Experimental test of a helical induction pump with rotating core

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Abstract: A design of a new type of liquid metal electromagnetic pump for medium flow rates and moderate pressure heads has been developed. The major difference compared to existing concepts is that the central iron core, which closes the magnetic flux lines, is fabricated from a single iron piece, which may freely rotate in order to avoid magnetization losses. The pump was designed and manufactured at KIT and tested in the liquid metal NaK loop of the MEKKA facility. Its performance curve (pressure head vs. flow rate) and efficiency have been determined for a variety of frequencies and magnitudes of applied 3-phase current.

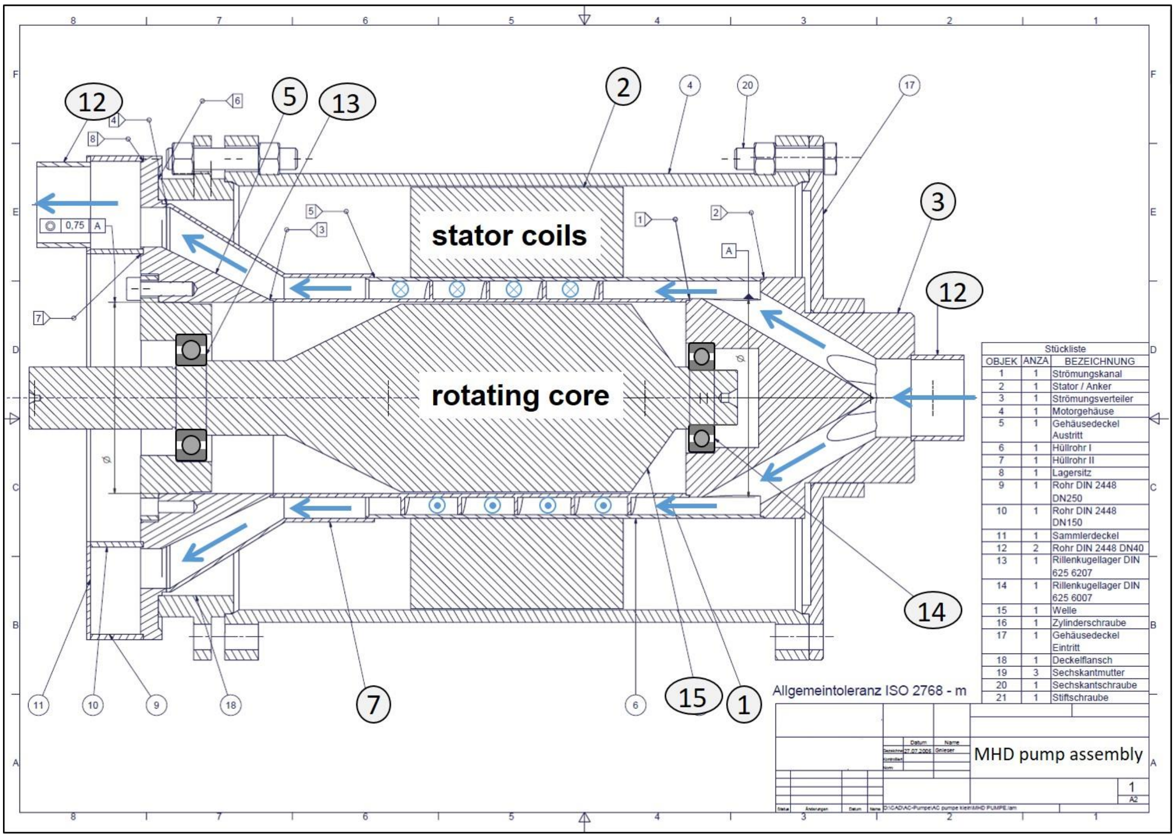
Key words: Liquid metal EM pumps, helical induction pump, rotating iron core

Preface The present work results from a collaboration of both authors. We had the idea to design, manufacture and test a medium-scale liquid metal pump at reasonable costs. Although the work had been completed already several years ago, the results were never fully published, neither at a conference nor in a journal, despite the intention of doing so. Unfortunately, in December 2023 the second author, our dear friend and colleague Robert Stieglitz, unexpectedly passed away. Upon this sad circumstance, I remembered our collaboration on EM pumps and that it could be a good idea to publish the results now, in order to recall to the magnetohydrodynamics community Robert’s unforgettable achievements in MHD and in particular the Karlsruhe geo-dynamo experiment [1, 2].

1. Introduction Liquid metals, such as sodium Na, sodium-potassium NaK, Lithium Li and lead-lithium PbLi, have been proposed as coolants in fast nuclear reactors or in blankets of future fusion reactors due to their high thermal conductance, their applicability at high temperature, and their favourable interaction with neutrons for fuel breeding purposes. For circulation of those electrically conducting fluids through circuits and heat exchangers on reactor scales, usually large annular linear induction pumps (ALIP) are the preferred choice at high flow rates [3]. Electromagnetic pumps have the advantage that they are hermetically tight with no penetration of a rotating axle. The latter could pose risks of potential leaking, which would represent a safety issue in case of alkali liquid metals or in nuclear applications. However, on medium scales ALIPs operate at quite poor efficiency, as shown for instance in [4], where the maximum efficiency was about only 5% or smaller.

For applications on a laboratory scale, permanent magnet rotor pumps became an interesting option for moderate flow rates and pressure heads due to their relatively simple design [5, 6]. Higher pressure heads can be achieved by a helical design of the pump channels [6]. Instead of a rotating magnetic shaft as used in the latter references, it is possible to apply rotating magnetic fields created externally by 3-phase currents as proposed e.g. in [7] for pumping of liquid metals.

Based on the physical principles of helical induction pumps, we developed a design of a new type of liquid metal pump for medium flow rates and moderate pressure heads. The design is shown in Figure 1. The main components are the helical annular pump channel (1), which is placed in the stator (2) of a former 11kW induction motor that became available at the institute. The flow is supplied to the annular channel through a DN40 pipe (12) followed by an axial-radial manifold (3). After passing the helical pumping channel (1), the liquid metal continues its path through a conical diffuser (5, 7). Finally, the fluid passes openings at the end of the diffuser body and it is collected in a larger annular compartment before it leaves the pump through the DN40 exit pipe (12). Magnetic flux lines are closed via a soft iron core (15). While in previous designs of helical induction pumps such as e.g. [7], the laminated core fabricated from thin transformer plates for reducing induction losses, was entirely submerged in the liquid metal flow, we have chosen here a different approach. In the present design, the iron core, which is fabricated from a single solid piece, is fully accessible from one side (the left side in Figure 1). For minimization of magnetization losses, the core is mounted on two ball bearings (13) and (14) and permitted momentum-free rotation. During the start-up of the pump, the core accelerates quickly until the rotation rate reaches the frequency of the stator field for which induced currents and Ohmic losses in the iron core then vanish.



Stückliste		
OBJEK	ANZA	BEZEICHNUNG
1	1	Strömungskanal
2	1	Stator / Anker
3	1	Strömungsverteiler
4	1	Motorgehäuse
5	1	Gehäusedeckel Austritt
6	1	Hüllrohr I
7	1	Hüllrohr II
8	1	Lagersitz
9	1	Rohr DIN 2448 DN250
10	1	Rohr DIN 2448 DN150
11	1	Sammlerdeckel
12	2	Rohr DIN 2448 DN40
13	1	Rillenkugellager DIN 625 6207
14	1	Rillenkugellager DIN 625 6007
15	1	Welle
16	1	Zylinderschraube
17	1	Gehäusedeckel Eintritt
18	1	Deckelflansch
19	3	Sechskantmutter
20	1	Sechskantschraube
21	1	Stiftschraube

Figure 1 Design of the helical induction pump, MHD pump assembly.

In the following, we estimate some properties of the pump. As structural material for the spiral channel walls, stainless steel with a wall thickness of 2mm was used with electrical conductivity $\sigma_{\mathrm{steel}}=1.24\times10^{6}$ 1/Ωm and magnetic permeability μ_0 of free space. A typical penetration depth $\delta=\sqrt{2/\mu_0\sigma\,\omega}$ for magnetic inductive waves at a frequency of $f=\omega/2\pi$ =30Hz is about δ_{steel}=83mm in stainless steel so that the shielding effect, i.e. the reduction of magnetic field in the fluid by eddy currents in the wall, remains small at about

2.5%. For the liquid metal NaK (σ_{NaK}=2.79×10^6 1/Ωm) we may estimate at the same frequency δ_{NaK}=55mm which indicates that the traveling magnetic field affects the fluid in the entire spiral gap which has a radial dimension of 10mm. The field drops across the pump channel by roughly 17%. If the fluid moved synchronously (no friction losses, no pressure drop) at the mean spiral radius r_s, i.e. with the mean rotation speed $r_s\omega$ of the magnetic field, we could expect at 30Hz a flow rate through the 10mm×30mm cross section of the spiral channel (Figure 2) as $\dot{V}_s = 3.45\times10^{-3}\,\mathrm{m}^3/\mathrm{s}$. This leads with fluid density (ρ_{NaK}=863 kg/m^3) to an upper limit for mass flowrate of $\dot{m}_s = 2.98\,\mathrm{kg/s}$. With viscous effects and Ohmic losses present, and when the pump has to deliver a certain pressure head, the flow rate will become smaller than these ideal values.

The pump was manufactured at the KIT workshop. Photographs displayed in Figure 3 show the finished pump and its components before assembly. After a pressure test and confirmed tightness, the pump was inserted for testing in the liquid metal NaK loop of the MEKKA facility [8]. In order to enable entire draining of the spiral channel by gravity after the tests are completed, the pump was installed with the rotation axis in vertical orientation and inflow from below. A 3-phase power supply with adjustable frequency and current was used during the experiments. The temperature of the liquid metal was monitored by thermocouples in front and after the pump, primarily for determination of temperature-dependent fluid properties. The flowrate was measured by a Coriolis flow meter in the NaK loop and the pressure head developed by the pump was detected through a capacitive differential pressure transducer [8]. In addition, the rotation rate of the iron core was measured by an optical sensor.

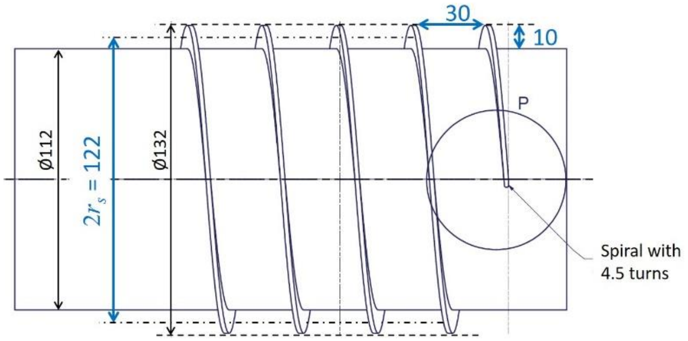


Figure 2 Details of the helical channel.

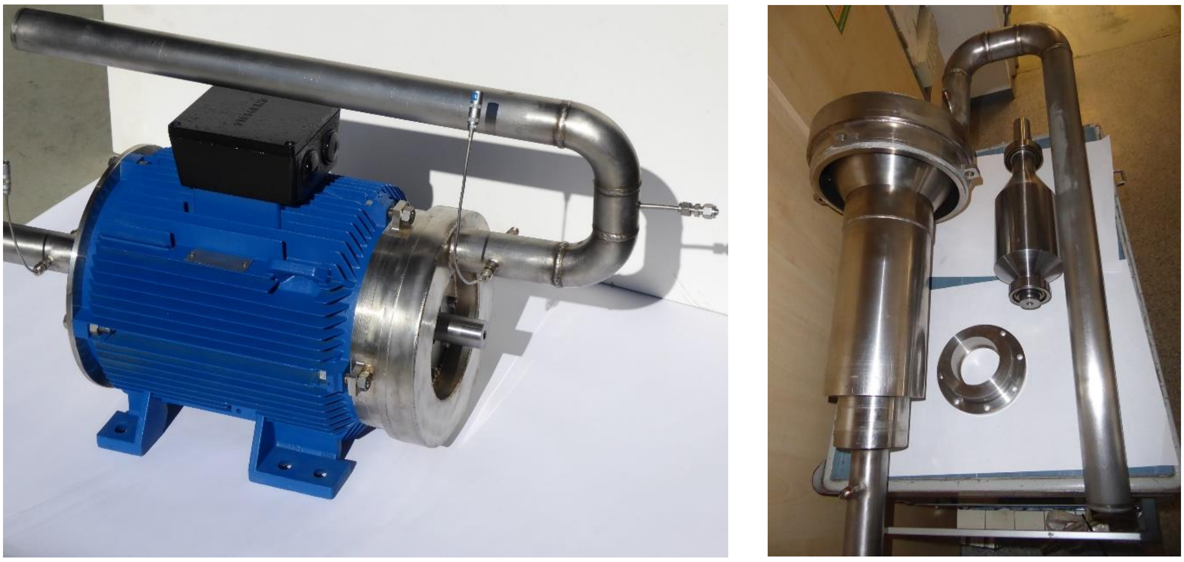


Figure 3 Photograph of the assembled pump (left) and its components (right).

2. Experimental results Experiments have been performed by setting the frequency and magnitude of currents in the 3-phase stator coils to predefined values while the flow loop is initially closed by a valve. Then the control valve is opened in small increments leading to a stepwise increase of the flow rate. The pressure head developed by the pump and the flow rate are measured after steady state conditions established. In the following, the pump characteristics are shown with a focus on pressure head $\Delta p(\dot{m})$ and efficiency $\eta(\dot{m})$ for the specified frequency and current magnitude I. Here, I denotes the sum of currents over all three phases. The pump efficiency η is defined as the ratio of the delivered hydrodynamic power $\Delta p\dot{V}$ in terms of pressure head Δp and volumetric flow rate $\dot{V}$, and the electric power P_{el} supplied to the engine, i.e. $\eta = \Delta p\dot{V} / P_{el}$.

In a first series of experiments the total current is fixed to I=60A while the pump performance is tested for various frequencies in a range from 20Hz to 60Hz. Results displayed in Figure 4 reveal, as expected, that the pressure head Δp decreases with increasing mass flowrate $\dot{m}$. With increasing frequency, 20Hz → 30Hz → 40 Hz, the maximum mass flowrate increases further, due to a higher rotation rate of the magnetic field. However, beyond 40Hz the maximum mass flow does apparently not increase further and the maximum pressure heads become smaller. The maximum efficiency is achieved at a frequency close to 30Hz.

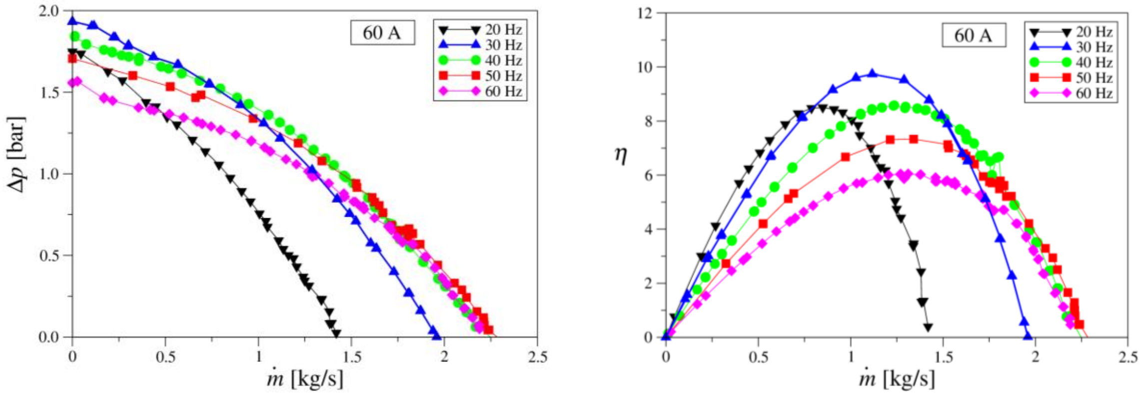


Figure 4 Pressure head Δp (left) and efficiency η (right) versus mass flowrate $\dot{m}$ for a total current I=60A and various frequencies.

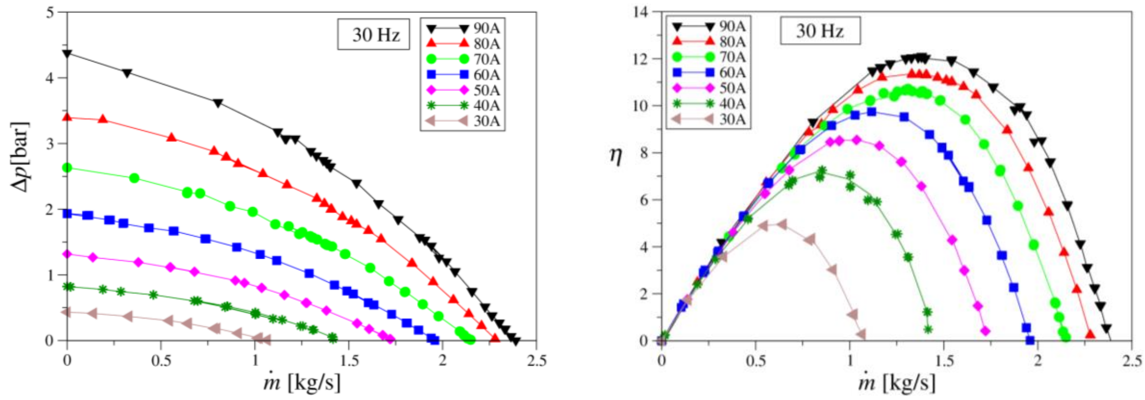


Figure 5 Pressure head Δp (left) and efficiency η (right) versus mass flowrate $\dot{m}$ for a frequency of 30Hz and various strengths of currents I.

In a next step, the frequency is fixed at 30Hz, which is considered close to an optimum value with respect to pressure head and efficiency. In a series of experiments, it is analyzed how the pump performs with different strengths of applied current. Results for pressure head

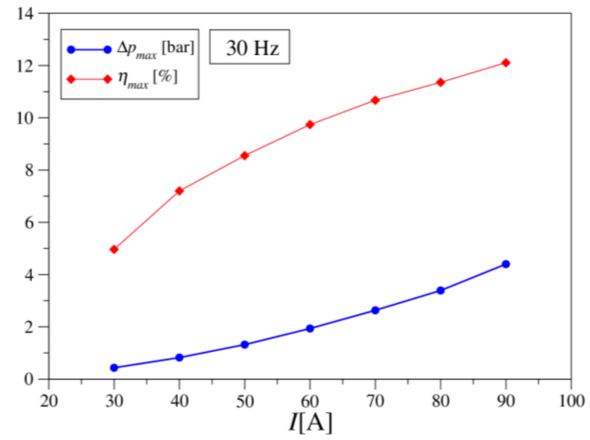


Figure 6 Maximum values Δp_{max} and η_{max} as function of I for a frequency of 30Hz.

Δp and efficiency η are displayed in Figure 5. It can be observed that the maximum pressure head Δp_{max} as well as the efficiency η_{max} increase monotonically with increasing currents. Results for Δp_{max} and η_{max} are summarized in Figure 6. At the highest investigated current I=90A, a maximum pressure head Δp=4.4bar and efficiency η=12.1% are achieved. From the results it can be anticipated that with currents higher than I=90A even higher Δp and η values should be possible. Unfortunately, in the present experimental campaign, higher currents could not be applied in stationary conditions due to a lack of active stator cooling and the upper bound on coil temperature.

3. Conclusions A new type of helical induction pump has been designed, built, and tested using NaK as liquid metal. The pump works best close to 30Hz and results are quite promising. The pump delivers a maximum pressure head Δp = 4.4bar and maximum flowrate of about 10m^3/h. The highest efficiency of η = 12.1% at a slip $s = (\dot{V}_s - \dot{V}) / \dot{V}_s = 0.53$ seems quite good, despite the fact that so far no optimization has been performed for the pump channel geometry. Moreover, with forced (internal) cooling of the stator, it should be possible to allow for larger currents with further increase in Δp and η. Since the central core is fully accessible from outside, it should be also possible to replace it by an active 3-phase-powered non-rotating one for future improvement.

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