LIQUID METAL IN NUCLEAR APPLICATIONS

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Abstract: For decades, the development of liquid metal technologies for nuclear applications is a main research topic in the research program of the Institute of Physics of the University of Latvia (IPUL).

1. Introduction

The recent 3–5 years can be characterized by a growing interest to liquid metals. Such interest is connected with the developing neutron spallation source facilities in some countries, ADS tasks, new generation of nuclear reactors, as well as with the building of an ITER facility in France.

The Institute of Physics, University of Latvia, is well known as a centre for Liquid Metal (LM) MHD research with a long year experience in different research fields, which have been involved in both theoretical and applied studies and experiments. Let us mention a few examples. The IPUL participated in the development of equipment for a setup, where the strong temperature dependence for corrosion in PbLi was discovered, including corrosion provoking conditions due to cavitation. The IPUL is involved also in the development of the LM target for the Neutron Spallation Source facilities, where one of the main problems is the protection of the container walls from pressure waves generated by the pulsing proton beam. Concerning the loop technique, a recently completed setup for PbBi should also be mentioned.

Effective international collaboration is crucial for the success here. In general, the IPUL cannot be directly involved in the design of the final full power installations. Its task is mainly the search for new approaches, along with physical preparations, prototyping, etc. In this regard, the IPUL activities are really diverse. The same could be said also about the on-going tasks. A hydraulic prototype of liquid metal PbBi version of the target for the European Spallation Source (ESS) is under investigation at the IPUL. The proposed by IPUL fast moving liquid gallium structures have been accepted as candidates for divertor protection in the potential fusion power plant, a next step project after ITER and DEMO. According to the Collaborative Project on European Sodium Fast Reactor (CP-ESFR), the IPUL must focus on high performance electromagnetic pumps and instrumentation for various electrically conducting liquids. As new and acute, the project SILER (Seismic-Initiated Events risk mitigation in Lead - cooled Reactors) should be emphasized. The IPUL is invited to analyze the situation with electromagnetic pump stability under the condition of seismic risk and to elaborate rules for optimal positioning of such pumps. The IPUL is interested to remain in the team developing later the EURISOL project. The aim is the design of a facility for the production of exotic radioactive ion beams. The IPUL must consider a version of the liquid metal proton/neutron converter, which is squeezed in a very limited space.

These and other questions related to LM will be presented in the report.

2. Fission related Liquid Metal researches

At the IPUL, the unique experience in different liquid metal technologies mainly associated with nuclear energy plants has been accumulated. The importance of this potential is confirmed by the fact that the IPUL participates in the coordinating SNEPT program (Sustainable Nuclear Energy Technology Platform) since the program very beginning. First, the problem of stability of powerful electromagnetic induction pumps for liquid metals has been chosen. At due time at the IPUL the warning has been stated that such pump can become unstable if its specific parameters are exceeded. The importance of these criteria has been proved practically.

This instability leads to the formation of counter flow, pressure losses and limited usage of EMP. The instability criterion has been theoretically derived in [1], the boundary between flow stability and instability has been determined experimentally. Experimental and numerical results are compared in [2]. Although qualitative agreement between theoretical predictions and experiment can be observed, a more detailed analytical study [3] and an experiment with controlled velocity/magnetic field perturbation implementation are necessary for a more profound understanding of the instability mechanisms in the EMP. Experimental investigations of this instability are planned with the newly installed 125 mm sodium loop.

The high productive pump has to be designed for the needs of the 4th generation nuclear reactor when all the assignments are achieved. Note that ready for use technical solutions preventing instability will be completely new for the design of reliable and efficient high productive pumps. The solutions described above will offer a long-term opportunity to develop liquid metal systems much faster and to satisfy the requirements for the 4th generation reactors with liquid metal systems and also their industrial applications.

3. Fusion related liquid metal researches

The concept of liquid metal use, especially liquid lithium, as the plasma-facing surface was raised many decades ago. Liquid metals have many advantages especially on the lifetime of the divertor components. Their surface is not subject to erosion, melting, craters and, in general, to surface damage. Also, the maintenance and the replacements of a liquid divertor is not so stringent as a solid material divertor. The liquid Li surface can also effectively lower the hydrogen isotopes' recycling and getter the impurities in fusion reactors. In addition, liquid Li surface has the ability to transfer heat out of the limiter/divertor region and continually provide a clean surface to plasma.

Suitable materials will be needed on DEMO to handle safely the high power loads in the divertor and beyond the limits of the current technology. In this framework, a possible solution has been found for the application of liquid metals as plasma facing materials (Li, Sn, Ga) realized in a capillary porous system (CPS) configuration in order to counteract the MHD forces on the liquid metal surface.

In contrast to CPS, a fast moving free surface flow is beyond comparison. To eliminate the intensity of the MHD interaction right from the beginning, preference was given to the fast moving jet or droplet screens. Promising are the results obtained on ISTTOK [4]. A limiter formed by a thin 2.5 mm Ga jet at velocities of 1.5-2.0 m/s was able to exhaust 2.4 kW in a 14.5 kW (Ohmic) discharge. The parameters of the discharge remained practically unchanged. With the IPUL superconducting solenoid (up to 5 T, D = 30 cm; L = 100 cm), three d = 2.14 mm InGaSn jets were targeted towards a cylindrical non-wetted SS wall. The result was somewhat striking: in up to 4 T fields the jets remained stable and well organized over the full length of their path.

The other aim of our works is focused on the understanding of the mechanism and features of the thin liquid metal film creation on the stainless steel matrix. For the successful use of lithium and other conductive liquid metals, it is necessary to investigate the influence of many technological factors on wetting and metal flow continuity. To conduct the experiments with pure surface of Li, a particular vacuum setup was designed and manufactured. A specially designed multi-channel distributor was installed into the setup. This enabled to drive a stable film flow of liquid metal on a steel SS 316L substrate at a temperature up to 450 °C.

The influence of a strong magnetic field on homogeneous distribution of the liquid metal along a stainless steel plate has been experimentally proved. Theoretical and practical research of the MHD effect, taking place inside the multi-channel distributor device, shows the applicability of this method to improve the distribution of liquid metal on the stainless gradient plate and could be considered as a theoretically promising divertor prototype.

It should be noted that the choice of construction materials for the blanket of the fusion reactor has not fully resolved. Still undecided is the problem of material corrosion in the liquid metal, under the radiation conditions and at relatively high temperatures. At present, the lead–lithium (Pb-17Li) eutectic is considered as the most suitable tritium breeder material. As an optimum version, EUROFER 97 steel is proposed, the corrosion rate of which in the liquid Pb-17Li eutectic is the least. However, these results have been obtained without taking into account the influence of a strong magnetic field. At the same time, this influence must be essential because of the variation of liquid metal flow hydrodynamics and because of the interaction of the magnetic field with ferromagnetic steel. Our task was to assess the magnetic field action on the corrosion process of EUROFER steel in the liquid PbLi at a temperature up to 550 °C. For the solution of this task, a special setup has been developed.

Some experiments carried out at the IPUL have shown that the magnetic field greatly affects the corrosion processes for austenitic and martensitic steels [5].

4. Neutron Spallation related liquid metal researches

Neutron scattering provides basic microscopic information on the structure and dynamics of materials, which add to our understanding of condensed matter in such fields as biology, material science, chemistry, earth science and physics. Europe is pre-eminent in this field, and the present proposal for the next generation neutron source, for the European Spallation Source will ensure the availability of highest quality neutron beams to a wide range of users from academic studies and industrial applications.

In the case of the European Spallation neutron Sources, the Lead Bismuth eutectic (LBE) target as a comparative solution has been chosen. Within the framework of the ESS Design Study, the liquid metal spallation target loaded with power of several megawatts is a critical component and needs a new advanced technology [6].

In order to develop a liquid metal (LM) target, it is necessary to test and investigate the thermo-hydrodynamics of LM flow, the hydraulic and structural behavior of the target for various inlet flow conditions (i.e. mass flow rates) and, in particular, for nominal operating flow rates and pressure in the system, as well as to determine the heat transfer conditions between the proton beam window and the coolant-liquid LBE.

The LBE neutron converter target, named METAL:LIC and developed by KIT and IPUL as a comparative solution for ESS, has been chosen for tests on LBE loop at the IPUL. The complete test campaign was carried out in two sessions:

- in the first session, all measuring and control systems, including the heating of the loop and target mock-up, were checked;
- in the second session, the distribution velocity and temperature of the liquid metal (PbBi) in the target module depend on the window temperature, and the liquid metal flow rate in the loop was investigated.

We consider the heat transfer in the Pb-Bi loop with an inductive heat source as a model for the proton beam caused heat deposition. The results of the first session experiments showed the following:

- The inductive heating can be successfully used for modelling of the integral heat deposition in the spallation target.
- By adjusting the frequency, it is possible to achieve different depth of heat deposition.

Nevertheless, reliable determination of the total power might require some additional measurements of the temperature upstream and downstream the heated zone.

In the ESS project with beam power up to 5 MW, a gas-cooled solid tungsten rotating target was used. The cooled rotating target concepts provide a larger proton beam facing window surface and thus the lower heat loads on the target window in comparison with the classical coaxial target window. An LM cooled rotating target is also under consideration at the IPUL. The LM cooled rotating target has several advantages if compared with the rotating gas cooled target. The advantages are the following: better heat transfer conditions, much smaller pressure and fluid flow velocity in the target, no necessity to synchronize the movement of the proton beam charges, as well as, smaller weight.

References

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