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Gravitational flow of a thin film of liquid metal in a strong magnetic field

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ABSTRACT

The influence of a poloidal magnetic field of the spherical Tokamak on super thin ($h \approx 0.1$ mm) film flow of liquid metal driven by gravity over the surface of the cooled divertor plate is addressed. The experimental setup developed at the Institute of Physics, University of Latvia (IPUL) is described, which makes it possible to drive and visualize such liquid metal flows in the solenoid of the superconducting magnet "Magdalena". As applied to the above setup, the magnetic field effect on the operation of the capillary system of liquid metal flow distribution (CSFD) is evaluated by using molten metal (lithium or eutectic InGaSn alloy) with a very small linear flowrate $q \leq 1$ mm^2/s, spread uniformly across the substrate. The magnetic field effect on the main parameters of the fully developed film flow is estimated for the above-mentioned liquid metals.

An approximation technique has been proposed to calculate the development of the gravitational film flow. A non-linear differential second order equation has been derived, which describes the variation of the film flow thickness over the substrate length versus the flowrate q, magnetic field B and the substrate sloping α.

Results of InGaSn film flow observations in a strong ($B = 4$ T) poloidal magnetic field are presented. Analysis of the video records evidences of experimental realization of a stable stationary film flow at width-uniform supply of InGaSn.

1. Introduction

The use of liquid lithium as a plasma facing component can change the characteristics of Tokamak plasmas significantly and enhance their performance [1–4]. Liquid lithium can absorb plasma particles (hydrogen isotopes), which otherwise hit the wall and return as neutral atoms so cooling the plasma edge. At the same time, liquid lithium can be replenished, thus providing a stationary low recycling plasma regime. The utilization of these unique lithium properties might lead to flattened plasma temperature profiles and to valuable improvements in plasma confinement and stability. Fusion devices of smaller size with burning plasma become feasible [5].

Recently, research on the so-called small aspect ratio or spherical Tokamak has been stimulated by its potential use as an effective source of neutrons [6]. Since the main function of such facilities is the production of neutrons, these facilities differ from energy reactors in size and produce much less thermo-nuclear power. It is expected that the fusion conditions in such Tokamaks could be realized with relatively small auxiliary heating power. These expectations rely on the use of liquid lithium as a plasma facing surface for impurity control and absorption of the plasma particles. The resulting enhancement of the plasma confinement can compensate for the typical reduction in energy confinement time in small-sized devices.

An example of the divertor area in the small spherical Tokamak is shown in Fig. 1. The magnetic surfaces of the poloidal magnetic field B_p in an operational regime are calculated in Refs. [7,8]. The toroidal field B_t is normal to the picture plane and highly non-uniform in the low aspect ratio configurations of the spherical Tokamak:

$$B_t(r) = B_0 \frac{R_0}{r}, \quad (1)$$

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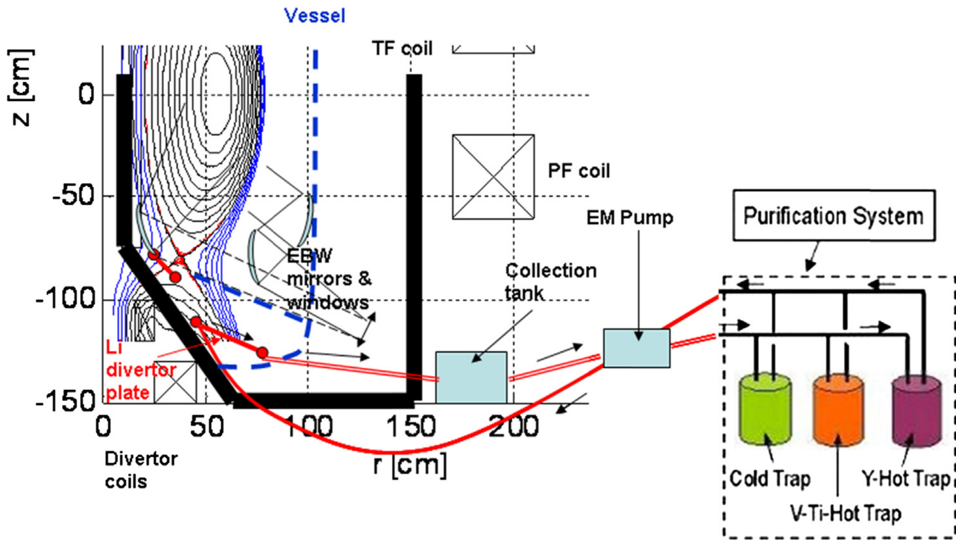

Fig. 1. Schema of the divertor area in the small spherical Tokamak.

where r is the radius of the Tokamak in cylindrical coordinates, R_0 is a reference major radius, and $B_t = B_0$.

Estimates for such spherical Tokamak operation show that the heat is transported through plasma particle flows, leaving the periphery of the plasma filament (pinch) and moving along the force lines of the magnetic field $B = B_p = B_c$, and power densities can exceed 10 MW/m^2. However, the heat fluxes, which in the divertor zone concentrate in the vicinity of the branches of the separatrix of the poloidal magnetic field B_p, can be completely removed by the active cooling of the solid divertor plates. In this case, the lithium film, slowly flowing over the plate surface, simply accumulates the plasma particles falling on it and prevents sputtering of the plate surface. Such small thicknesses of the film are determined mainly by the restrictions to the temperature on the liquid lithium surface. The intensive evaporation of lithium can negatively affect the parameters of high temperature plasma.

Fig. 1 schematically illustrates the location of the divertor plates over which such a lithium film flows. Below we will discuss mostly the outer divertor plate, which is crossed by a branch of the field B_p separatrix farther from the center as was shown in Ref. [4]. In spherical Tokamaks, most of the exhausted power goes through this branch of the separatrix.

In order to study the effect of the magnetic field on the super thin film flow of liquid metal over the surface of the divertor plate, an experimental setup has been developed and manufactured at the Institute of Physics, University of Latvia, which makes it possible to initiate and visualize such liquid metal flows in the solenoid of the super conducting magnet Magdalena.

It should be noted that in the experiments with liquid lithium, along with the persistent technological problems of reliable wetting under conditions of high vacuum in the "hot" vacuum chamber ($T \approx 300-350\,^{\circ}$C), the problems of reliable and long-term visualization of the objects under observation arise. These are attributed to the high chemical activity of lithium vapor, which makes any optical system prone to malfunction. Therefore, in the first stage of experiments, the eutectic alloy InGaSn was used as a working medium.

Despite the fact that the physical properties of InGaSn differ greatly from those of lithium, the above-mentioned experiments are reasonable first of all from the methodological point of view. These experiments will allow verification of the proposed solutions of the main problem, i.e., the practical realization and visualization of super thin film flow of liquid metal in a magnetic field.

Keeping in mind that exposed surfaces of flowing eutectic experience oxidation accompanied by the formation of an adsorbed oxide film (though to a lesser degree than liquid lithium), the experiments with InGaSn must be also conducted under high vacuum. In fact, the presence of the adsorbed surface film, especially in the case of lithium, can significantly alter the hydrodynamic characteristics of the free liquid surface and crucially affect the possibility of physical realization of a super thin film flow.

The use of gallium covering a copper plate as a substrate (which assists the motion of the eutectic) in preliminary experiments ensures sufficient wetting of the plate and hence good electric contact between the eutectic and the substrate.

Such a choice of the substrate material, in general, is in accord with the above-described concept of the divertor system of the spherical Tokamak. It is assumed here that the liquid lithium runs over a surface made of stainless steel, a thin layer of which ($h_{st} \leq 0.1$ mm) clads a massive copper plate equipped with systems for both heat supply and removal. The presence of stainless steel is motivated by the need to protect the copper, which has high heat and electrical conductivity, from the action of liquid lithium.

So far, most of the experimental and theoretical investigations of the film magnetohydrodynamics address the effect of a strong toroidal (co-planar to the substrate) magnetic field B_t on the liquid metal flows. In the experiment described below, gravitational film flow was driven in a uniform magnetic field B_p, which had both a normal field component to the plane substrate and a component directed along the flow.

In that case, the substrate was oriented relative to the force lines of the magnetic field such that an electromagnetic force induced in the liquid metal streaming downwards along the substrate would have a normal component in the direction of the corresponding component of gravity. It is presumed that with this orientation of the substrate, the magnetic field might stabilize the film flow.

Additionally, the magnetic field effect on the motion of liquid metal under the above conditions will be evaluated. For comparison, Table 1 compares the values characterizing the physical properties of liquid lithium ($T \approx 300-350\,^{\circ}$C) and InGaSn ($T \approx 30-50\,^{\circ}$C).

2. Experimental setup

In the central part of the cylindrical ($D = 300$ mm) working region of the superconducting magnet "Magdalena" (where the magnetic