to less than 80% resolved kinetic energy. However, less than 50% resolved kinetic energy is only in few patches.





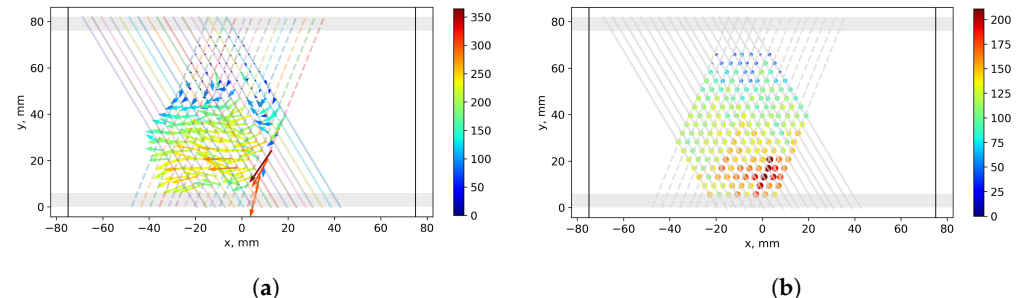
**Figure 6.** Resolved kinetic energy over total kinetic energy. Shown with cell threshold: (a)  $f_1 = 0.8$ ; (b)  $f_1 = 0.5$ .

## 5. Results and Discussion

### 5.1. Experimental Results

Velocity measurements in the linear part of the channel were conducted using a PUDV (Particle Image Velocimetry) device, employing the parameters described in the previous section. Multiple experimental series were carried out, with pauses in between to prevent metal overheating and excessive introduction of oxides into the melt volume. The measurements were initiated a few minutes after activating the rotor to ensure that any effects arising from the undeveloped flow were not recorded.

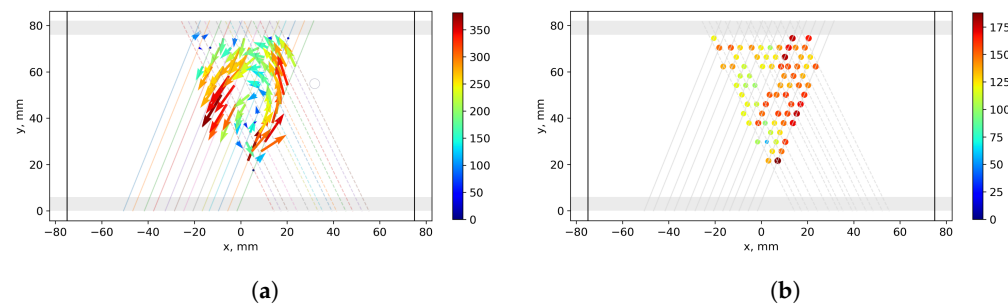
The measurements revealed a unidirectional flow against the x-axis, with an average velocity of approximately 220 mm/s and velocity fluctuations (pulsations) of approximately  $\pm 130$  mm/s, as illustrated in Figure 7b. Near the wall, the velocity slightly decreases but does not tend to zero. The estimated velocity (6) at a frequency of 8.3 Hz in the GaInSn model yields  $v_x = 170$  mm/s, which aligns well with the experimental observations.



**Figure 7.** (a) Liquid metal velocity field (mm/s) reconstruction, maximum flow EM pump regime; the gray horizontal area indicates the sides of the plexiglass, the vertical lines delimit the linear part of the channel, the sloping lines indicate the ultrasonic beam on which the measurements are made both upstream and downstream; (b) Velocity (mm/s) standard deviation in the EM pump regime.

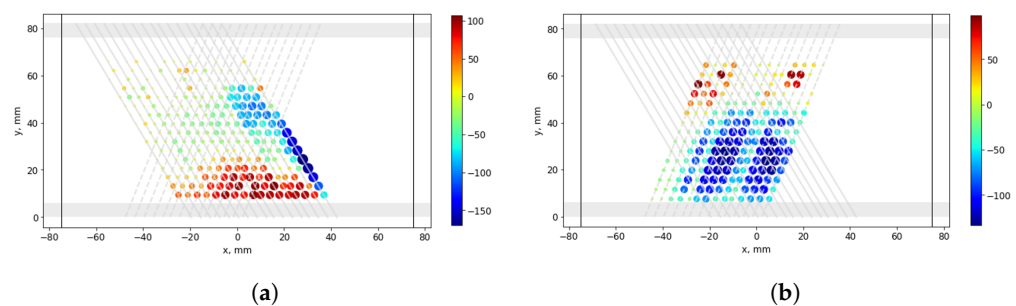
In Figure 8a velocity field has been reconstructed from the measurements made at  $y = 0$  mm side obtaining a flow with one vortex. Flow with one vortex around  $x = 0$  mm is formed, the maximum velocity jets are at  $|x| = 20$  mm with  $v_{max} = 300\text{--}350$  mm/s, the average velocity over the measurement area is  $v_{avg} = 220$  mm/s. Velocity pulsation distribution graph can be seen in Figure 8b. Velocity pulsations are above  $v_{sd} = \pm 100$  mm/s and the average value is  $v_{sd} = \pm 130$  mm/s.

The expected flow pattern in the channel was characterized by two vortexes, with counter flow along the channel's walls. However, Figure 8a does not support this expectation. The inconsistency in velocity measurements, as depicted in Figure 9, suggests that the flow in the channel may not be stationary. The figure shows two velocity components measured at angles  $\alpha = 35^\circ$  and  $\alpha = 55^\circ$  with respect to the x-axis. Probes on one side of the channel recorded nearly zero signal in the central region, while probes on the other side recorded a strong signal in the same region. Due to signal oversaturation, no qualitative data could be collected near the  $y = 82$  mm wall.



**Figure 8.** (a) Liquid metal velocity field (mm/s) reconstruction from  $y = 0$  mm, closed flow degasser regime; the gray horizontal area indicates the sides of the plexiglass, the vertical lines delimit the linear part of the channel, the sloping lines indicate the ultrasonic beam on which the measurements are made both upstream and downstream; (b) Velocity (mm/s) standard deviation that is used to characterize the velocity pulsations in the degasser regime.

In case of Figure 9a, the velocity component undergoes a sign shift at  $y = 20$  mm, while in case Figure 9b, the shift occurs near the middle of the channel. The symmetry of the experimental geometry would suggest that in case Figure 9a, the velocity would shift again near  $y = 60$  mm, but no data was collected to confirm this.



**Figure 9.** Velocity components (mm/s) measured from  $y = 82$  mm side in the degasser regime. (a) The velocity component undergoes a sign shift at  $y = 20$  mm; (b) The shift occurs near the middle of the channel.

In order to model an electromagnetic (EM) pump, the channel was operated at its maximum flow rate. The reconstructed velocity field for this regime is displayed in Figure 7a. The measurements were taken from the  $y = 82$  mm side, and the results indicate that better velocity measurements can be obtained closer to the opposite wall. Near the wall, the velocity decreases but does not reach zero. This behavior can be attributed to the increased volume of the final measurement, where the ultrasonic beam has already diverged and does not describe as small a volume as it does near the probe. Due to signal limitations, no qualitative measurements were taken closer to the  $y = 82$  mm wall for a distance of approximately 20–30 mm. As a result, the available distance for comparing velocity reconstructions between measurements from each side is reduced.

The experimental system has successfully shown the effectiveness of permanent magnet pump for liquid metal. The system reaches up to 180 mL/s for the GaInSn alloy. The experiments conducted under the degasser regime revealed an intense turbulent flow. Such flow, if replicated on an industrial scale, could be intense enough to break argon bubbles during aluminum degassing process and to disperse particle agglomerates for applications in metal matrix composite production. However, these proposed applications can only be tested experimentally with aluminum, as these processes rely on the properties of the alloy being used. The channel, developed through additive manufacturing, has introduced a novel technique for constructing specialized laboratory experiments involving liquid metal.

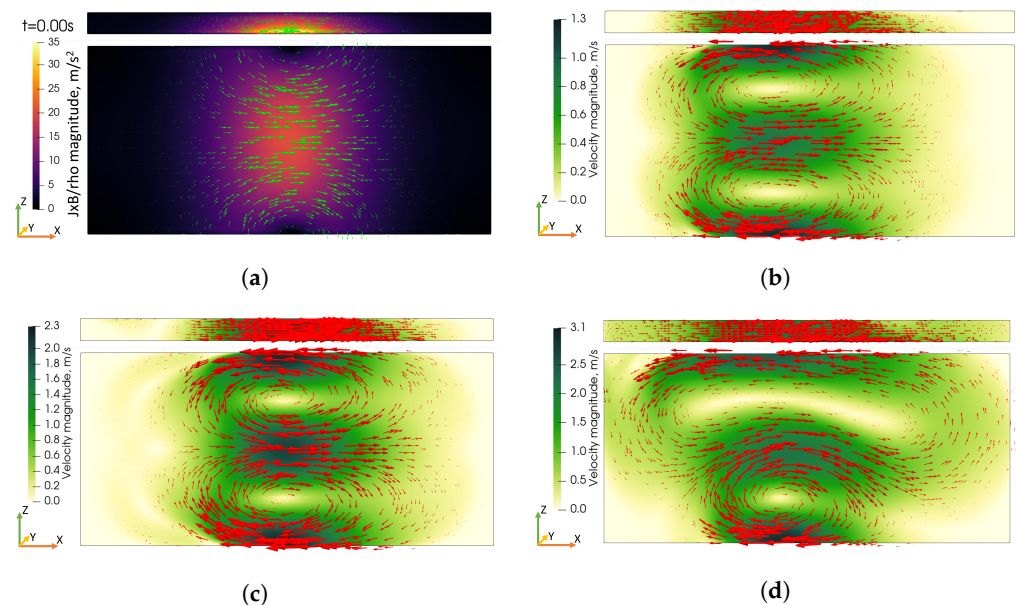
## 5.2. Numerical Results

### 5.2.1. Steady State

Figure 10a presents the force distribution at  $t = 0$  s when the liquid metal is stationary ( $\mathbf{u} = \mathbf{0}$ ). The volume force is symmetric with respect to the width of the channel, implying an expected symmetric flow velocity distribution.

Steady-state calculations in the flat part of the channel at lower magnet rotation frequencies did yield symmetric solutions, as depicted in Figure 10b,c. However, at  $f = 33.2$  rev/s, the flow became asymmetric (Figure 10d). The solution continued to change and did not converge even after 10 thousand iterations. In contrast, at  $f = 8.3$  rev/s, the solution converged after 2302 iterations.

For the steady-state simulation in the rectangular section, a residual tolerance of  $10^{-3}$  was set to determine convergence.



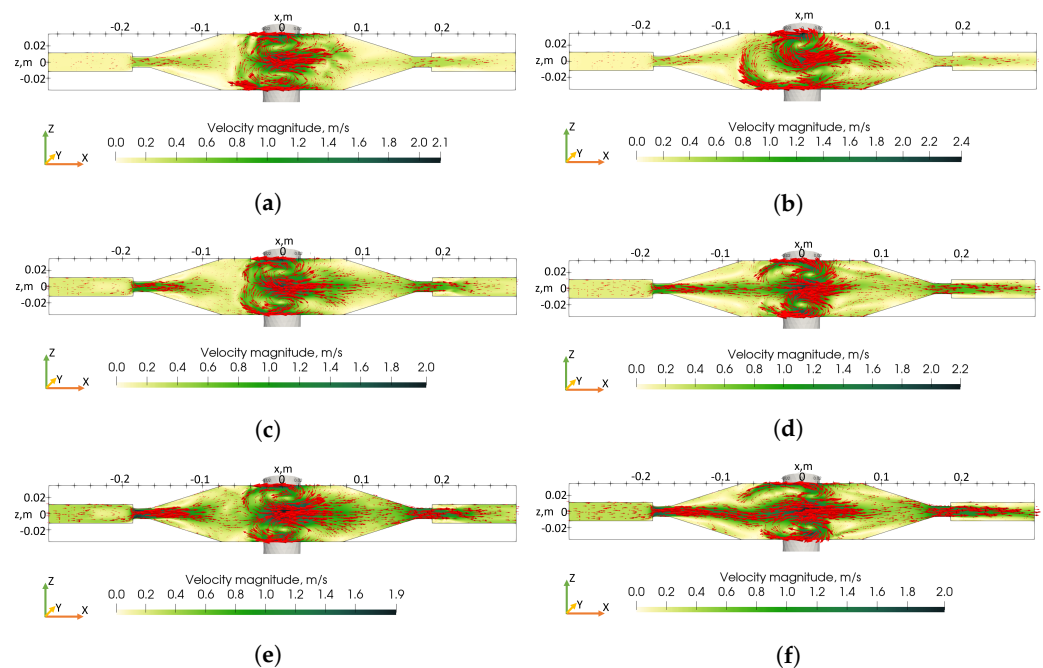
**Figure 10.** Vertical cross section (above) and horizontal cross section (below) of numerical simulation results. Initial force distribution (a).  $k-\omega SST$  steady state solver results: (b)  $f = 8.3$  Hz; (c)  $f = 24.9$  Hz; (d)  $f = 33.2$  Hz.

In the next set of calculations, a steady-state calculation was performed in a longer section of the channel, spanning from one manometer location to the other (Figure 11). In these calculations, a flow rate was specified at the inlet, and a zero pressure condition was set at the outlet to determine the characteristic p-Q curve.

Initially, the residual tolerance was set to  $5 \times 10^{-3}$ , and the results converged with a roughly symmetric flow distribution (Figure 11a,c,e). However, as the calculation was allowed to continue by decreasing the residual tolerance to  $10^{-4}$ , the flow eventually became asymmetric (Figure 11b,d,f).

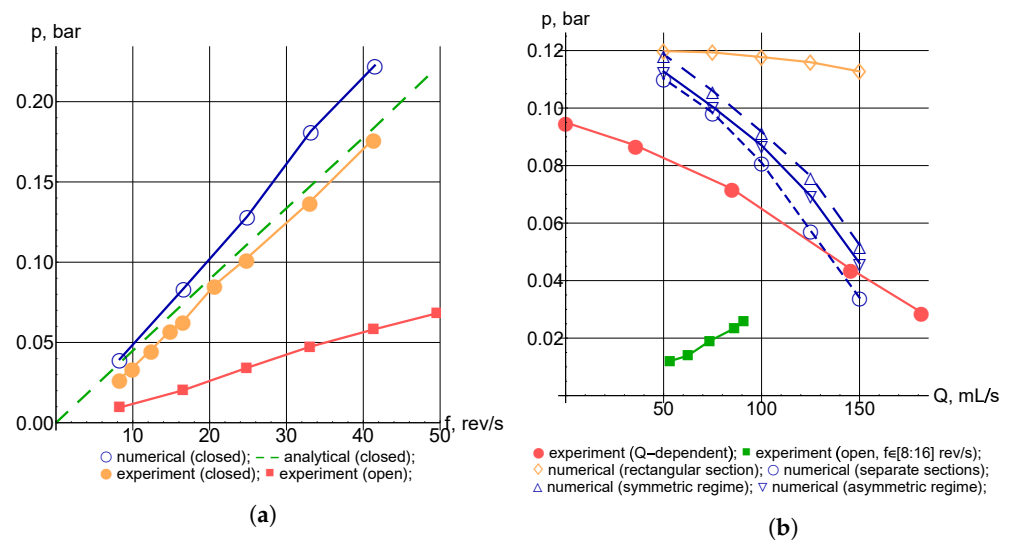
Furthermore, Figure 11 illustrates that strong circulation is present in the flat part of the channel, even at considerable flow rates.

Figures 10 and 11 demonstrate the challenges associated with finding a consistent solution using a steady-state solver in the presence of such an asymmetric flow regime. Figure 12a presents the pressure difference across the channel as a function of the rotational speed of the magnet rotor. It characterizes the pressure developed by the system in both the pump mode (red lines with filled squares) and the degasser mode (orange lines with filled circles). In the experimental study up to 50 Hz, the relationship between pressure difference and rotational speed is linear and does not saturate. The numerically calculated pressure in a closed container is depicted with blue lines and empty circles. The pressure estimation based on Equation (5) with a magnetic field strength of  $B = 0.2$  T is shown as a green dashed line. On average, the estimation is higher than the experimental measurements by 10 mbar.



**Figure 11.** Numerical (open, steady-state,  $f = 24.9$  Hz): (a,b)  $Q = 50$  mL/s; (c,d)  $Q = 100$  mL/s; (e,f)  $Q = 150$  mL/s. (a,c,e) initial symmetric regime, (b,d,f) after asymmetric regime manifested. Red arrows show flow direction.

Figure 12b displays the characteristic pressure and flow rate curve of the pump. The measurements conducted while changing the hydraulic resistance at a constant magnet rotation speed (24.8 Hz) are represented by the red solid line and filled circles. The measurements performed while changing the rotation frequency of the rotor are indicated by the green solid line and filled squares. Both curves can be described by a quadratic function, confirming that the pump operates in a linear mode.



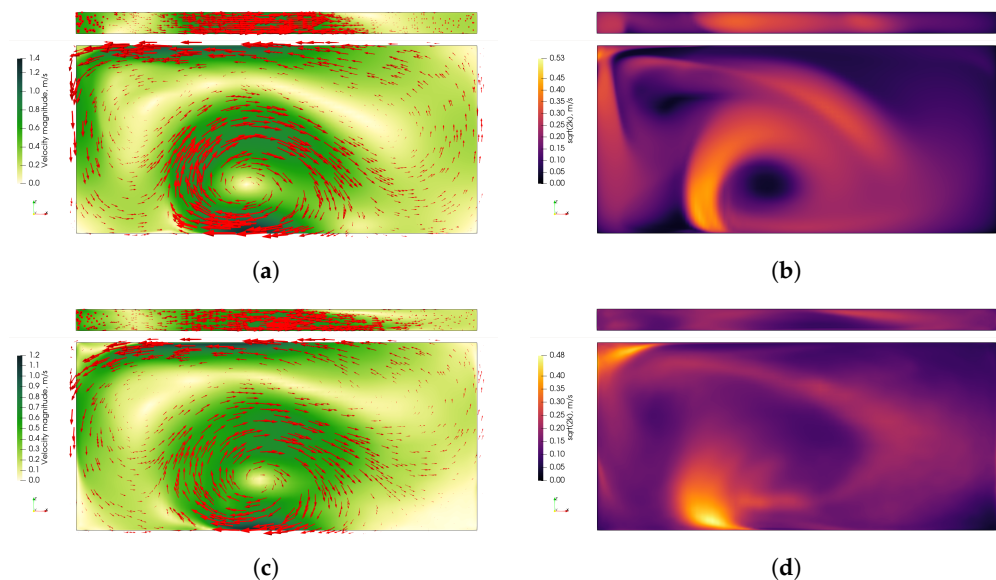
**Figure 12.** The pressure difference on both sides of the channel as a function of: (a) the rotational speed of the magnet rotor; (b) flowrate. Experimental measurements for both degasser and channel regime are compared to numerical simulation results and analytical estimation (for  $f$ -dependency).

The numerical pressure was initially calculated separately in the rectangular region (orange solid lines with empty diamonds) and then supplemented with separately calculated pressure from the confuser and difuser to obtain an approximate pressure drop of the pump section (short-dashed blue lines with empty circles). Additionally, Figure 12b includes the results of the initial symmetric regime (long-dashed blue lines with empty upwards

triangles) and the regime after the manifestation of asymmetry (solid blue lines with empty downwards triangles) in the simulation of the full pump geometry (corresponding to the flow distribution depicted in Figure 11).

### 5.2.2. Transient

Numerically calculated time averaged velocity distributions are similar between transient  $k\text{-}\omega\text{SST}$  simulation (Figure 13a) and LES (Figure 13c). However, the calculated fluctuation distribution is quite different (Figure 13b,d).



**Figure 13.** Time averaged transient numerical results ( $f = 8.3$  Hz): (a,c) velocity distribution (Red arrows show flow direction.); (b,d) fluctuation magnitude. The turbulence model: (a,b)  $k\text{-}\omega\text{SST}$ ; (c,d) LES.

The difference in fluctuation distribution between the  $k\text{-}\omega\text{SST}$  simulation and LES can be attributed to the nature of the velocity distribution in each method. In the  $k\text{-}\omega\text{SST}$  simulation, the velocity distribution reaches a quasi-stationary pattern with small fluctuations after the initial spin-up phase. As a result, the fluctuations in the simulation are mostly modeled by the turbulence model.

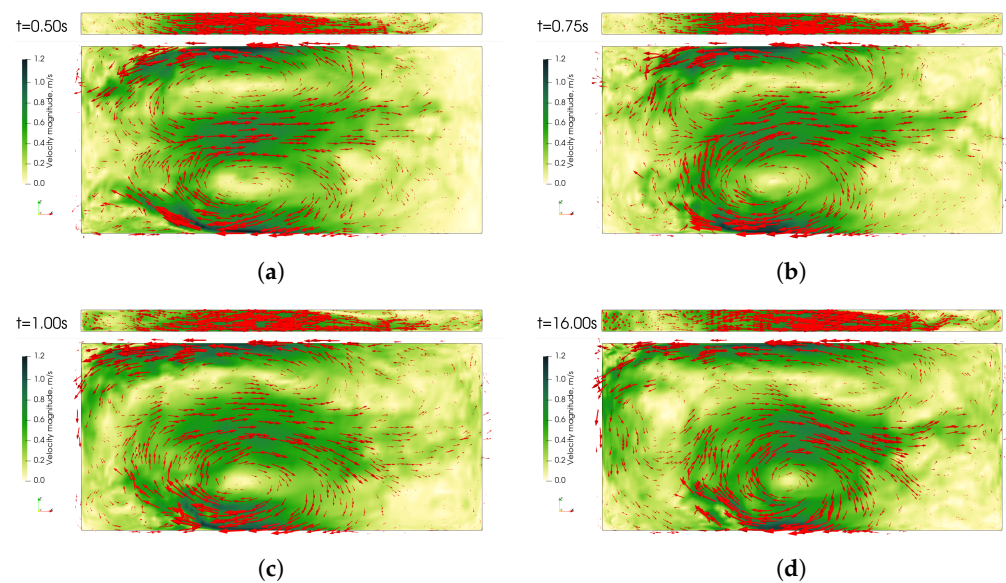
On the other hand, in LES, the velocity distribution exhibits noticeable variations over time. The snapshots from LES at different time steps reveal a detailed flow structure, capturing the resolved fluctuations (Figure 14). These resolved fluctuations contribute to the more pronounced and detailed fluctuation distribution observed in LES compared to the time-averaged velocity distribution (Figure 13c) or the modeled fluctuations in the  $k\text{-}\omega\text{SST}$  simulation.

Therefore, the difference in the behavior of fluctuations between the two methods can be attributed to the fact that the  $k\text{-}\omega\text{SST}$  simulation predominantly models the fluctuations, while LES resolves a significant portion of the fluctuations in the flow.

In Figure 15, the numerically calculated time evolution of the velocity component across the channel width is shown. The streamwise velocity in the middle of the rectangular section (Figure 15c) remains relatively constant during the simulation time. However, there are short pulsations present, particularly noticeable in the sidewise velocity (Figure 15d). The largest swirling motion is located slightly upstream (Figure 14), resulting in the largest fluctuations in that region.

Figure 15a,b display variations between larger streamwise velocity peaks in the middle of the channel width and a more smeared out velocity distribution with larger peaks in the sidewise direction. This could indicate a down and upstream movement of the large swirl, similar to the observed behavior in Figure 14c,d, with a time scale ranging from 0.1 to 0.5 s. Downstream velocity fluctuations (Figure 15e,f) are smaller compared to upstream fluctuations, but there seems to be changes occurring over a longer time scale ranging from 2 to 10 s.



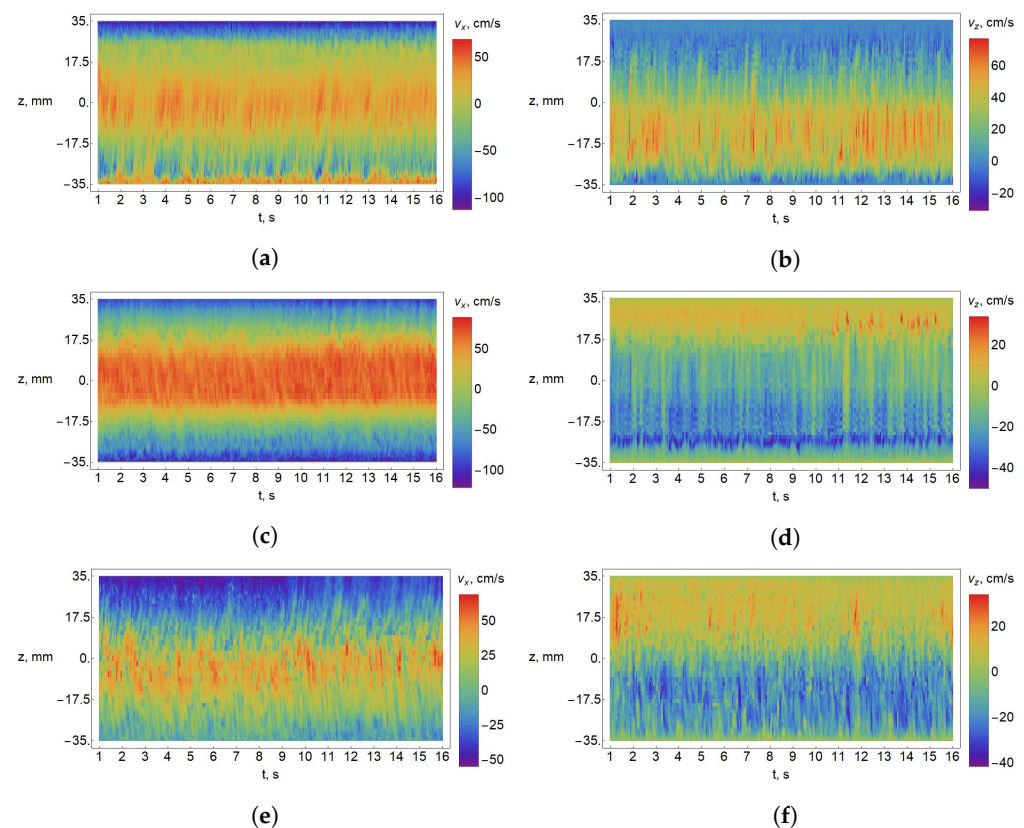


**Figure 14.** Numerical LES ( $f = 8.3$  Hz): (a)  $t = 0.5$  s; (b)  $t = 0.75$  s; (c)  $t = 1$  s; (d)  $t = 16$  s. Red arrows show flow direction.

The stirring regime, which corresponds to a closed duct in the experiment and was numerically modeled as a closed rectangular volume, is interesting because the resulting flow is asymmetric despite the symmetric setup. In the numerical simulation, the “right” swirl becomes the dominant one and maintains its state for the rest of the simulation (Figure 14). The selection of the dominant swirl is accidental, and in the experimental setup, it could depend on small differences in the initial conditions, which may vary between experimental runs.

The geometry of the container likely plays a role in how often the dominant swirl switches from “left” to “right” or if such switching occurs at all. A parametric study of flow regime dependence on geometry has been conducted for low Reynolds numbers in a system where a rotating permanent magnet generates flow in a surrounding ring channel [27]. A follow-up study further investigated the switching of the secondary flow [28], demonstrating that large-scale flow changes can occur over long viscous time scales, but the switching events are chaotic in nature. While the geometry of the current study is different, there are similarities in the resulting flows. In the ring channel setup, the asymmetry occurs in the secondary meridional flow, and the switching is maintained by a nonlinear interplay between the azimuthal and meridional flows. The asymmetric flow is lost when the meridional flow is suppressed by choosing a thinner channel width [27].

In the current study’s setup, the main flow can return along the height of the container or along each of the sides. If we consider the main return path to be along the height, then the swirling flows around the sides become the secondary flow, making the situation almost analogous to the ring setup. However, with the current rectangular geometry, unlike in a ring duct, it is also possible to suppress the main return path unintentionally, as achieved by choosing a very thin height for the container. With a suppressed main return path, the resulting large-scale flow becomes almost two-dimensional, and the secondary flow might not undergo switching from “right” to “left” swirl. Enabling such large-scale switching of swirling flow direction could potentially enhance stirring efficiency. However, further studies would be required to optimize rectangular container geometry specifically for stirring purposes.



**Figure 15.** From LES obtained spatiotemporal diagram (a moving average over 5 time steps) of stream wise velocity,  $v_x$ , and side wise velocity,  $v_z$ , component on the vertical midplane ( $y = 0$ ) across the channel width ( $z \in [-35, 35]$  mm) at x-coordinate: (a,b) 35 mm upstream, (c,d) 0; (e,f) 35 mm downstream.

## 6. Conclusions

- The experimental model demonstrates promising results in achieving liquid metal flow within a closed channel using a single permanent magnet rotor. The average velocity within the measurement area was recorded as  $v = 220$  mm/s at  $f = 8.3$  Hz, corresponding to a flow rate of  $q = 100$  mL/s. By employing a closed channel and  $f = 42$  Hz, a pressure of  $p = 0.175$  bar was attained.
- There is some agreement observed between the experimental and numerical p-Q curves. However, the numerical calculations tend to predict higher pressures compared to the actual results obtained in the experiment.
- Numerical simulations of closed channel mixing exhibit asymmetric patterns characterized by long lifetimes exceeding 16 s. The occurrence of asymmetric flow in the studied setup appears to be reliant on initial conditions and may vary between individual runs.
- Obtaining accurate velocity distribution measurements experimentally proves to be challenging, occasionally yielding inconsistent results. Two primary factors contribute to this issue. Firstly, impurities emerge in GaInSn after prolonged intense mixing, which results in a degradation of the UDV (ultrasonic Doppler velocimetry) signal. Secondly, the utilization of only one UDV probe in a single experiment limits the significance of combining results from multiple positions and angles unless the flow pattern remains consistent. The inconsistencies observed in experimental measurements and numerical simulation results suggest the opposite: the flow pattern is unpredictable and can vary between experiments lasting longer than 30 s. To address this, conducting experimental measurements over an extended time period could yield flow patterns with long-lived asymmetric characteristics averaging close to zero.

Alternatively, employing multiple probes simultaneously to monitor the flow pattern over time is another viable option.

- Despite the channel being a closed system and undergoing purging with an inert gas prior to filling, the quality of the measurements deteriorated during prolonged experiments. This deterioration is likely caused by the distribution of residual oxides present in the melt while the metal is in motion.

**Author Contributions:** Conceptualization, A.B. and T.B.; methodology, I.G., D.B. and A.B.; software, D.B.; validation, D.B., M.K. and I.G.; formal analysis, I.G.; investigation, A.G., D.B. and M.K.; data curation, A.G. and M.K.; writing—original draft preparation, M.K. and D.B.; writing—review and editing, D.B., M.M. and M.K.; visualization, M.K. and D.B.; supervision, T.B.; project administration, T.B.; funding acquisition, T.B. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data that support the findings of this study are partially available within the article. Additional data are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors report no conflict of interest.

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