EXPERIMENTAL STUDIES OF LIQUID LITHIUM FILM FLOW IN MAGNETIC FIELD

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Abstract. Possibility of practical realization of a super thin (h ≈ 0.1 mm) gravitational film flow of liquid lithium on a flat substrate exposed to a strong magnetic field oriented under some definite angle to the substrate surface is discussed. Results of the first experiment on the observation of such film flow formation performed at IPUL are reported.

1. Introduction.

A problem is considered related to the development of liquid metal (lithium) receiving contact devices for the divertor zone of small spherical tokamaks [1-3]. The latter might be used as an effective source of neutrons [4, 5]. It is assumed that in such devices the heat power of plasma flows concentrated at the separatrix of the poloidal magnetic field can be completely removed by the cooled solid divertor plates, but the liquid lithium film, slowly flowing over the surface, serves only to absorb the falling on it plasma particles.

It should be noted that in the experiments with a liquid lithium flow having a free surface, additionally to the stubborn technological problems of reliable wetting under the conditions of deep vacuum in the “hot” vacuum chamber (T ≈ 300-350 ^{0}C), there arise problems of reliable and long-term visualization of the objects under observation. These are determined by the high chemical activity of lithium vapours, the direct impact of which makes any optical system to malfunction.

All said above gives grounds to the use of pure lithium in experiment, so excluding its contamination with the materials adsorbed onto the inner surfaces of the liquid metal paths. Deep vacuum must prevent the possibility of adsorbed film formation of the free surface of liquid lithium. In fact, the presence of the adsorbed by the film substance on the lithium film surface can significantly alter the hydrodynamics of such a thin film flow and hence to crucially affect the physical realization of the super thin film flow.

2. Description of the experimental setup.

To perform experiments on the observation of the liquid lithium film flow, a setup has been developed at IPUL, which makes it possible to drive and visualize such flows in the solenoid of the super conducting magnet (SCM) “Magdalena”. In the central part of the cylindrical (D = 300 mm) working zone of the SCM (where the magnetic field is practically uniform), a cylindrical vacuum chamber was placed coaxially, with a plane substrate and a capillary system for liquid metal flow distribution (CSFD) situated inside the chamber. The setup cross-section by a vertical plane passing across the magnet axis is shown schematically in fig. 1. The substrate (3), 175 mm in length and 100 mm in width, was made from 8 mm thick copper sheet cladded with a 0.5 thick plate made of AISI 316L austenitic steel. Such choice of substrate materials agrees with the above-described concept of the divertor system of the spherical tokamak. The presence of stainless steel is needed to protect the heat and electrically conducting copper from the action of liquid lithium.

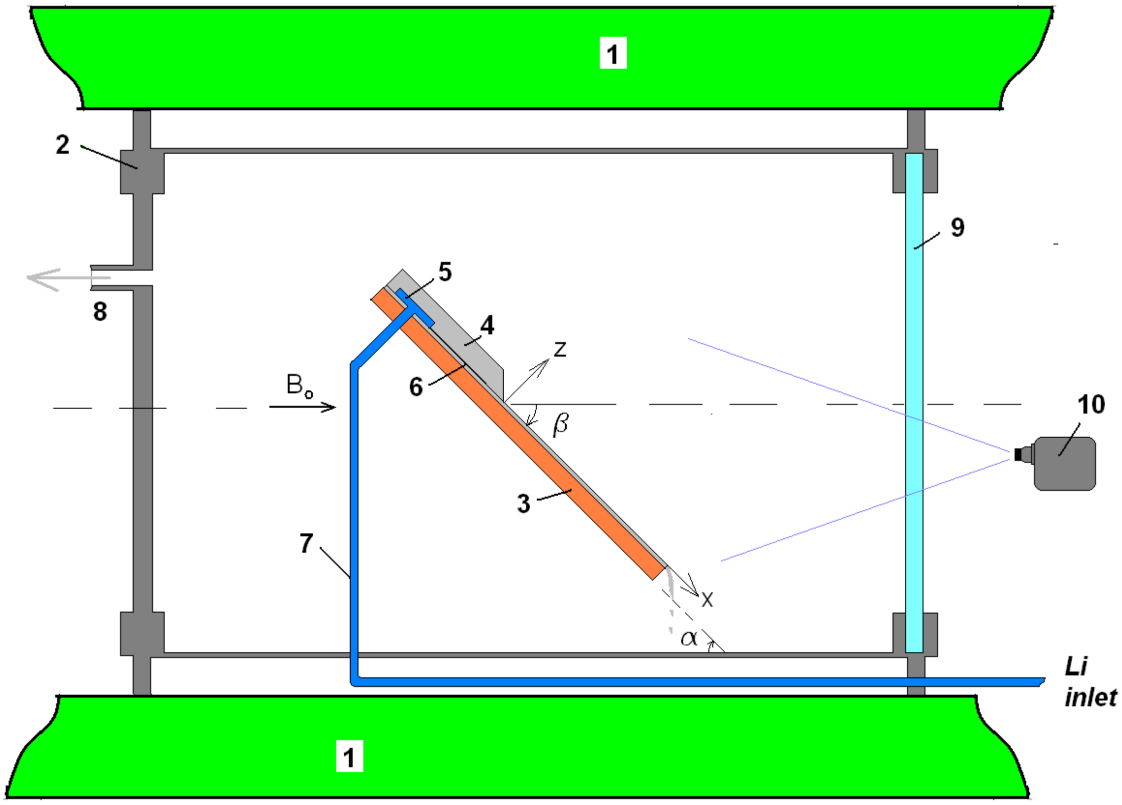

Fig.1: Schematic presentation of the experimental setup. 1 – superconducting magnet; 2 – vacuum chamber; 3 –substrate; 4 – stainless steel head; 5 – bath for liquid metal supply; 6 – zone of capillary channels; 7 – pipe for liquid metal supply; 8 – branch pipe of the vacuum system; 9 – quartz glass hole window; 10 – video camera.

The CSFD is a combination of a substrate and a head (4) made of the same stainless steel as thick as 6 mm. A reservoir (5), as deep as 3 mm, for liquid lithium supply to the capillary system was cut at the inlet end of the head. Paths, 2 mm wide and 0.2 mm deep, were engraved on the bottom surface of the head as far as 2 mm from each other. At a 10 mm distance from the outlet, all grooves between the paths were removed. In such a way, after the head was placed on the substrate, the reservoir (5) was connected to a slot nozzle (90 x 0.2 mm^2) by 22 capillary channels of 40 mm in length. The liquid metal was supplied to the CSFD through a stainless steel pipe (7), which passes through the substrate (3) near to the reservoir center.

As shown in fig. 1, the substrate with the CSFD was tilted at the angle $\beta = -45^o$ to the axis of the superconducting magnet such that the magnetic field $\mathbf{B}_0$ had both a normal to the substrate (B_z) and a tangential (B_x) component. Note that β is a sharp angle between the axial line of the magnet and the substrate measured from the axis in the anticlockwise direction.

The liquid lithium was supplied to the substrate as though a gas system as by using a special bellows device providing liquid lithium constant supply (cycle duration 320 sec) with the very small flowrate $Q = 90\ mm^3/sec$. Observations were made using a video camera (10) through a quartz glass hole window (9).

Thus the above-described setup made it possible to observe a gravitational flow of liquid metal over the flat substrate tilted at $\beta = 45°$ to the horizon and at $\beta = -45^o$ to the force lines of the uniform magnetic field.

3. Estimation of the magnetic field influence on the CSFD operation.

The idea to use the proposed CSFD is based on an assumption that the main action on the distribution of the flow from the slot nozzle comes from the hydraulic resistance of the capillary channels. It is assumed that the pressure losses between the inlet and outlet of the capillary channels determined by the liquid lithium flow are much bigger in value than the pressure drops accompanying the liquid lithium flow in the separation reservoir.

If one assumes that the magnetic field, by significantly increasing the pressure drops in the capillary channels, does not so noticeably increase the pressure drops in the reservoir, the efficiency of the CSFD operation with the field increase will still enhance.

Detailed estimations of the efficiency the CSFD operation due to its orientation about the acting gravity and magnetic fields are presented in [6]. These estimates were obtained under the assumption that the capillary channels were enveloped by a solid well-conducting material. For the CSFD system under consideration, those estimations of the transverse magnetic field effect can be evaluated as a little higher.

Let us evaluate the magnitudes V_g and V_g^B calculated using the formulas in [6] for a situation realized in the experiment with $\beta = 45°$, $\beta = -45^o$, $B_0 = 1T$:

$$V_g = 23.1 \text{ mm/s}, \; V_g^B = 1.65 \text{ mm/s}.$$

Since the value of $V_g^B << 10$ mm/s, one can expect a sufficient effectiveness of the used CSFD in the magnetic field $B_0 = 1$ T.

4. Estimation of the magnetic field action on the fully developed liquid lithium film flow.

Gravitational film flow in a uniform magnetic field is described in [6]. In Table 1 one can find parameters of the developed flows of liquid lithium calculated from the formulas in [6] under the experimental conditions ($\beta = 45°$, $\beta = -45°$), with the linear flowrate q = 1 mm^2/s and some values of the magnetic field B_0 of the solenoid.

Table 1. q = 1 mm^2/s, $\beta = 45°$, $\beta = -45°$

B_0, T	0	0.25	0.5	0.75	1.0
H, mm	0.076	0.091	0.16	0.306	0.522
$\langle V \rangle$, mm/s	13.2	11.05	6.25	3.27	1.92
f_{em}^*	0	-0.509	-0.982	-1	-1
p_0	1	0.651	0.211	0.074	0.32

Along with the values of the film flow thickness h and mean film velocity $\langle V \rangle = q/h$, f_{em}^* values are listed in the Table, which characterize the value of the normal to the substrate component of the electromagnetic force on the free surface related to the corresponding component of the gravity force $f_{gz} = -\rho g\cos\alpha$: $f_{em}^* = f_{emz}(h)/f_{gz}$. The dimensionless value p_0 characterizes the pressure of liquid lithium on the substrate related to the $\rho gh\cos\alpha$ value.

Table 1 gives evidences that in the situation realized in the experiment the normal to the substrate component of the electromagnetic force is directed opposite to the gravitational force that at $B_0 = 1$ T practically results in complete weight loss of the draining down molten lithium. All the above can significantly affect the very possibility of realization of a stable film flow.

5. Observation results on the Li film flow formation

In our experiments, the procedure described in [6] was applied. With the bellows device being switched on and supplying the liquid lithium with the flowrate Q = 90 mm^3/s, some liquid lithium was additionally supplied by the gas system for quicker filling of all delivering systems and the reservoir 5 as well as for liquid lithium supply onto the dry substrate. The appearance of lithium was registered by the video camera when numerous small drops of liquid lithium occurred practically over the entire width of the slot nozzle. This fact, to some extent, evidences of a sufficient enough effectiveness of the operation of the CSFD used in the experiment.

Due to the continuing supply of the liquid metal, these drops, enlarging in size, started to agglomerate that resulted in seven large drops distributed uniformly enough at the outlet nozzle. The gravitational forces made the drops to stream down the substrate, leaving behind glittery traces on the lithium-wetted surface. The further flow of lithium went on over these paths. Moreover, due to the action of surface tension [6], rather large agglomerations of liquid lithium were formed at the substrate bottom, in the zone where the surface bends. The lithium from the substrate drained in drops. In some moment of time, some of the above agglomerations combined with the neighbouring ones at the substrate bottom.

Then the video camera registered an unexpected phenomenon, i.e. the non-wetted surface between two paths was being covered with the liquid lithium and the process was going from the bottom upwards (opposite to the gravitational forces) and completed when the liquid lithium came up to the slot nozzle. It can be suggested that such an unusual behaviour of the molten metal in this case could be determined by the action of electromagnetic forces.

Upon completion of the process, it was decided to supply additionally an amount of liquid lithium through the gas system. This melt portion, draining, gradually covered the most of the substrate surface.

Unfortunately, the experiment was terminated at that stage because of the lithium vapours affecting the hole windows and making them opaque, which drastically distorted the image under observation.

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