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DRESDYN – A NEW PLATFORM FOR SODIUM RELATED THERMOHYDRAULIC STUDIES AND MEASUREMENT DEVELOPMENTS

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Abstract

The safe and reliable operation of liquid metal systems in innovative reactor concepts like sodium cooled fast breeder reactors or lead-bismuth targets in transmutation systems requires appropriate measuring systems and control units, both for the liquid metal single-phase flow as well as for gas bubble liquid metal two-phase flows. We report on the liquid sodium facility DRESDYN (DREsden Sodium facility for DYNamo and thermohydraulic studies), presently under construction, that will comprise experiments with geo- and astrophysical background as well as experiments for thermohydraulic studies and for the development and the test of measurement techniques for sodium flows.

1. Introduction

The crucial advantage of Sodium-cooled Fast Reactors (SFR) is their capability to utilize available fissile and fertile materials considerably more efficiently than light water reactors. They are also designed for closing the fuel cycle by managing high-level wastes, in particular plutonium and other actinides. The SFR concept is characterized by important safety features, including a large margin to the boiling point of sodium, a long thermal response time, a primary system that operates near atmospheric pressure, and an intermediate sodium system between the radioactive sodium in the primary system and the power conversion system.

Within the framework of the Generation IV International FORUM (GIF), the last years have seen a remarkable renaissance of SFR's. With the ASTRID prototype in France [1], the PFBR in India [2], CEFR in China [3], JSFR in Japan [4], BN-800 [5] in Russia, KALIMER-600 in South Korea [6], and the envisioned Travelling Wave Reactor in the US [7], a significant number of SFR projects are presently under deployment or development.

Notwithstanding the mentioned advantages of SFR's, the use of sodium is connected with two main challenges: the first one is a positive void reactivity, the second one is the high chemical reactivity, which requires special precautions to prevent and suppress fires. With view on these two challenges, there is a growing need for small and medium sized liquid sodium experiments to study various thermohydraulic and safety aspects of SFR's, comprising sodium boiling, argon entrainment, bubble detection, sodium flow metering, etc. [1].

A less discussed aspect of SFR's is the theoretical possibility of magnetic-field self-excitation (dynamo effect) in helical sodium flows, although early papers by Bevir [8] and Pierson [9] had considered the conditions for self-excitation in the pumps as well as in the core. A very first attempt to reach self-excitation in a liquid sodium flow was undertaken at a test facility for fast breeder pumps in the Leningrad Scientific Research Institute of Electrophysical Apparatus in 1987 [10]. Ten years later, in 1999, a modified version (the so-called *Riga dynamo experiment*) of this experiment led to first experimental realization of the homogeneous dynamo effect [11]. Almost simultaneously, the *Karlsruhe dynamo experiment* proved evidence for self-excitation in an assembly of 52 spin-generators [12], a structure which is already very similar to the flow structure in the core of an SFR. In 2006, self-excitation was also observed in the so-called von-Kármán-dynamo experiment in Cadarache (France), though only in the presence of soft-iron impellers [13]. The latter fact is remarkable with view on the plans to replace the austenitic steel of the claddings of SFR's by ferritic/martensitic or ODS materials. It is certainly worthwhile to continue the interesting investigations of Plunian et al. [14] on the influence of this material change on the dynamo conditions in the core.

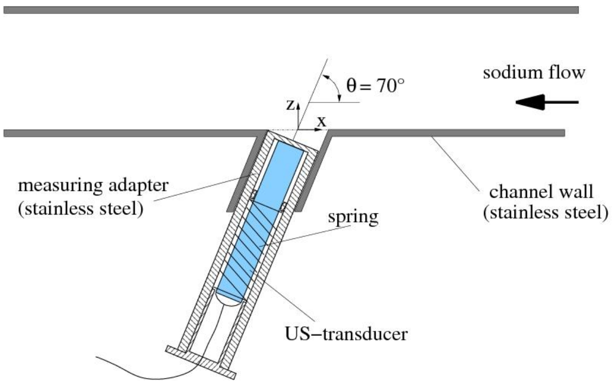
The planned DRESDYN project (DREsden Sodium facility for DYNamo and thermo-hydraulic studies) at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) is intended to become a European center for investigations of various aspects of liquid sodium flows. It will combine activities with geo- and astrophysical motivation, including the dynamo effect and the magneto-rotational instability, with studies of the thermo-hydraulic and safety behavior of SFR's. In the present paper, we will delineate the experiments planned within the DRESDYN project. Prior to this, we will give a summary of our previous achievements with possible relevance to the SFR.

2. Previous achievements

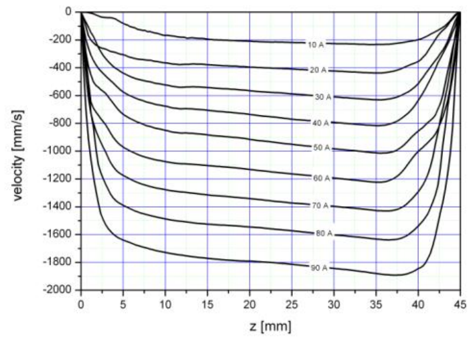
2.1 Measuring techniques for flow velocities

Starting with the primary pumps in the reactor vessel, there are a number of further places in an SFR where the reliable and accurate measurement of global or local flow data is of significant interest. For example, spatially resolved velocity determination above the core could help to quickly detect any sort of blockage in the subassemblies. An ambitious, but not unrealistic, project is related to the contactless determination of the complete velocity field structure within the reactor vessel.

During the last 20 years the Ultrasonic Doppler Velocimetry (UDV) has become a powerful and widely used technique for flow velocity measurements, in particular for opaque fluids. To demonstrate the capabilities of the UDV technique with respect to the applicability for sodium flows, we performed experiments at the existing sodium loop at HZDR which has an inventory of 100 l (for more details, see [15,16]) . The facility operates with a sodium flow in the temperature range between 120°C and 350°C. An electromagnetic pump is used to generate the mean flow with maximum velocities of about 1.7 m/s in a square test section of 45x45 mm^2. As shown in Figure 1a the US transducer was installed inside a cylindrical measuring adapter with an angle of 70° with respect to the mean flow. Doppler measurements require the presence of scattering particles inside the fluid. Artificial or natural particles, like gas bubbles, oxide particles or other solid impurities can serve for this purpose. The quality of the signal is influenced by the particle concentration, the morphology (e.g. size, shape) and the acoustic properties of the reflecting tracers. Within our study we found that the sodium contains a sufficient amount of oxide particles which act as suitable reflecting tracers.



(a)

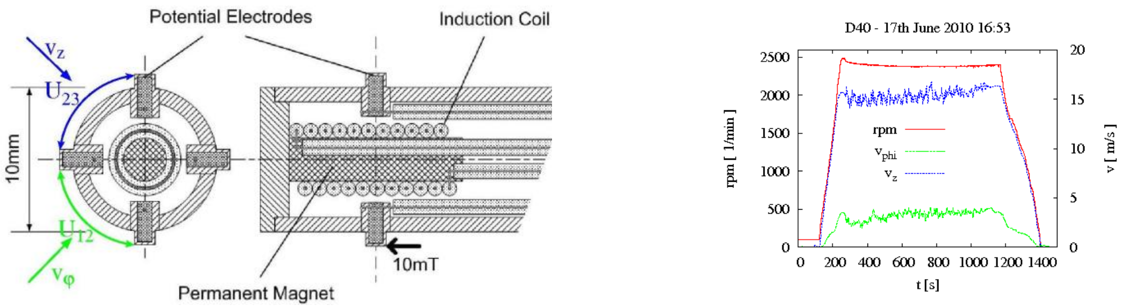


(b)

Figure 1 (a) Schematic view showing the installation of the ultrasonic transducer at the sodium channel flow at HZDR. (b) Time averaged velocity profiles of the sodium flow in the duct measured by UDV for variations of the current of the pump between 10 and 90 A.

The velocity measurement were carried out by the DOP2000 (Signal Processing Lausanne) with a 4 MHz probe of a high temperature series (TR40405). The mean velocity profiles were calculated averaging 256 single profiles corresponding to a measuring time of about 5.6 s. The spatial resolution was 1.25 mm in liquid sodium. A velocity resolution of 9 mm/s was achieved in these experiments. Figure 1b presents the time-averaged velocity profiles measured for various values of the current in the electromagnetic pump. The turbulent profiles exhibit an asymmetrical shape that may arise from the cavity in the channel wall in front of the measuring adapter which has a braking effect on the flow field in its vicinity. Moreover, an inaccurate sensor alignment may distort the measurements. In case of steep Doppler angles as considered here, small uncertainties concerning the direction of the ultrasonic beam may cause perceptible measuring errors. Especially, an inaccuracy of 1 per cent with respect to the sensor alignment would cause a velocity deviation of about 5 per cent.

Another probe that has been developed at HZDR is a modified version of the well-known Vives probe [17], see Figure 2a. In order to withstand the high velocities in the Riga dynamo experiment, is has been designed in a very robust form with the electrodes positioned at the rim of the cylinder instead of at the tip. The probe has been calibrated at the sodium loop at HZDR. Figure 2b shows a typical result of this probe from one of the recent campaigns at the Riga dynamo experiment. The red curve shows the time dependence of the propeller rotation rate, the blue and green curves show the measured axial and azimuthal velocity components. At each instant, the data are averaged over 10 seconds in order to average out the effect of the oscillating magnetic eigenfield which adds to the field of the permanent magnet. The observed increase of the velocities during the measurement is very likely related to the decreasing back-reaction of the magnetic eigenfield on the flow due to the rising sodium temperature which is connected with rising electrical resistivity. In this particular campaign the dynamo was not working properly because of the sub-optimal ratio of azimuthal to axial velocity, a fact that is clearly visible in Figure 2b.



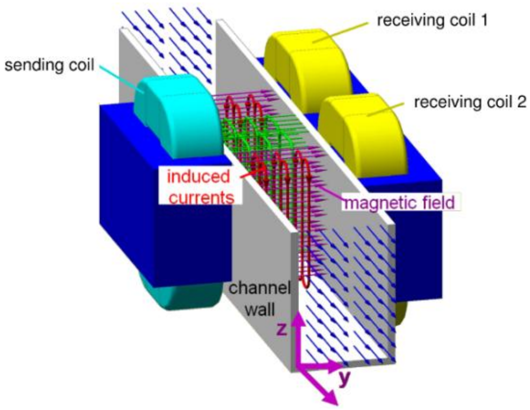
(a) (b)

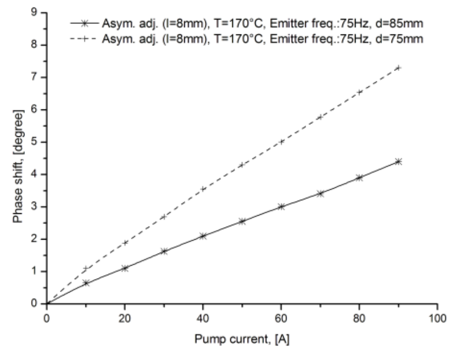
Figure 2 (a) A modified Vives probe for the utilization in the Riga dynamo experiment. The induced voltage U_{12} is proportional to the azimuthal velocity v_φ, the voltage U_{23} is proportional to the axial velocity v_z. (b) Measured axial and azimuthal velocity components at the Riga dynamo experiment. At each instant, the voltages are averaged over 10 s.

A new type of a contactless flowmeter that was also developed at HZDR is delineated in Figure 3a. This so-called phase-shift sensor works with an alternating magnetic field produced by the emitter coil on one side of the flow channel. On the opposite side two receiver coils are placed. The whole set-up is working like an intersected transformer with two secondary coils. We distinguish between the symmetric adjustment and the asymmetric adjustment with some deliberate displacement between the emitter and the receiver coils. The flow in the duct causes a change of the alternating magnetic field. In principle, the amplitude change as well as the phase change can be used for flow rate measurements. In the present realization, the phase difference between two measuring points is used as measuring quantity. More details, in particular a theoretical description of the measuring principle, can be found in [18].

The utilized phase-shift sensor is equipped with an emitter coil of 500 turns placed at one side of the channel, whereas two receiving coils with 1000 turns are located on the opposite side. The emitter coil is fed by an alternating current up to 3 Amperes. For concentrating and conducting the magnetic flux both the emitter and the receiver coils are furnished with transformer iron of a high permeability (flux-iron). The specific arrangement has been realized for applications at higher temperatures. Both the emitter and receiver coils are protected from the hot channel or pipe by plates made of the ceramic material MARCOR which can resist temperatures up to 800°C. The measurements considered here were conducted with an asymmetric adjustment of the operating coils with a shift of 8 mm. The sensitivity of the sensor is determined by the resolution of the lock-in amplifier. For the measurements in sodium as considered here one obtains a velocity resolution of about 5 mm/s.

Figure 3b presents measurements of the phase shift frequency response in an asymmetric adjustment of the phase-shift sensor for an input current of 500 mA. The asymmetric sensor adjustment is preferred because of an increase of the sensitivity with respect to the symmetric adjustment. The measurements were performed at the same sodium channel as shown in Figure 1, with a cross section of 45x45 mm^2 and a wall thickness of 2.5 mm. Figure 3b displays the linear dependency between the flow-induced phase shift and the performance of the electromagnetic linear pump.

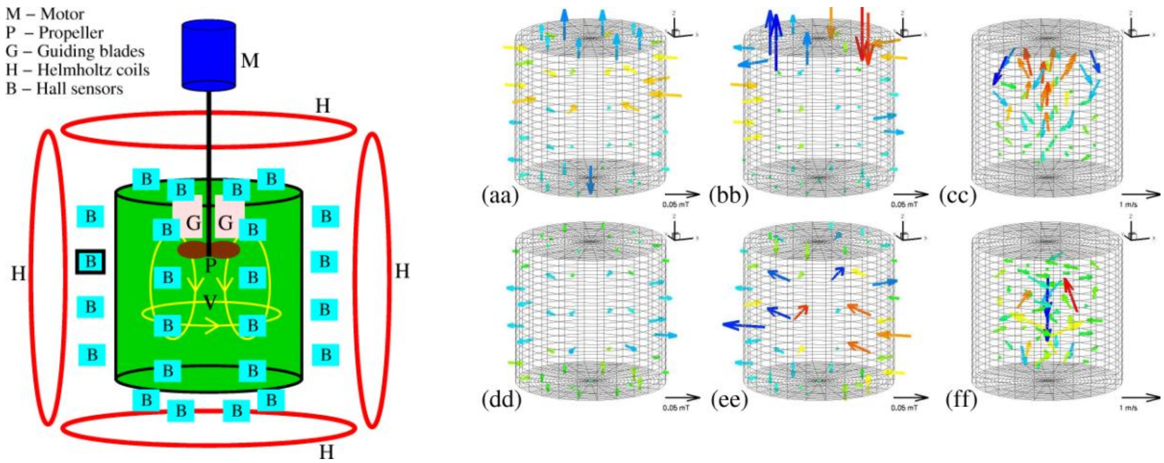




(a) (b)

Figure 3 Principle of the phase-shift flowrate sensor. The phase difference between the signals at the two receiving coils is used as a measure for the flow rate in the channel (a). Linear dependence of the measured phase-shift in an asymmetric configuration, with a displacement length of 8 mm and the two measurements widths of 75 mm and 85 (b).

Apart from the preceding three methods to determine local velocities (or velocities along a beam as in the UDV case), we have also developed a global method that aims at reconstructing whole three-dimensional velocity fields. This method, which is now called Contactless Inductive Flow Tomography (CIFT), relies on the fact that externally applied magnetic fields are disturbed by the flow of a conducting medium, with the magnetic Reynolds number being a measure of the ratio of disturbed to applied magnetic fields. By applying the external field subsequently in different directions it is possible to reconstruct the whole three-dimensional velocity field. For more details on the mathematical foundation of this method and its first application in the metallurgical context, see [19,20,21]. Figure 4a shows the schematic sketch of a liquid metal experiment in which the feasibility of CIFT was proved for the first time. The propeller driven flow of liquid GaInSn in a 17.2 cm diameter/18 cm height cylinder is determined by subsequently applying a magnetic field of around 4 mT in vertical and in horizontal direction. For the two cases of upward and downward pumping of the propeller, Figure 4b shows the induced magnetic fields for vertically applied field (a and d, respectively) and horizontally applied field (b and e, respectively), as well the reconstructed three-dimensional velocity field (c and f, respectively).



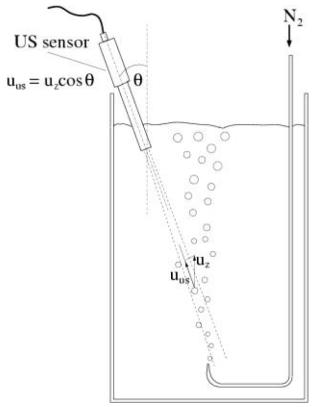
(a) (b)

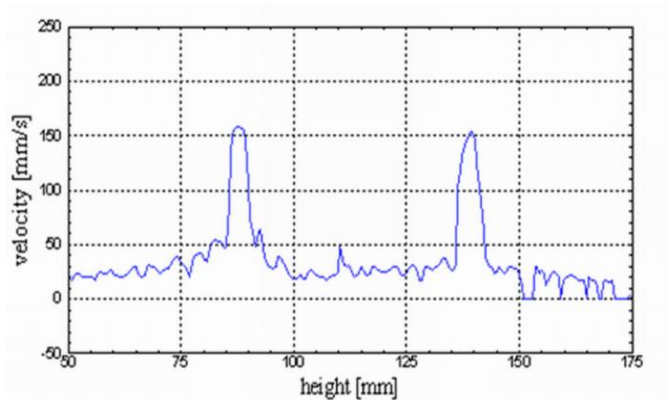
Figure 4 (a) Schematic sketch of the CIFT experiment: Two Helmholtz-like pairs of coils produce subsequently a vertical and a horizontal magnetic field in a cylindrical volume filled with GaInSn that is stirred by a propeller. (b) The flow field is reconstructed from the externally induced magnetic field measured at 48 positions. Induced magnetic fields for vertically applied field (aa and dd) and for horizontally applied field (bb and ee), as well as the reconstructed velocity field (cc and ff), for the case of upward pumping propeller (top row) and downward pumping propeller (bottom row).

2.2 Two-phase flows

The reliable and timely detection and characterization of two-phase flows plays an important role in various SFR-related problems, including argon entrainment and downward transport to the core region, sodium boiling in the core, and the appearance of hydrogen bubbles in the proximity of leaks in the steam-generator.

At HZDR, we have developed and tested various methods for the measurement of two-phase flows. The first of them relies again on the UDV technique. It has been tested in a two-phase experiment as shown in Figure 5. Nitrogen bubbles were injected into the eutectic alloy PbBi at a temperature of 270°C by means of a single orifice with diameter 0.5 mm. A cylindrical container made of stainless steel with a diameter of 125 mm and a height of 250 mm contains a stagnant pool of about 2.5 l liquid metal. The ultrasonic probe with a special acoustic wave guide [22] was positioned through the free surface at the top with a vertical distance of 150 mm from the orifice position. The measurements were restricted to a single bubbly flow regime at small gas flow rates. A typical velocity profile obtained from the bubbly flow is depicted in Figure 5b. The lower velocity at the small measuring depths corresponds to the liquid metal flow which is driven by the rising bubbles. Two bubble signals were detected showing a higher velocity as the surrounding liquid. In the region of low gas flow rates it was possible to clearly distinguish between the bubble and the liquid velocities. Accurate measurements of the velocity of a single bubble and the corresponding wake structure in the liquid can be obtained if the ultrasonic sensor is positioned behind the gas injection point. The sensor position above the rising bubble as considered in Figure 5(a) does not allow for capturing the bubble wake.

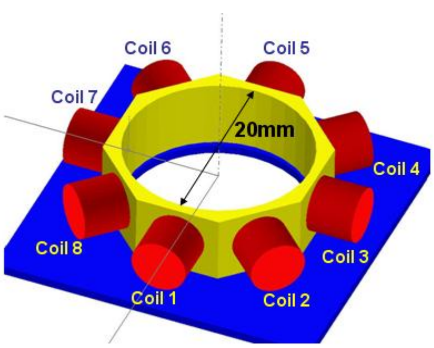




(a) (b)

Figure 5 (a) UDV measurements of a bubbly flow in PbBi. (b) Typical height dependence of the raw velocity data, containing two bubble signals.

Another method to investigate two phase flows has been developed by the group of A. Peyton at the University of Manchester. It relies on the dependence of the mutual inductance between two neighboring coils on the material properties in their vicinity. The method has been successfully applied for the determination of the two-phase flow structure in the submerged entry nozzle of a physical model of continuous steel casting at HZDR [23].



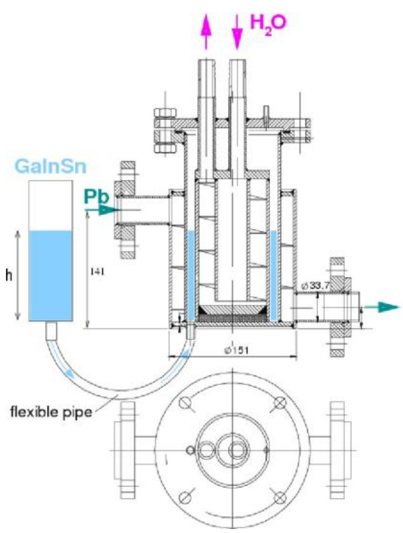
(a) (b)

Figure 6 (a) Coil configuration used in the Mutual Inductance Tomography for determining the conductivity distribution of a two-phase GaInSn/Argon flow in the nozzle of a continuous casting model (figure courtesy N. Terzija). (b) Liquid metal surface reconstruction in dependence on time (vertical axis), as reconstructed by Mutual Inductance Tomography (data courtesy N. Terzija, figure courtesy Th. Wondrak).

Figure 6a shows the assembly of 8 coils surrounding the submerged entry nozzle. Using subsequently each of the coils as emitter and the remaining coils as receivers, the method allows the tomographic reconstruction of the distribution of the liquid metal (here GaInSn) and argon. Figure 6b shows an example of the reconstructed time dependence of the liquid metal boundary in the submerged entry nozzle with interesting shape changes.

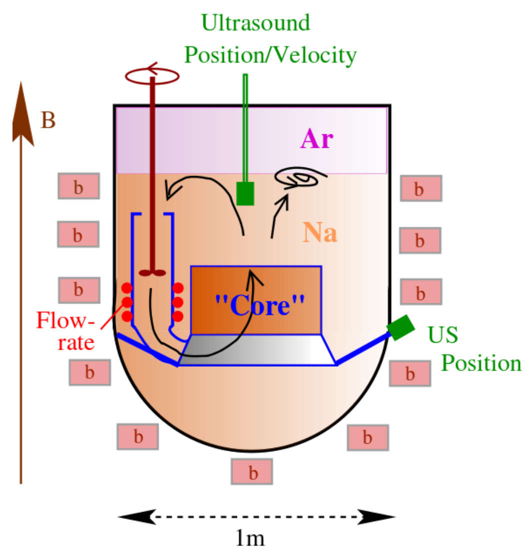
2.3 Smart heat-exchanger

One of the most critical places of an SFR is the heat exchanger where large amounts of sodium are in close proximity to large amounts of water and steam. This proximity makes the system prone to energetic reactions. In principle, any sodium-water reactions due to leaks in the steam generator tubes could be avoided by using an intermediate heat transport medium.



(a)

Figure 7 Smart heat exchanger with GaInSn as an intermediate heat transport medium between hot lead and water. The facility is used for cooling in the photo-neutron source nELBE at HZDR.



(b)

Figure 8 Schematic sketch of the In-Service-Inspection experiment planned in the framework of DRESDYN, including a primary pump and a mock-up of a core.

Although for a quite different purpose, such a heat exchanger between a hot liquid metal and water has been constructed for use in the photo-neutron source nELBE working with a liquid lead target at HZDR [24]. Its main intention was to exclude the possibility of lead-water reactions in the case of leaks by using GaInSn as an intermediate heat transport medium. The configuration shown in Figure 7 has also the interesting advantage that the thermal expansion of GaInSn provides an ideal means for passive regulation of the heat transfer.

2.4 Magnetic field self-excitation and related instabilities

In November 1999, magnetic-field self-excitation had been observed in the *Riga dynamo experiment* [11] which consists basically of a strong helical flow of liquid sodium complemented by a straight back-flow. One month later, the *Karlsruhe dynamo experiment* became operative [12]. This experiment consisted of 52 spin generators, a configuration that is already very similar to the conditions in the core of SFR with its wire-wrapped fuel bundles [25]. HZDR has contributed significantly to the simulation, optimization, and data analysis of the Riga dynamo experiment [26]. Concerning the Karlsruhe experiment, we have found that a slight geometric modification would have led to a transition from a non-axisymmetric to an axi-symmetric eigenfield [27].

In 2006, a third liquid sodium experiment has shown self-excitation [28]. This so-called *von-Kármán sodium* experiment (VKS) consists if a compact cylindrical vessel wherein two counter-rotating impellers produce a flow with two poloidal and two toroidal vortices. Astonishingly, the observed magnetic eigenfield turned out to be more or less axisymmetric. This was in contrast to all numerical simulations, as was the rather low critical magnetic Reynolds number. In a recent paper [29] we have explained both facts by the dominant role that is played by the soft-iron impellers, without which no self-excitation was observed up to present in the VKS experiment.

3. DRESDYN

For the liquid sodium installations in the framework of DRESDYN a new experimental hall with an area of approximately 500 m^2 will be erected between 2012 and 2014. The total inventory of sodium will be 15 m^3, a significant part of which (around 10 m^3) will be needed for the precession dynamo experiment to be discussed below.

3.1 In-Service-Inspection and thermohydraulic experiments

A significant portion of the SFR-related experiments will be conducted at an In-Service-Inspection (ISI) set-up the principle sketch of which is shown in Figure 8. Basically, it will consist of a heated stainless steel vessel with a diameter of approximately 1 m filled with liquid sodium covered by argon. The internal components will comprise a simple mock-up of a reactor core and a primary pump. The main goal of this facility is to test a variety of measurement techniques for the position of internal components, for flow velocities and argon bubble detection. The latter will include experiments on Argon entrainment on the free surface. DRESDYN will also comprise a liquid sodium loop, which in the long term will replace the presently existing one. This loop will contain various test sections, among them one section for the test of smart heat exchangers with intermediate heat transfer media. Another suit of experiments will be devoted to the important problem of sodium boiling [30]. Starting with very small experiments at a flat wall, we will go over later to boiling experiments at rods or rod bundles. For the visualization of the boiling we plan to use the above mentioned Mutual Inductance Tomography, as well as X-ray radiography [31] and, in collaboration with another group at HZDR, the ultrafast X-ray tomography [32].

3.2 Experiments with geo- and astrophysical background

The most ambitious project in the framework of DRESDYN is a large scale precession dynamo experiment. This experiment is intended to be a truly homogeneous dynamo in the form of a cylindrical vessel of 2 m diameter and height, rotating with up to 10 Hz around its axis, and with up to 1 Hz around a perpendicular axis. The mechanical and safety demands for such a large scale sodium experiment are tremendous. With a total mass of approximately 10 tons (including the stainless steel wall) the filled cylinder will have a moment of inertia of around 5000 kg m^2. With the two rotation rates of 10 and 1 Hz, this amounts to a gyroscopic moment of 2×10^6 Nm. This tremendous moment requires a massive and solid basement. The second experiment with geo- and astrophysical background is basically a large Taylor-Couette-Experiment with a diameter of 1 m and a height of 2.5 m, embedded into a large coil that produces a strong vertical magnetic field, and the possibility to guide independent electrical currents along the center and through the liquid sodium in the Tayler-Couette cell. This installation will be used to carry out experiments on the magneto-rotational and related instabilities.

Depending on the results of presently ongoing computer simulation concerning the effect of ferritic/martensitic materials on the self-excitation condition in the core, we also consider to do experiments on this topic.

4. Conclusions

In this paper, we have summarized our previous work on measurement techniques and on the dynamo effect in liquid metals, and we have given a sketch of the activities that are planned in the framework of the DRESDYN project. However, DRESDYN is open for further projects to study various aspects of sodium flows, and corresponding proposals are highly welcome.

5. Acknowledgments

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