MAGNETOHYDRODYNAMICS Vol. 48 (2012), No. 4, pp. 651–666

FREE-SURFACE MHD FLOWS AS A POTENTIAL TOOL FOR HIGH HEAT FLUX REMOVAL IN FUSION APPLICATIONS

V. V. Buryak[2], *A.A. Kolesnichenko*[2], *A.F. Kolesnichenko*[1], *S. Smolentsev*[3]

[1] *Net Shape Cast, Inc., 11643 Anhinga, Venice, Fl, 34292, USA*
[2] *Net Shape Cast (Ukraine), 87, 18/1 Rusanivska Naberezhna, Kiev, 02147, Ukraine*
[3] *University of California, Los Angeles, USA*

We consider liquid-metal free-surface flows subject to a strong magnetic field, including film, droplet and jet flows, as potential means to remove high heat fluxes of (5–15)·10^6 W/m^2 or larger in fusion applications. These considerations are partially based on the earlier experimental studies of free-surface flows performed in the Tokomak-3 reactor in the city of Shatura, Russia. We also review recent studies of free-surface MHD flows and those of 1980–1990 on the implementation of free-surface flows in several industrial applications rather than fusion, such as semi-levitation metallurgical devices, hot dip coating of hard metals and metallization, and MHD atomization and granulation of liquid metals. As shown, all free-surface flows in a strong magnetic field suffer with MHD instabilities. To mitigate this critical issue under the fusion reactor conditions, we propose a new MHD-controlled film-flow device called the "in-and-out honeycomb" to be used as a plasma-facing component. The two main ideas of the proposed concept are: 1) to create a "short" flow with the minimum distance between the flow inlet and the drain channels to decrease the area, where surface instability can develop, and to minimize the surface temperature, and 2) to apply a special surface retaining electromagnetic force. Due to the strong retention effect, the flow can be oriented at almost any angle, including vertical and horizontal upside down orientations. In this paper, we introduce a pre-conceptual design and describe R&D plans, including physical experiments and modelling. Also, first numerical results computed with a 2D MHD code are presented, which demonstrate stable free-surface behaviours once this special retaining force is applied.

1. Introduction. Free-surface magnetohydrodynamic (MHD) flows are considered as a promising means for high heat flux removal in fusion applications starting since the 1980s [1–5]. Three possible candidates are capillary jets, droplet streams and film flows. Free-surface flows of either liquid metals (LMs) or molten salts offer many advantages if compared to other cooling techniques, such as improvements in plasma stability and confinement (when using lithium), capability of high heat/particle flux removal, and elimination of mechanical or thermal stresses compared to solid structural materials. Of potential coolants, LMs (lithium, gallium or tin) are primary candidates due to their high thermal conductivity, low viscosity and relatively low vapour pressure. However, being good electrical conductors, LMs may suffer from various magnetohydrodynamic (MHD) effects due to interactions between the induced electric currents and a strong plasma-confining magnetic field. Various physical aspects of LM free-surface flows in a magnetic field under conditions relevant to fusion applications, such as hydrodynamic stability and thermal behaviour, had been investigated in the former USSR [1, 2, 6–13], and more recently in the USA [14-20] including APEX and ALPS studies [20]. In spite of a significant progress, many key scientific and engineering issues of free-surface flows have not been resolved yet, and, as a matter of fact, the practicality of any of the proposed free-surface flow concepts for either the first wall or divertor components has not been demonstrated. However, many issues of the free-surface flows as applied to fusion cooling devices have been identified and associated studies progressed. These issues run into free major categories: (1) plasma-liquid interactions, (2) stability and flow control, and (3) heat transfer and temperature control. The advantages, main issues and investigation approaches are, however, different among the three reference groups of free-surface flows, and can also vary from concept to concept.

In this paper, in Section 2, we review previous studies of free-surface flows in a magnetic field as applied to cooling processes in a fusion reactor. In Section 3, particular considerations are given to various flow instabilities in the presence of a strong magnetic field and to high heat flux removal capabilities by the free-surface flows. As shown, all free-surface flows in a strong reactor-like magnetic field can suffer from MHD instabilities. To mitigate this problem, in Section 4, we propose a new MHD-controlled film-flow device called the "in-and-out honeycomb" to be used as a plasma-facing component. In Section 5, some results of 2D numerical computations for the proposed concept are discussed, and conclusions are summarized in Section 6.

2. Comparison of three types of free-surface flows for fusion cooling applications.

2.1. Film flows along a solid substrate seem to be the most natural type of free-surface flows. Flowing liquid-metal films with a free surface facing the plasma have been considered worldwide in MFE (Magnetic Fusion Energy) and IFE (Inertial Fusion Energy) programs as a potential option for high heat flux components, such as divertors and chamber walls. Such flows have the potential for continuous removal of large amounts of heat, impurity and for vacuum pumping, as well as for protection of underlying solid surfaces and for improving plasma performance. There is currently a significant program in the USA on the behaviour of liquid lithium surfaces in plasma devices at facilities at PPPL in LTX and on the installation of free-surface divertors in NSTX [16, 19]. These flows can, however, be affected by gravity and especially by strong MHD forces, which may lead to various surface instabilities and, in the worst case scenario, will result in detachment of the liquid from the wall and/or in disintegration of free jets and films. Thus, it is important to apply an external force to drive the liquid flow and restrain it against the solid wall. Three approaches can be mentioned, which utilize different types of restraining force [20]. The first approach is called Gravity-Momentum Driven (GMD). In the GMD concept, the liquid is injected at the top of the reactor chamber. The fluid adheres to the curved first wall by means of centrifugal force and is collected and drained at the bottom of the chamber. In the Electromagnetically Restrained (EMR) flow concept, a force pushing the liquid against the wall is generated by injecting an electric current to the flow in the poloidal direction. The injected poloidal current interacts with the toroidal magnetic field to create a flow restraining electromagnetic force. Another concept is based on the idea of the magnetic propulsion proposed by Zakharov [20, 21], where a flow driving pressure gradient is created through the interaction of the gradient toroidal magnetic field with an externally applied longitudinal electric current in the liquid film. This resultant pressure gradient causes the flow to accelerate from the inboard, where the magnetic field is stronger, to the weaker field outboard region. As shown in the APEX study [20], liquid layers of lithium or lithium-tin of the thickness of the order of 0.5 to 2 cm and velocity of about 10 m/s are potentially capable of removing of 2 MW/m^2 surface heat flux from the first wall, while the surface temperature of the liquid is still below the maximum allowable temperature. In Japan, a novel cascade-type first wall concept is presently considered for the IFE divertor. Although encouraging results have been found regarding trapping of particles and clean-up of plasma impurities, many uncertainties and concerns still exist, due, in part, to results from the lithium exposure experiments in the DIII-D reactor in the USA [17], that a molten liquid metal film can be mobilized by contact with plasma in high power tokomaks, or by disruptive forces associated with ablation in IFE.

2.2. Free jets and droplet streams have also been considered for high heat flux removal. The associated cooling schemes remain popular even though first studies demonstrated that free jets and films in a strong magnetic field could experience various MHD instabilities [6, 8–10, 22]. For example, in the APEX study [20], an idea of integrated liquid first wall and droplet divertor was proposed, where the cooling LM layer at the first wall was then broken in the divertor area to form a droplet stream prior to collection at the bottom of the chamber. The droplets are formed with a comb-like set of radial baffles mounted onto the lower portions of the plasma-facing surfaces. In the same way, thin capillary jets, 2–3 mm in diameter, can be produced to form the divertor surface. Jets and especially droplet streams seem to experience lesser MHD effects if compared to the film flows as the liquid does not contact directly with the electrically conducting wall and also due to the fact that no electrical contact exists between two separate jets or droplets. One of the major concerns of the implementation of jets and droplet streams for divertor cooling seems to be related to the fact that both jets and droplets always experience a surface-normal heat flux, which may result in a significant temperature increase of the liquid at the free surface.

3. Stability and heat removal considerations for free-surface flows.

3.1. Stability considerations. The implementation of free-surface flows in fusion applications and their potential instability, which may manifest itself in various ways, including hydrodynamic and, in particular, MHD instabilities, are considered in [1–4, 7–11, 23]. Thermal instabilities [24], e.g., those caused by temperature-driven gradients on large free surfaces (Marangoni convection) were also considered and found to be especially important for divertor applications, where surface heat fluxes and associated temperatures and temperature gradients can be extremely large. Different instabilities can appear simultaneously that makes the practical implementation and the analysis very challenging. In fact, the effect of the magnetic field can result in either stabilization of the free surface via the direct action of the electromagnetic force on the flow and due to Joule dissipation (e.g., turbulence suppression) or vice versa can cause surface destabilization, as illustrated below.

The efforts to avoid surface instabilities have resulted in two main ideas: first, to decrease the area of the open surface and, second, to account for the surface tension force as a main force responsible for the suppression of surface instabilities (e.g., [1, 2, 6]). Numerous exploratory studies of the free surface flows (droplet streams and free capillary round jets) had been conducted in the former Soviet Union in 1982 to 1988 by the group headed by Prof. Kolesnichenko at the Institute of Electrodynamics of the Ukrainian National Academy of Sciences [1–4, 6–9, 13]. Most of those studies were aimed at implementation of free surface flows in the Tokomak-3 reactor as a means of wall protection (a project supervised by the USSR Ministry of Power Engineering) located in the city of Shatura, Russia. The experiments with jets and droplet streams, as shown schematically in Fig. 1, were conducted in the presence of both a magnetic field and deuterium plasma.

In these experiments, free jets and droplet flows were formed using an MHD granulator equipped with cylindrical nozzles for injecting the liquid metal into the

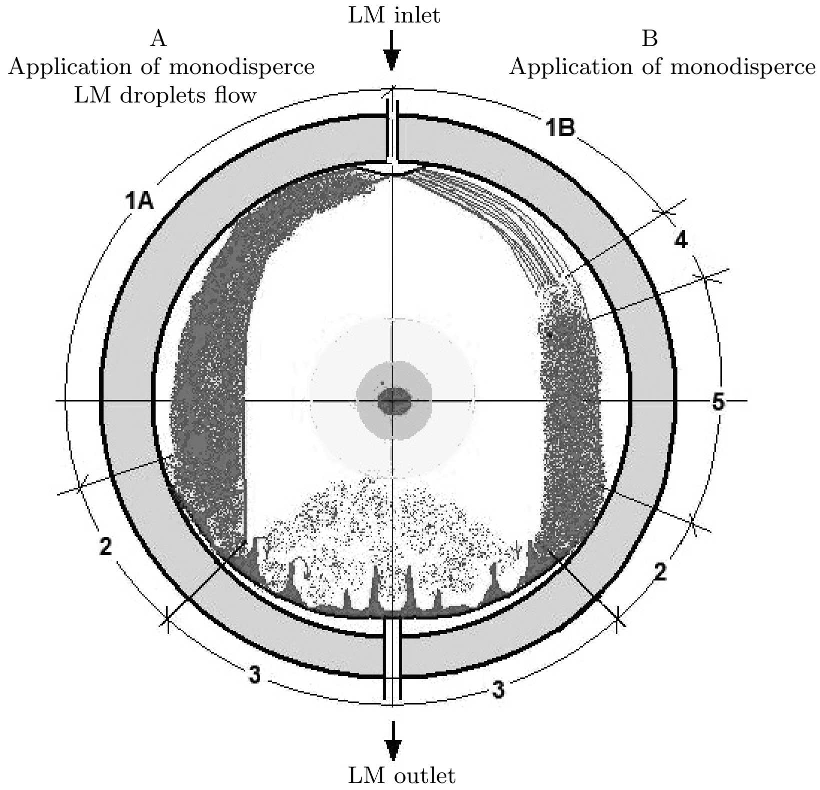


Fig. 1. Sketch of free-surface flow experiments on wall protection by droplet streams (A) and by round capillary jets (B). Zone 1A: Liquid surface formed by controlled monodisperse droplets; (B) liquid surface formed by round capillary jets. Zone 2: Droplets impinging on the reactor wall. Zone 3: Large liquid metal bulk with unavoidable MHD instabilities and chaotic atomization. Liquid injections and small droplets can reach plasma. Zone 4: Uncontrolled LM free jet disintegration into droplets. Zone 5: Uncontrolled polydisperse droplet flow.

chamber [3, 4, 6, 7]. Generating droplets of exactly the same size is based on the principle of electromagnetically controlled disintegration of free round liquid-metal jets also known as the Raleigh resonance breakup. When the MHD granulator is not energized, it produces free round jets. Droplets of the same size (monodisperse droplets) are needed to assure uniform heating of the liquid by plasma radiation. Monodisperse droplets also allow for the formation of droplet streams as dense as necessary for protecting the solid wall of the reactor chamber from radiation by absorbing all radiation heat flux. Uncontrolled jet disintegration (natural breakup) into polydisperse droplets caused by capillary instabilities occurs in Zone 4 (Fig. 1). Those experiments had revealed practical issues of the implementation of free surface flows under the conditions of a real fusion device. First of all, the trajectories of jets or droplets can hardly be controlled due to the complex effect of the initial flow momentum, gravity forces and magnetic field. Second, the jets are subject to capillary instabilities and eventually break up into polydisperse droplets – this process is difficult to control. Severe problems were faced when collecting and extracting the liquid metal at the bottom of the vacuum chamber (Zone 3 in Fig. 1). Here, the turbulence and disintegration of large liquid masses resulted in splashing and mist formation, such that small droplets or even big splashes could penetrate

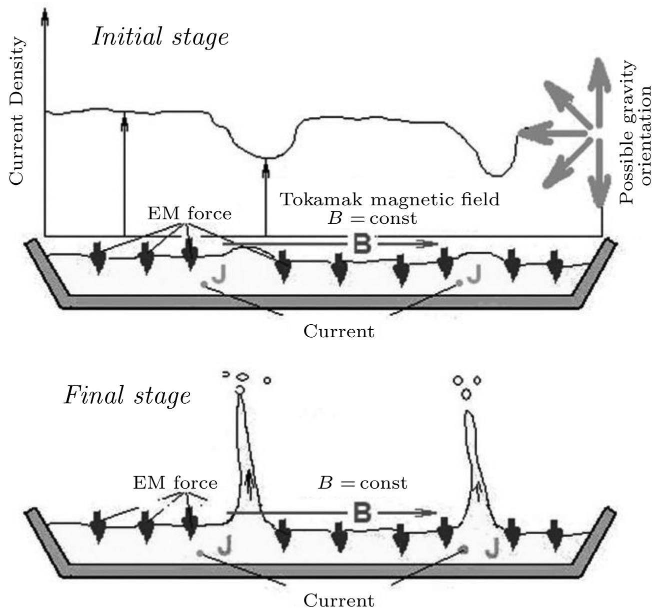


Fig. 2. Instability mechanism in the LM layer subject to a steady magnetic field and cross electric currents.

the bulk plasma. Despite the strong perturbations, the free surface of the liquid collected at the bottom of the chamber remained mostly horizontal, as illustrated in Figs. 1 and 2.

The mechanisms of MHD instabilities on the surface of the liquid-metal bulk at the chamber bottom associated with the applied electromagnetic force are illustrated in Fig. 2 for a liquid-metal layer subject to a steady magnetic field and cross external currents. Although the direction of the resultant electromagnetic Lorentz force coincides with the gravity force, significant instabilities and splashing are unavoidable and, in fact, are related to the electromagnetic force itself. Such instabilities were observed in the experiments at the Institute of Physics, Latvia [25, 26], and also in other similar experimental studies [7, 22] for both stagnant and flowing layers at various orientations of the layer with respect to the horizon. The physical mechanism of the observed instabilities is, in fact, very similar to the kink instability mode in plasma physics. Namely, the Lorentz force is weaker at the locations, where the liquid layer is thicker and stronger in the thinner layer regions. The difference in Lorentz force between "hills" and "pits" on the surface causes the originally small perturbations to grow that leads eventually to large liquid injections.

The same MHD instability mechanism is inevitably present if the first wall of the reactor is covered with a free flowing liquid metal film, when the electromagnetic Lorentz force is utilized as a flow retaining force, as demonstrated in [7, 8, 26]. The inability of the bulk electromagnetic force itself to stabilize the flow completely has eventually led to a new idea of utilizing, in addition, surface forces. One of the promising approaches of this type (Fig. 3) was to confine the free surface layer within a metallic-fiber porous structure (sponge), as proposed and analyzed in [11]. However, even in this case, liquid splashing occurred.

The fact that the liquid splashing is caused by MHD phemonena has been confirmed in experiments, where the electromagnetic force is not applied [7]. In those

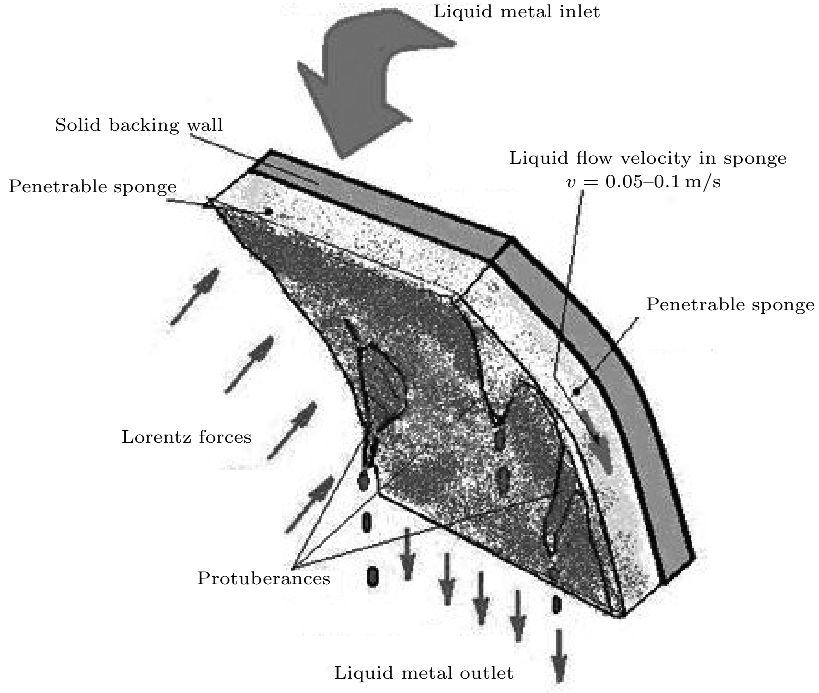


Fig. 3. Free-surface flow confinement in a porous structure (sponge) still evidences of liquid splashing if a magnetic field is applied.

cases, the flow remained stable due to the retaining action of capillary (Laplace) forces. Unlike the MHD flow cases, no liquid leakages occurred over a large surface area of $300 \times 200\,\mathrm{mm}^2$.

More than 30 years ago several approaches to stabilize free-surface flows had been considered for fusion applications and successfully applied in metallurgy, for instance, for continuous casting of light metals into the electromagnetic crystallizer [27]. With those approaches, the use of tangential alternating magnetic fields (with the field strength much smaller if compared to that in fusion devices) had resulted in stable vertical liquid metal large area surfaces. The vertical size of those surfaces achieved 0.4 m, while the horizontal dimension was not restricted.

Since 1995, Net Shape Cast, Inc. has been actively involved in the development of series of industrial-scale free surface MHD devices for metallurgical industry. The first one in the row is a new MHD partial levitation system for the Twin Roll Steel Strip Caster (a full-size model), which has been developed and fabricated for Inland Steel, Inc., USA, and tested in Kiev, Ukraine. The levitation system provides the formation of stable vertical surfaces of liquid metal. The surface has a trapezoidal shape with a height of 0.4 m and a width of 0.5 m at the top and of 0.1 m at the bottom of the device. In 2003, Net Shape Cast, Inc. developed, fabricated and tested a semi-levitation MHD unit for the production of hot-dip Zn-Al coatings for automotive steel strips and for brazing of wires in the framework of a contract with Inland Steel, Inc., USA. During 2005–2009, Net Shape Cast, Inc. also developed, fabricated and tested a semi-levitation MHD Galvanizer for Danieli SpA, Italy (Fig. 4). In the first version of this device, the area of the steady free surface was $340 \times 25\,\mathrm{mm}^2$, while the melt level was 260 mm.

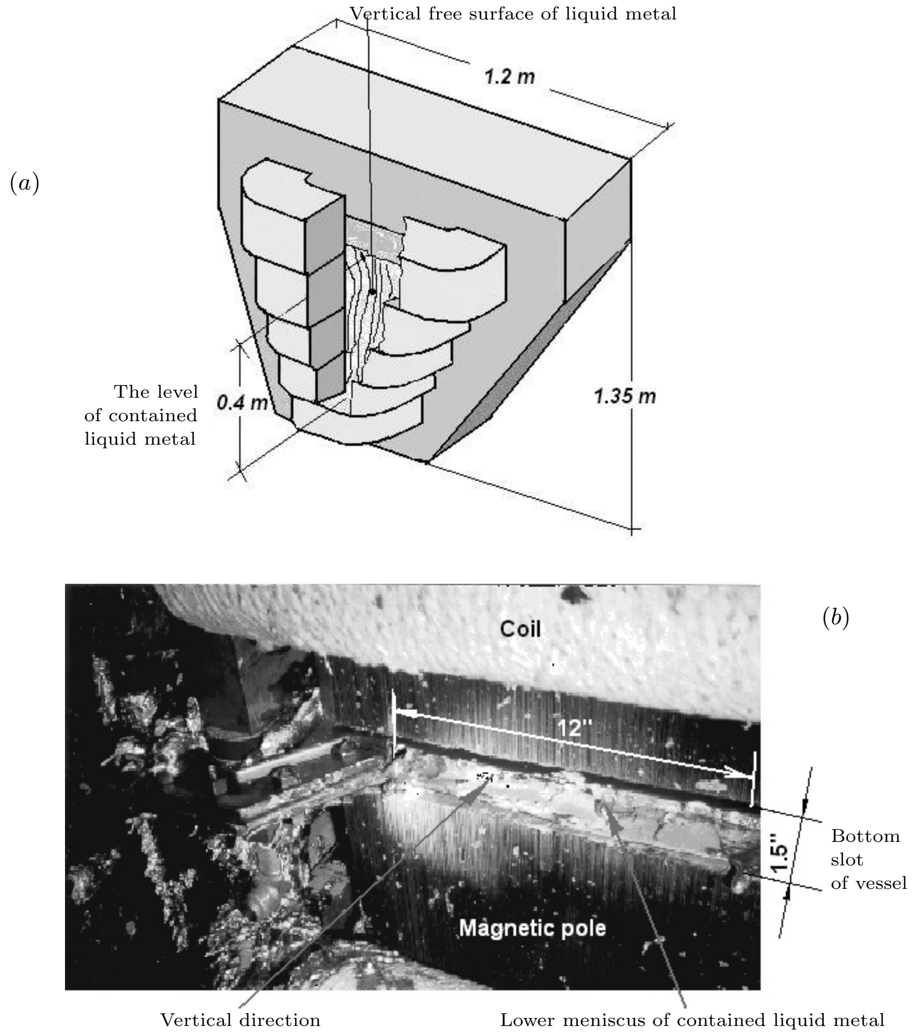


Fig. 4. MHD partial-levitation systems developed by Net Shape Cast, Inc.: (*a*) vertical free surface for the Twin Roll Strip Steel Caster for Inland Steel Inc. (USA), 1997, and (*b*) upside down Zn free surface for hot dip Zn-Al coating of steel strips and wires for Inland Steel, Inc. (USA), 2003, and for Danieli SpA (Italy), 2009.

The weight of the contained zinc was 280 kg. The free surface was stable and no leakages from the free surface occurred. A similar MHD Galvanizer device has the free surface area of $2019 \times 30\,\mathrm{mm}^2$. The weight of the partially levitated liquid zinc was 2100 kg. At present, this system is used as a commercial device by Danieli SpA, Italy.

All the above-mentioned MHD devices are based on a pioneering technique of the active flow control patented by Net Shape Cast, Inc. together with its customers. This technique intended for flow stabilization is based on applying concurrently gradient steady magnetic fields (magnetic field strength $0.3 \div 0.4\,\mathrm{T}$, field gradient $50\,\mathrm{T/m}$) and an alternating magnetic field of $90 \div 120\,\mathrm{Hz}$. Strong magnetic field gradients are created due to the special design of the magnetic poles along with the special shape of the melt-containing tank.

This technique on the stabilization of liquid metal free-surface flows was developed in 1997 using a simple practical method called the "forbidden zone" principle, which was formulated by Kolesnichenko (see, e.g., [28, 29]). According to this principle, as soon as any liquid particle on the free surface moves away from its stable position, the electromagnetic field and the Lorentz forces increase locally and return the free surface to equilibrium. In practice, such a feedback mechanism for suppressing instabilities and preventing any liquid metal leakages from the surface is realized by applying an alternating magnetic field. This is different from conventional stabilization methods in MHD, where only steady magnetic fields are typically used to stabilize the flow.

3.2. Heat removal considerations. In fusion applications, the liquid surfaces can affect the edge and core plasmas by releasing impurities through sputtering, recycling and evaporation. The maximum tolerable evaporation rate specifies the maximum surface temperature of the liquid. In the course of the above-cited APEX project [20], these maximum temperatures were evaluated under specific DEMO-like conditions for several liquid metals used as liquid first walls or divertors. For example, the divertor temperature limit for lithium was found at 475°C and for gallium at about 1200°C. For tin-lithium, the maximum allowable temperature at the first wall is 740°C. These maximum temperatures suggest the minimum flow velocities. Rough estimations of the required minimum velocity to remove the surface heat flux from plasma can be made using a simple formula

$$q''LK = \rho V h C_p (T_2 - T_1).$$

Here, q'' is the surface heat flux from plasma absorbed by the flowing liquid, L is the flow path between the flow inlet and outlet, K is the coefficient of heat absorption, ρ is the fluid density, V is the flow velocity, h is the characteristic flow dimension in the direction of the applied heat flux, C_p is the specific heat, and T_1 and T_2 are the flow inlet and outlet temperatures. The estimates (assuming Li as a work fluid) show that all types of free-surface flows (droplets, free jets and films) are potentially capable of removing high heat fluxes of 15 MW/m^2 typical to the divertor area, at the flow velocities of the order of several m/s. However, in the plasma-confining magnetic field of the fusion reactor, such high velocities will inevitably give rise to MHD instabilities. As seen from the above formula, it is possible to decrease the flow velocity only through the reduction of the flow path L between the flow inlet and outlet.

As shown in the next section, of all free-surface flow concepts, the proposed "in-and-out honeycomb" seems to be the most effective one due to the very short flow path of only 1 cm, requiring velocities of the order of few cm/s or less. Such low velocities assure laminar flows and can be easily realized in practice providing the flow is stable.

4. The "in-and-out honeycomb" device for high heat flux removal.

4.1. Key principles. We propose a device called the "in-and-out honeycomb" as a means for high heat flux removal and as a PFC device (first wall or divertor) of the fusion reactor as an alternative to the reviewed above free-surface approaches. Conceptually, the device is also based on the utilization of free-surface MHD flow, which absorbs the radiation heat flux and volumetric heating by neutrons from plasma. The device is potentially capable of removing high heat flux of 15 MW/m^2 and greater due to the very short flow path, if compared to other free-surface flow concepts, and to the application of the "forbidden zone" principle explained above.

The device is equipped with a specially designed magnetic system to generate a high-gradient magnetic field along with an alternating magnetic field, which both are responsible for the flow retaining effect. This field is localized at the free surface and hence does not distort the applied magnetic field of the reactor. In doing so, high heat removal capabilities and flow stabilization are provided through two basic principles. First, the specific flow dimension between the flow inlet and outlet is as small as possible to keep the surface temperature below the maximum allowable temperature and to minimize surface perturbations. Second, the electromagnetic Lorentz force is used to retain the flow against the solid structure and provides continuous suppression of surface perturbations as soon as they appear. The associated stabilization mechanisms are possible due to the particular nature of the electromagnetic force, which has both conventional bulk and additional surface components. An additional surface force component is created by adding an alternating magnetic field.

The circulation of the liquid metal and its transportation to the active zone to remove heat and to other parts of the device are provided mostly by a liquid metal pump and partially due to self-pumping. The liquid metal is transported to the active zone (where the free surface flow is formed) through staggered injection nozzles and drained from the surface through orifices around the nozzles, which look like honeycombs (Fig. 5).

The proposed in-and-out honeycomb can be integrated into the divertor or into the first wall basing on the module principle. Particular characteristics of each module and its dimensions must be specified depending on the local thermal load and spatial orientation of the module with respect to the horizon. The latter is especially important for the design of the first wall, where the module orientation can vary from near horizontal at the bottom to almost upside down at the chamber top.

The main advantages of the proposed device are the following:

– the module has the ability of self-control. In other words, it allows for tuning the flow thickness and for changing the local velocity to meet heat removal requirements;

– continuous stabilization of the free surface is assured at all times;

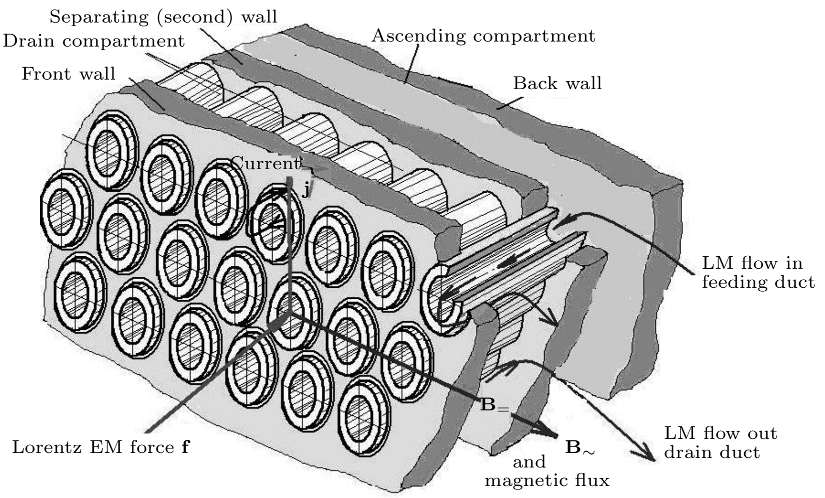
– direct current supply to the coolant is not necessary;

– utilization of surface tension for free surface stabilization is also possible;

– due to small dimensions of the flow (short distance between the flow inlet and outlet), the Marangoni effect is expected to be minimal.

4.2. Conceptual module design. The module is shown schematically in Fig. 5. The main component of the module is a liquid-carrying vessel with nozzles for liquid injection and with drain orifices around the nozzles for collecting and draining the liquid. The module also requires a magnetic field system, whose main part is a magnetic inductor for local adjustments of the regular direct magnetic field to create required magnetic field gradients at the free surface. The inductor induces alternating currents inside the flow. Both the induced currents and the retaining electromagnetic Lorentz force experience strong gradients at the free surface. The induced current circuit includes diodes, such that the induced current is unipolar.

4.3. Stainless steel or ceramic vessel. The vessel has 3 walls: front (first), separation (second), and back (third) wall. The front wall of the vessel has nozzles (round- or rhombic-shaped), which distribute the liquid over the front wall, where the free-surface flow is formed. The liquid enters through the nozzles from the feeding duct (the space between the back wall and the separation wall). A liquid metal pump is used to deliver the liquid metal from the external section of the loop into the feeding duct. Once injected from the nozzles, the liquid metal forms a film flow on the front wall by the action of the retaining electromagnetic Lorentz



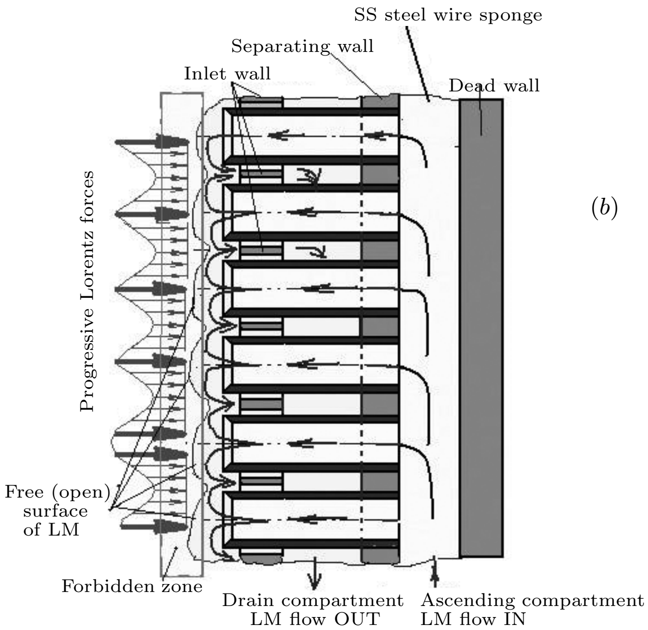


Fig. 5. The "in-and-out honeycomb" produces a free-surface film MHD flow to remove heat flux at the first wall or/and divertor: (*a*) conceptual design, (*b*) schematics of application of the retaining Lorentz force to the liquid metal in the vicinity of the free surface.

force, which is created by the induced unipolar current and a resultant magnetic field, as shown in Fig. 5. The liquid metal is extracted from the surface of the front wall through the thin 2–3 mm drain orifices located between the supplying nozzles and the front wall. This allows to minimize the distance between the coolant injection and the extraction zones. The extracted liquid is collected in the drain duct (the space between the front and separation walls). Under the actual fusion conditions, the liquid metal flow absorbs the heat from plasma and then collects in the drain duct, from which the liquid metal is further transported to outside for power conversion.

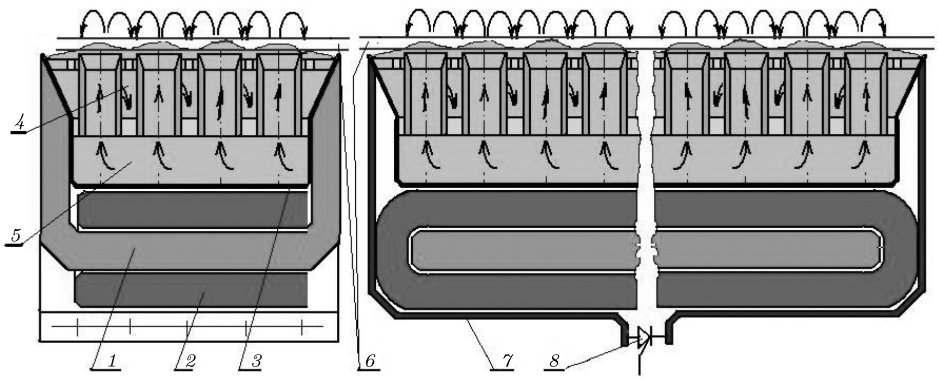


Fig. 6. Electromagnetic system of the "in-and-out honeycomb": *1* - ferromagnetic core, *2* - AC fed coil, *3* - SS vessel with nozzles, *4* - drain duct, *5* - feeding duct, *6* - "forbidden zone" for preventing liquid metal splashes, *7* - copper current bypass, *8* - diodes.

4.4. Magnetic inductor and magnetic field. The vessel with the liquid metal is exposed to both alternating and regular steady magnetic fields. The alternating magnetic field is generated by inductors *1* and *2* (Fig. 6). The inductor is energized through a power source of variable frequency ($f = 0 \div 400\,\text{Hz}$). The alternating and steady magnetic fields can be either in the same direction (version 1) or orthogonal (version 2), but in both versions the magnetic field vectors are tangential to the free surface. Note that in the fusion environment, the plasma-confining magnetic field (toroidal-poloidal field) can be used for these purposes, while the alternating component needs to be added. Being localized within the thin liquid layer, the alternating magnetic field will not interfere with the plasma-confining reactor field and hence will not negatively affect the reactor plasma.

Version 1. Both magnetic fields are in the same direction. The superposition of the alternating B_{alt} and steady B_{st} magnetic fields, in this case, gives a resultant alternating unipolar field if $B_{\text{st}} > B_{\text{alt}}$. The resultant magnetic field induces alternating currents in the liquid metal. To assure the induced current is unidirectional, a copper bypass is used (Fig. 6). The frequency of the alternating magnetic field controls the intensity of the skin effect and the efficiency of the "forbidden zone" for suppression of perturbations on the free surface. The Lorentz force has constant and alternating unidirectional components. The alternating force component is responsible for the efficiency of the "forbidden zone" to suppress instabilities, while the constant force component is responsible for driving the liquid through the system to overcome the flow opposing forces.

Version 2. Vectors of the alternating and steady magnetic fields are orthogonal, but both fields are tangential to the free surface. In this case, the electromagnetic force transforms into an alternating Laplace force, which is responsible for the skin effect at the free surface of the liquid and eventually for the efficiency of the "forbidden zone" to suppress instabilities. The vector of the alternating magnetic field is orthogonal to the vector of the steady field and coincides with the direction of the alternating current $\mathbf{j}_{\text{alt}}$. In this case, the Lorentz force $\mathbf{f} = \mathbf{B}_{\text{st}} \times \mathbf{j}_{\text{alt}} = 0$. Providing the melt velocity near the free surface is high enough, the stabilizing force $f = \sigma V B_{\text{st}}^2$ (here, σ is the electrical conductivity, V is the liquid metal velocity) appears as a result of the interaction between the steady field and the current, which is induced due to the motion of the liquid metal in the steady magnetic field. The stabilizing effect, in this case, can be doubled due to both the "forbidden zone" principle and the "smoothing" effect of the steady magnetic field.

Both versions of the magnetic field orientation have to be tested before making the final choice. The version, which leads to better flow stabilization should be accepted. The important aspect of the design is the configuration of the magnetic core and poles, which have to provide an effective "forbidden zone" that prevents liquid metal leakages from the free surface. When the liquid metal moves into the "forbidden zone", an opposing force is induced, which finally stops the fluctuating motion and prevents any leaks from the surface. Another important requirement is to get bulk electromagnetic forces localized very close to the free surface so that any vortex formation in the fluid can be prevented. With reference to our previous experience, the density of electromagnetic forces in the liquid metal bulk close to the free surface should exceed the gravitational forces in approximately 15 times. This consideration determines the required level of magnetic induction in the magnetic gap.

4.5. Test loop and its components. For test purposes, the proposed module is integrated into a liquid metal loop, as shown in Fig. 7. The loop includes components for melt preparation, pumping, heating, draining, purification, and for flow and temperature monitoring. The design and the construction of the loop aimed to test the proposed in-and-out honeycomb module are based on our previous experience of testing various metallurgical LM MHD systems, which were designed

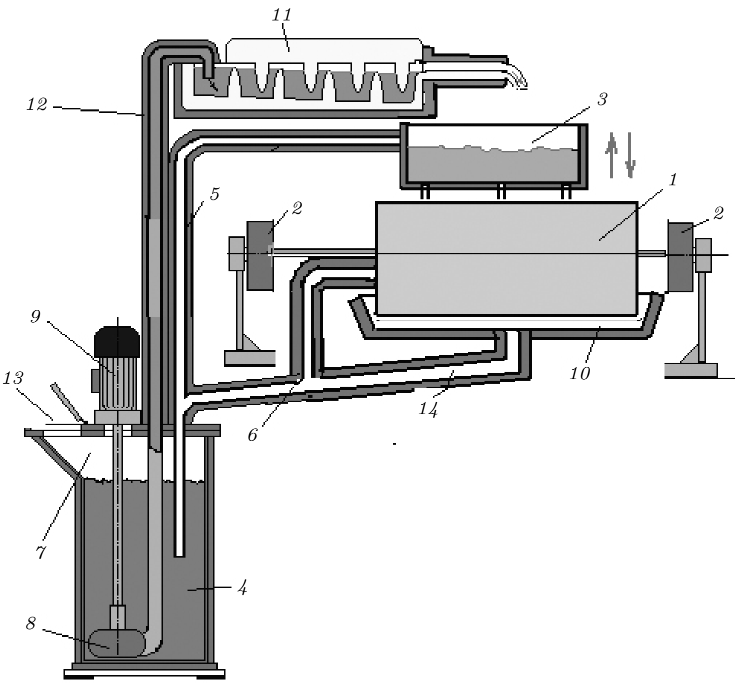


Fig. 7. The Sn-Bi circulation loop for in-and-out honeycomb module tests. *1* - in-and-out honeycomb, *2* - module tilting system, *3* - LM level control, *4* - melting oven/supply tank, *5* - overflow from LM level control, *6* - discharge pipe, *7* - space filled with nitrogen, *8* - liquid metal pump, *9* - pump motor, *10* - LM collector, *11* - sedimentation chamber, *12* - pressure feeder, *13* - hatch for loading chips, *14* - discharge pipe.

and fabricated by Net Shape Cast, Inc. and by the Institute of Electrodynamics of the Ukrainian National Academy of Sciences in 1986–1989, 1996, 1998, and recently. The Sn-Bi eutectic alloy was chosen as a work liquid, as Net Shape Cast, Inc has already used this alloy in experiments. The alloy has the melting point of 145–232°C (depending on the composition). The melt is prepared inside an electric-resistance oven, which also serves as a liquid metal supply (storage) tank. The tank can be moved downward or upward so that a centrifugal impeller or a permanent magnet pump can be installed directly in the tank. The pump has a controlled RPM and can be equipped with a pneumatic drive or with any electric motor, e.g., an induction or an asynchronous motor.

The pump outlet is connected to the module by a flexible metallic tube (bellows). All pipes are heated and thermally insulated to prevent melt solidification. The temperature of all parts of the loop is monitored by the VENESCO automatic temperature controllers, which are also used to control heating. The melting chamber is evacuated first and then filled with nitrogen gas to protect the melt from oxidation. In order to clean the liquid metal before it enters the module, a sedimentation chamber is installed, where the separation of solid particles (intermetallic compounds and/or oxides) occurs due to gravity. The module is placed on bearings, which allow to tilt the module at arbitrary angels, with respect to the horizon, from zero to 180^o. A collector tray is installed directly under the module to collect leaking liquid metal if such leakages occur. At the beginning of the experiments, the melting chamber is loaded with Sn-Bi chips for melting. To perform heat transfer tests, the liquid metal is heated from the side of the free surface by a plasmatron. The plasmatron is rigidly attached to the module frame.

5. Numerical simulations. Numerical simulations for the liquid layer subject to both alternating and direct steady magnetic fields $B_{\mathrm{st}} + B_{\mathrm{alt}}$ described in Section 4 include 2D electromagnetic computations for the extreme upside down orientation such that the gravity force tends to remove the liquid down from the substrate, as shown in Fig. 8. The numerical procedure [29] consists of two subsequent steps. First, the electric currents and the associated electromagnetic forces are computed for the fixed shape of the free surface using a built-in electromagnetic module of the computational code ANSYS. As the next step, the computed electromagnetic forces are used as input data to compute the flow velocity and new free surface location using the ANSYS/CFX and VOF (volume-of-fluid) method for tracking the free surface. These two steps are repeated many times using a

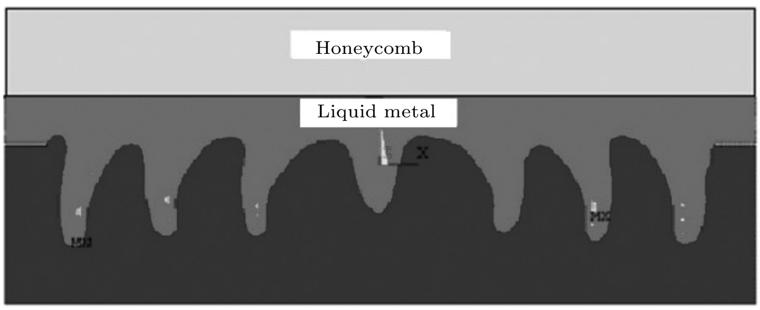


Fig. 8. The view of the upside down liquid metal surface in 0.2 s after energizing the inductor. The magnetic field below the free surface has not enough vertical gradient, hence, the electromagnetic field is not sufficiently large to prevent from leaking.

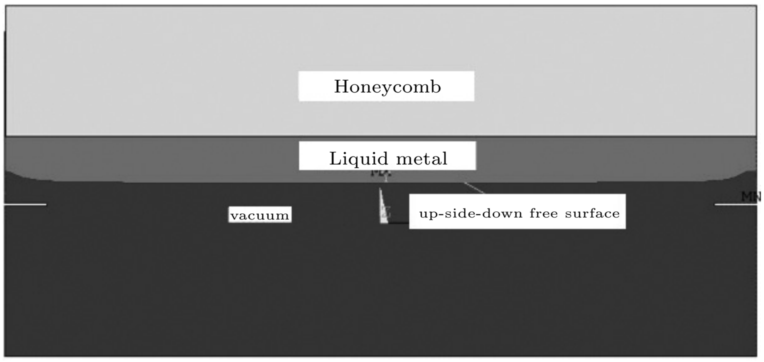


Fig. 9. Stable profile of the upside down liquid metal layer in a magnetic field with a vertical field gradient of 50 T/m.

small enough time increment to assure stable computations. The computations are continued until the desired moment of time is achieved. A computed case with a relatively small magnetic field gradient is shown in Fig. 8. The liquid metal leaks down because the flow retaining electromagnetic force is not strong enough compared to the destructive action of the gravity force. Providing the field gradient is large enough (Fig. 9), the free surface does not suffer with instabilities, hence, a desired smooth surface without any liquid metal leaking can be formed. The computations show that once the magnetic field gradient is about 50 T/m, the effective forbidden zone can be formed resulting in full suppression of the surface instabilities.

6. Conclusions. All free-surface flows (film, jet or droplet stream) under the conditions of fusion reactor will suffer with various instabilities even in the presence of applied electric currents. Of these instabilities, the MHD kink-like instability is one of the most dangerous instability types. In many previous film flow concepts proposed recently for fusion cooling applications, the application of external electric currents is recommended to create a strong Lorentz force, which could restrain the flow against the wall. However, this approach does not eliminate and often enhances the surface instabilities because the resultant electromagnetic force is of vortical nature. The newly proposed approach is based on implementation of a special magnetic field configuration, which has an alternating field component and a strong (~ 50 T/m) surface-normal gradient directly at the surface of the liquid metal layer. Such a field results in the restraining Lorentz force localized near the free surface, which tends to suppress any surface instabilities. The instabilities can also be reduced by decreasing the surface area between the flow inlet and outlet. These two principles are implemented in the proposed "in-and-out honeycomb", a device which can potentially remove high heat fluxes of 15 Mw/m^2 or larger typical of the divertor area of the fusion reactor. The numerical computations have confirmed that such stable flows can be formed even in the extreme case of upside down orientation.

REFERENCES

[1] A.F. Kolesnichenko, V.N. Demyanenko, E.V. Muravev, V.O. Vodyanyuk, E.K. Sergeev, A.M. Shapiro. Liquid-metal tokamak diaphragm. Formulation of tasks and first results. *Plasma Physics*, vol. 14 (1988), no. 5, pp. .

[2] B.O. Karasev, I.V. Lavrentev, A.F. Kolesnichenko, O.A. Lielausis, E.V. Muravev, V.N. Demyanenko, A.V. Tananaev. Research and development of liquid metal system for a tokamak reactor. *Fusion Engineering and Design*, vol. 51 (1989), no. 8, pp. 283–288.

[3] V.N. Dem'yanenko, B.G. Karasev, A.F. Kolesnichenko, I.V. Lavrent'ev, O.A. Lielausis, A.V. Tananaev. Liquid metal in magnetic field of a Tokamak reactor. *Magnetohydrodynamics*, vol. 24 (1988), no. 1, pp. 95–114.

[4] A.F. Kolesnichenko. *Electromagnetic processes in liquid materials in the USSR and East European Countries* (ISIJ International Issue, Japan, Tokyo, 1989), pp. 9–28.

[5] S.Yu. Khripchenko. *Electrovortex Flows in Channels of MHD Devices* (Yekaterinburg: URO RAN, 2009), 262 p. (in Russian).

[6] A.F. Kolesnichenko. *Technological MHD Units and Devices* (Kiev, Naukova Dumka, 1980), 190 p. (in Russian).

[7] A.F. Kolesnichenko, I.V. Kazachkov, V.O. Vodjanjuk, N.V. Lysak. *Capillary MHD Flows with Free Boundaries* (Kiev, Naukova Dumka, 1988), 176 p. (in Russian).

[8] I.V. Kazachkov, A.F. Kolesnichenko. Influence of alternate electromagnetic field on waves formation in a liquid metal film. *Magnetohydrodynamics*, vol. 21 (1985), no. 3, pp. pp. 272–278.

[9] I.V. Kazachkov, A.F. Kolesnichenko. Electromagnetic excitation of waves in the liquid metal film. *Magnetohydrodynamics*, vol. 21 (1985), no. 3, pp. 135–138.

[10] V.A. Bernshtam, S.V. Kozirev, V.I. Smirnov. Stability of flow of films of a conducting viscous liquid in longitudinal magnetic field. *Magnetohydrodynamics*, vol. 18 (1982), no. 2, pp. 132–136.

[11] S.M. Mirnov, V.B. Lasarev, S.M. Sotnikov, V.A. Evtikhin, I.E. Lyublinski, A.V. Vertkov. Li-CPS limiter in Tokamak T-11M. *Fusion Engineering and Design*, vol. 65 (2003), no. 3, pp. 455–465.

[12] B.G. Ganchev. *Cooling of Nuclear Reactor Elements with Flowing Films* (Moscow, Energoatomizdat, 1987), 191 p. (in Russian).

[13] A.F. Kolesnichenko, V.O. Vodyanyuk, V.N. Demyanenko, N.V. Lysak. *LiquidMetal Diaphragm of Tokamak in the Form of Dropping Screen* (Questions of Atomic Science and Technology, 1987) (in Russian).

[14] M. Narula, M.A. Adbou, A. Ying, N.B. Morley, M. Ni, R. Miraghaie, J. Burris. Exploring liquid metal PFC concepts – Liquid metal film flow behavior under fusion relevant magnetic field. *Fusion Engineering and Design*, vol. 81 (2006), pp. 1543–1548.

[15] N.B. Morley, S. Smolentsev, R. Munipally, M. Ni, D. Gao, M. Abdou. Progress on the modeling of liquid metal free surface MHD flows for fusion liquid walls. *Fusion Engineering and Design*, vol. 72 (2004), pp. 3–34.

[16] H.W. Kugel, M. Bell, L. Berzak *et al.* Physics design requirements for the national spherical torus experiment with a liquid lithium divertor. *Fusion Engineering and Design*, vol. 84 (2009), pp. 1125–1129.

[17] D.G. Whyte, T.E. Evans, C.P.C. Wong, W.P. West, R. Bastasz, J.P. Allain, J.N. Brooks. Experimental observation of lithium as a plasma-facing surface in the DIII-D Tokamak divertor. *Fusion Engineering and Design*, vol. 72 (2004), pp. 133–147.

[18] T. Morikawa, A. Ying, J. Burris, M. Abdou. Experimental analysis of soaker hose concept for first wall/divertor application. *Fusion Engineering and Design*, vol. 47 (2005), pp. 713–717.

[19] R. Majeski, L. Berzak, T. Gray, R. Kaita, T. Kozub, F. Levinton *et al.* Performance projections for the lithium tokamak experiment (LTX). *Nuclear Fusion*, vol. 49 (2009), p. 055014.

[20] M. Abdou, A. Ying, N. Morley, K. Gulec, S. Smolentsev *et al.* On the exploration of innovative concepts for fusion chamber technology - APEX interim report overview. *Fusion Engineering and Design*, vol. 54 (2001), pp. 181–247.

[21] L.E. Zakharov. Magnetic propulsion of intense lithium streams in a tokamak magnetic field. *Phys. Rev. Lett.*, vol. 90 (2003), p. 045001.

[22] Yu.P. Ladikov, V.F. Tkachenko. *Hydrodynamics Instabilities in Metallurgical Processes* (Moscow, Nauka, 1983), 248 p. (in Russian).

[23] M. Pasandilech-Fard, R. Bhola, S. Chandra, J. Mostsghimi. Deposition of thin droplets on a steel plate: simulations and experiments. *Int. J. Heat Mass Transfer*, vol. 41 (1998), pp. 2929–2945.

[24] Ye.G. Vorontsov, Yu.M. Tananayko. *Heat Transfer in Liquid Films* (Kiev, Tehnika, 1972), 194 p. (in Russian).

[25] V.V. Boyarevich, Ya.Zh. Freiberg, E.I. Shilova, E.V. Shcerbinin. *Electrovortex Flows* (Riga, Zinatne, 1985), 315 p. (in Russian).

[26] Yu.M Gelfgat, O.A. Lielausis, E.V. Scherbinin. *Liquid Metal under the Action of Electromagnetic Fields* (Riga, Zinatne, 1976), 270 p. (in Russian).

[27] Z.N. Getselev, G.A. Balahontsev, F.I. Kvasov. *Continuous Casting in Electromagnetic Crystallizer* (Moskow, Nauka, 1983), 151 p. (in Russian).

[28] A. Kolesnichenko, V. Buryak, M. Pavlicevic, A. Poloni, A. Codutti, F. Guastini. Mechanism and intensity of zinc coatings layer formation by electromagnetic hot dip zinc galvanizing. *Proc. the 5th International Symposium on Electromagnetic Processing of Materials* (Sendai, Japan, 2006), pp. 226–230.

[29] V.V. Buryak, A.A. Kolesnichenko, A.F. Kolesnichenko. Application of MHD levitation: what amount of liquid metal can levitate? *Proc. the 8th PAMIR International Conference on Fundamental and Applied MHD* (Borgo, Corsica, France, 2011), pp. 873–878.

Received 07.11.2012