MAGNETOHYDRODYNAMICS Vol. 51 (2015), No. 2, pp. 185–193

MHD ISSUES RELATED TO THE USE OF LITHIUM LEAD EUTECTIC AS BREEDER MATERIAL FOR BLANKETS OF FUSION POWER PLANTS

G. Aiello[1], *C. Mistrangelo*[2], *L. Bühler*[2], *E. Mas de les Valls*[3], *J. Aubert*[1], *A. Li-Puma*[1], *D. Rapisarda*[4], *A. Del Nevo*[5]

[1] *CEA-Saclay, DEN/DANS/DM2S, 91191 Gif Sur Yvette Cedex, France*
[2] *Karlsruhe Institute of Technology, Postfach 3640, 76021 Karlsruhe, Germany*
[3] *UPC-BarcelonaTech, C. Jordi Girona, 31. 08034 Barcelona, Spain*
[4] *Laboratorio Nacional de Fusión – CIEMAT, Avda. Complutense 40, 28040 Madrid, Spain*
[5] *ENEA UTIS-TCI, C.R. Brasimone, 40032 Camugnano, Italy*

The European Community is committed to the development of a DEMOnstration fusion power plant whose operation could start as soon as 2050. The blanket is one of the most critical components in a fusion reactor; three of the four blanket concepts currently under development are based on the use of the liquid eutectic alloy Pb-15.7Li. Since the blanket will operate under the strong magnetic field used to confine the plasma, electromagnetic forces will occur in the PbLi flow, giving rise to magnetohydrodynamic (MHD) phenomena.

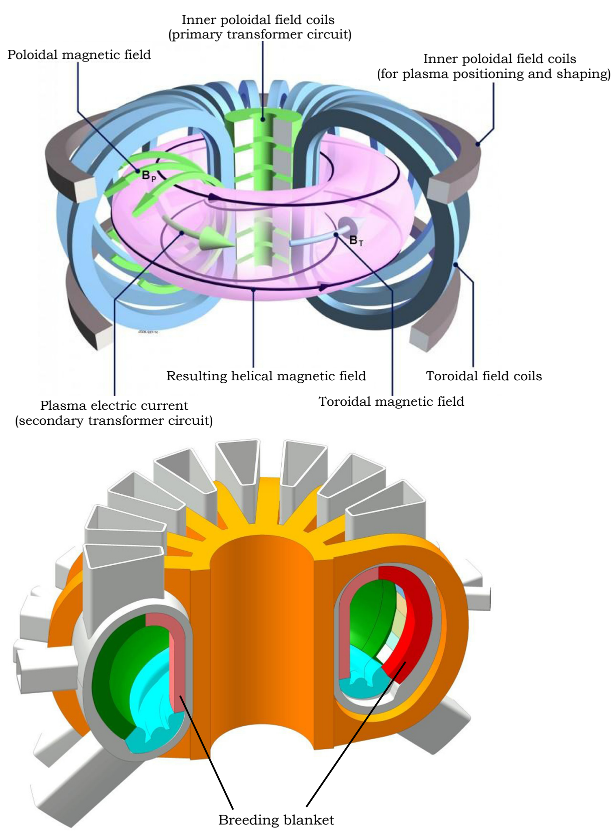
Introduction. In the constant search for new power sources, thermonuclear fusion could be the ideal solution to satisfy worlds energetic needs for the next centuries. Once the scientific and technological problems solved, the use of nuclear fusion to produce electrical power could mean a potential unlimited energy source which will be safe and environmental friendly.

The first effort to achieve controlled thermonuclear fusion in Europe dates back to the early 1950's [1–3]. A major milestone was achieved with the decision in 1973 to proceed with the design and construction of JET (the Joint European Torus) which is still operating in Culham (United Kingdom). As of today, the European Community is committed to the construction and operation of the International Thermonuclear Experimental Reactor ITER that is being built in Cadarache (France). ITER will be the first fusion experiment to produce net power although this power will not be used to generate electricity. This is the objective of the next generation fusion power device, the DEMOnstration power plant that will demonstrate the large-scale production of electrical power and tritium fuel self-sufficiency. The most recent European Fusion Roadmap [4] includes the development of the DEMO power plant, producing net electricity for the grid at the level of ~500 MW, with the aim to start operation with a closed fuel cycle by 2050. A conceptual design of this tokamak machine is expected to be delivered in 2020.

One of the most critical components in a fusion reactor is the breeding blanket, the first structure directly exposed to the plasma and submitted to extremely severe operating conditions in terms of the heat load and neutron damage. Its characteristics have a major impact on the overall plant design, performance, availability, safety and environmental aspects. After recalling the basic principle of fusion power, this paper will present the blanket concepts studied in the EU based on the use of the liquid metal eutectic Pb-15.7Li (PbLi afterwards). The general MHD issues to be solved in fusion blankets and their specific impact on each blanket concept will then be discussed.

1. The Tokamak configuration and the breeding blanket. Nuclear fusion is the process by which two atomic nuclei fuse to form a heavier nucleus. In order to obtain a fusion reaction, the two nuclei must overcome the long-range Coulomb repulsion force and approach one another as close as necessary to enable the short-range nuclear attraction forces to lead to the formation of a compound nucleus. To overcome the Coulomb repulsive force, the nuclei must be made sufficiently energetic, i.e. energies of the order of 10–100 keV (temperatures of 108–109 K) are required. At temperatures of millions of degrees, no physical wall can be used to confine the plasma: the magnetic confinement principle utilizes strong magnetic fields arranged in such a configuration that prevents the charged particles from escaping the plasma.

In a Tokamak [5] fusion reactor, the plasma is contained in a torus-shaped vacuum vessel and confined by an helical magnetic field, which is a combination of a magnetic field maintained in the direction of the magnetic axis by toroidal field (TF) coils and a poloidal magnetic field produced by high toroidal electric currents induced in the plasma ring by an external transformer (the central solenoid). Horizontal poloidal coils are needed to finally succeed in closing the magnetic field lines and to achieve plasma stability (Fig. 1). The toroidal magnetic field and the poloidal field must be generated by superconducting magnets: the most advanced superconducting material is Nb_3Sn used, for example, for the central solenoid and TF coils in ITER, which allows a magnetic field up to 13 T.



(*a*)

(*b*)

Fig. 1. The tokamak concept (*a*) and the breeding blanket (*b*).

The most suitable reaction for practical exploitation of nuclear fusion is the one between deuterium and tritium: $^2\mathrm{D} + {}^3\mathrm{T} \rightarrow {}^4\mathrm{He} + n$. The amount of natural tritium is, however, not sufficient to sustain a reactor, but neutrons produced in the D-T fusion can lead to tritium generation when captured by lithium isotopes: lithium compounds must, therefore, be present in the structure surrounding the plasma (the blanket) in order to regenerate (breed) the tritium, hence, the term 'breeding blanket'. The blanket is the first structure exposed to the plasma (Fig. 1). It has also the functions of converting the energy of fusion neutrons into heat suitable for electricity generation and protecting the reactor components and, in particular, the superconducting coils from excessive radiation damage. The blanket is the key nuclear component in a fusion reactor.

Several different types of breeder materials have been studied in the past both solid (essentially lithium ceramics in the form of pebbles) and liquid (pure lithium, Pb-Li alloys and FLiBe molten salts). Among the liquid breeders, the eutectic alloy Pb-15.7Li is now considered as the reference choice. Compared to solid breeders, the liquid ones have a number of inherent advantages, such as high thermal conductivity, practical immunity to irradiation damage, the possibility to transport the breeder material outside the blanket for tritium extraction, and, in general, they allow relatively simple blanket designs. The main problems of liquid metal breeder blankets are safety concerns due to the chemical reactivity of the liquid metal, activation products, tritium control and the influence of a strong magnetic field on liquid metal flows. The latter point is further discussed in this paper.

2. Critical MHD issues in fusion blankets. Critical issues related to MHD interactions of the moving PbLi with the magnetic field are due to the occurrence of increased pressure drops and special flow distributions. A review of MHD issues can be found, for instance, in [6]. Non-dimensional groups relevant to MHD flows are the Hartmann number Ha and the interaction parameter N. The former one gives a dimensionless measure for the strength of the magnetic field B. N describes the relative importance of Lorentz forces compared to inertia. MHD flows for fusion applications are characterized by intense magnetic fields B ($\mathrm{Ha}\cdot 10^4$) and small or moderate liquid metal velocities ($N = 10^4 - 10^5$). The described MHD phenomena are present in all liquid metal blankets, but their impact on the system performance is concept-specific. Of the four blanket concepts presently studied in the EU [7], three are based on the use of the PbLi eutectic (Table 1): the Helium Cooled Lithium Lead (HCLL), the Dual Coolant Lithium Lead (DCLL) and the Water Cooled Lithium Lead (WCLL).

Pressure drops that balance electromagnetic forces in MHD flows are proportional to the electric current density j induced in the fluid. The magnitude of j depends on the resistance of the current path, which is determined by the wall conductivity in electrically conducting ducts and by the conductivity of thin viscous layers in insulating channels. Therefore, in the latter case, a minimum current density is achieved. This explains why the MHD pressure drop reduction is obtained by electrically decoupling walls and fluid by means of suitable insulation. This can help to minimize pressure losses in long straight channels. However, this is ineffective in case of currents that close in the liquid metal. These currents are driven by axial electric fields that occur, for instance, in regions, where the magnetic field or the duct cross-section changes along the main flow direction.

For $\mathrm{Ha} \gg 1$ and $N \gg 1$, the flow is most likely laminar and the velocity is uniform in the core, where electromagnetic and pressure forces balance each other, and viscous effects are confined to very thin boundary layers. In electrically

Table 1. Main MHD issues for the proposed blanket concepts..

Blanket concept	**Critical MHD issues**
ALL	• 3D MHD pressure drop (bend, manifolds, non-uniform B, ...)
	• (mixed) magneto-convection
	• MHD enhanced corrosion
HCLL	• electric and thermal flow coupling
	• uniform flow distribution in BUs (manifold design)
DCLL	• pressured drop reduction by insulation
	• turbulence and instabilities in long ducts
	• flow imbalance in parallel channels
	• specific FCI-related flow features:
	– flow in gap between wall and FCI
	– need and influence of pressure equalization slot/holes
	– effects of FCI junctions/gaps/cracks
WCLL	• complex flow path around cooling tubes
	• electrical coupling of parallel ducts
	• uniform flow partitioning

conducting channels, high-velocity jets are present in layers parallel to **B**. In turns, this may affect corrosion of the structural materials [8]. A slug flow is instead expected in insulated ducts.

3. Concept specific MHD issues in EU blankets. The three EU blanket concepts (Fig. 2) presently under consideration share the same configuration. The blanket is divided in several modules arranged to follow as close as possible the plasma shape. Each module is constituted by a Eurofer steel box reinforced by an internal grid of stiffening plates to withstand the pressurization of the box in case of accident. In the volume inside the box (the 'breeding zone' – BZ), the grid defines a system of channels for the flow of the PbLi whose characteristics are specific to each blanket concept. The three concepts can be classified by the increasing difficulties and advantages they present. The WCLL uses water under pressurized water reactor (PWR) conditions (285°C – 325°C, 15.5 MPa) for cooling, which would allow re-using part of the technology known from fission power plants. The HCLL uses instead Helium (300°C – 500°C, 8 MPa), which allows for higher coolant temperatures and enhanced efficiencies of the power conversion cycle. The DCLL concept uses He, but also PbLi as a coolant which allows achieving even higher temperatures ($\geq$ 700°C).

3.1. Water-Cooled Lithium Lead (WCLL) blanket. In the WCLL blanket [9], the PbLi enters from the rear of the module in the bottom part, it flows frontward toward the FW, goes upward in the square channels formed by the stiffening grid, then backward in the top part of the module. The BZ is cooled by tubes bathing in the PbLi flow to collect the thermal power deposited by neutrons. Some plates have been foreseen at the module bottom and top to orientate the flow. Velocities are of the order of 5 – 10 mm/s.

In this blanket concept, from the MHD point of view, one should consider magneto-convection in long vertical channels, flows in ducts with internal obstacles, represented here by cooling tubes, and the pressure drop in distributing and collecting manifolds. Another important issue is the uniform distribution of Pb-Li in parallel ducts. Flow imbalance should be avoided to guarantee the uniform distribution of tritium concentration. Moreover, it has to be ensured that enough liquid metal reaches the FW and no recirculation or stagnant zones form. Numerical simulations are, therefore, required to predict the MHD pressure drop and

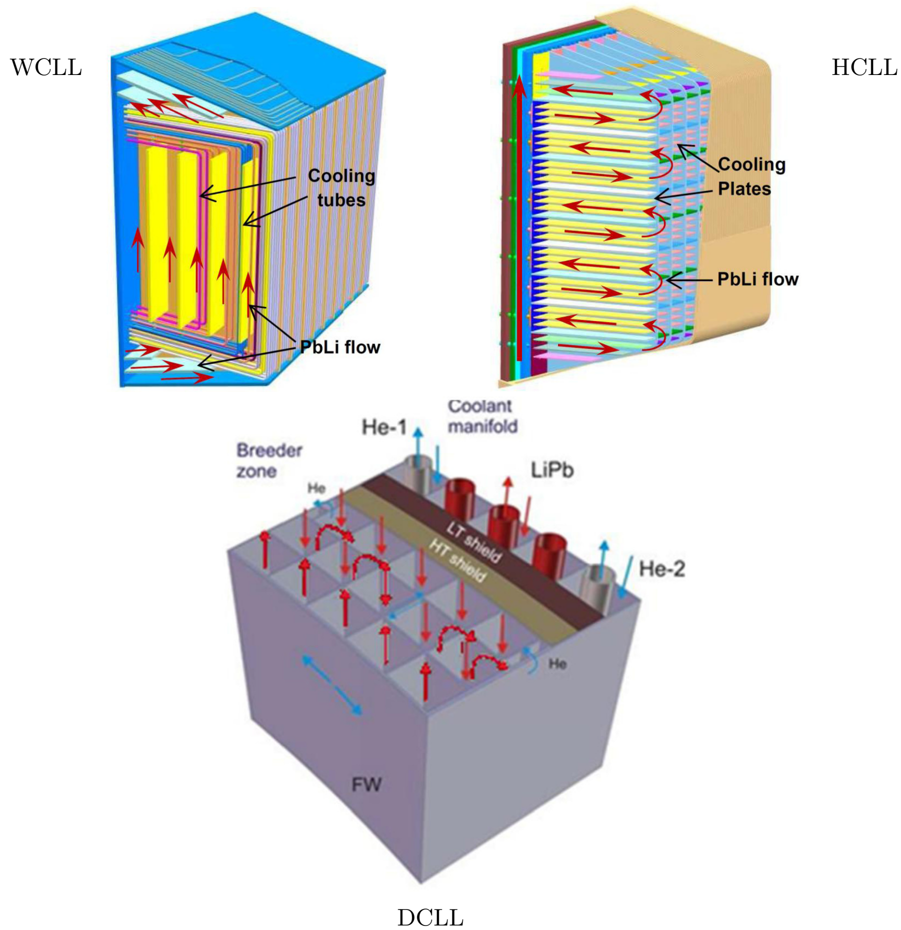


Fig. 2. Blanket concepts based on the use of Pb15.7Li.

velocity distribution. The latter one can be affected by electrical coupling due to exchange of currents across the electrically conducting stiffening plates.

3.2. Helium Cooled Lithium Lead (HCLL) blanket. In the HCLL blanket concept [10], the stiffening plates define a grid of elementary cells, called Breeding Units (BU), that are cooled by means of parallel cooling plates. All BUs in a column are fed in parallel through a vertical manifold on the back of the module. The inlet chamber feeds one out of two BUs, then the Pb-Li flows towards the FW, goes to the BU immediately above and then horizontally flows to the outlet chamber at the back.

MHD phenomena typical of HCLL blankets are related to electric and thermal flow coupling of neighboring channels. The so-called multi-channel effect depends on the wall electric conductivity, flow direction and the orientation of B. Electric flow coupling can be exploited for supporting uniform flow partitioning in the BUs [11]. It has been shown experimentally that the pressure drop in the BUs is not an issue due to the small velocities. Results have been extrapolated to ITER TBM and a total pressure drop lower than 0.3 MPa has been estimated [12]. However, in a blanket module, many BUs are fed by a single manifold, where velocities may reach large values. Here significant 3D MHD effects and pressure losses can occur. Simulations for MHD flows in HCLL model geometries (Fig. 3, 4) showed also

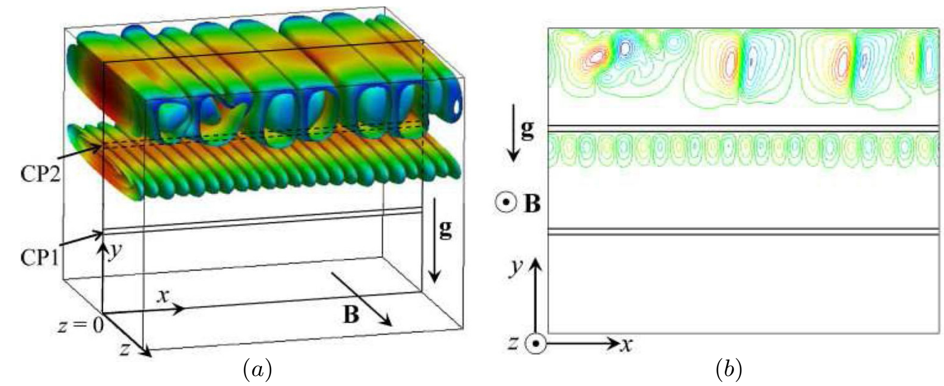


Fig. 3. (*a*) Isosurfaces of electric potential. (*b*) Potential isolines on the middle plane $z = 0$ for the flow at Ha = 2000 and $\mathrm{Gr}_a = 2.2 \times 10^7$.

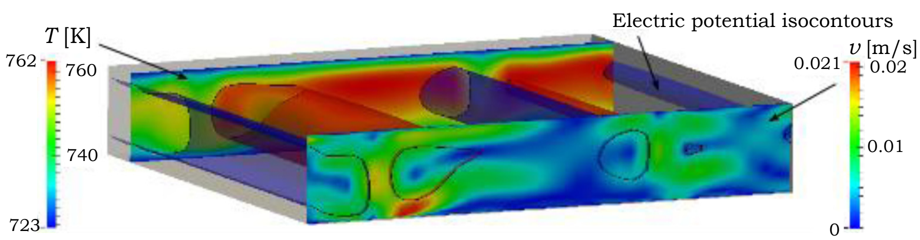


Fig. 4. Mixed convection MHD flow with uniform thermal load and perfectly conducting walls at Ha = 3000, Re = 770 and Gr = 2.6×10^{11}.

that natural convection could be intense resulting in large fluid recirculation and convective instabilities [13 – 15].

3.3. Dual Coolant Lithium Lead (DCLL) blanket. In the DCLL blanket, the PbLi flows poloidally in the channels defined by the stiffening grid without any additional cooling. In order to reduce the pressure drop caused by MHD interactions, poloidal Pb-Li channels are insulated by flow channel inserts (FCIs) made of sandwiched ceramic materials or SiCf/SiC that ensure the electrical decoupling of the liquid metal from the channel walls. However, the impact of 3D MHD effects on the pressure and velocity distribution has to be still thoroughly studied. 3D MHD flows that play a fundamental role in determining additional pressure drops are those in manifolds [16], in non-uniform magnetic fields, at junctions between FCIs [17], near gaps or holes for pressure equalization [18], close to possible cracks [19]. In [20], MHD pressure drops in a DEMO DCLL blanket were estimated. It was highlighted that available empirical formulations used for 3D MHD pressure drops $\Delta p_{3\mathrm{D}}$ were not derived for geometries comparable to the manifold design (Fig. 5). Therefore, the contribution of the 3D flow to p3D in this component remained the main uncertainty. Further studies are needed [21].

Due to imperfect insulation provided by FCI, higher velocities are present in parallel boundary layers which can be destabilized leading to the occurrence of turbulence. Recent calculations show the importance of mixed magneto-convection in the DCLL blanket [22]. FCI thermal and electrical properties and thickness have strong influence on the MHD pressure drop, velocity profile and thermal blanket efficiency. Thus, the correct design of such FCI is of crucial interest [23].

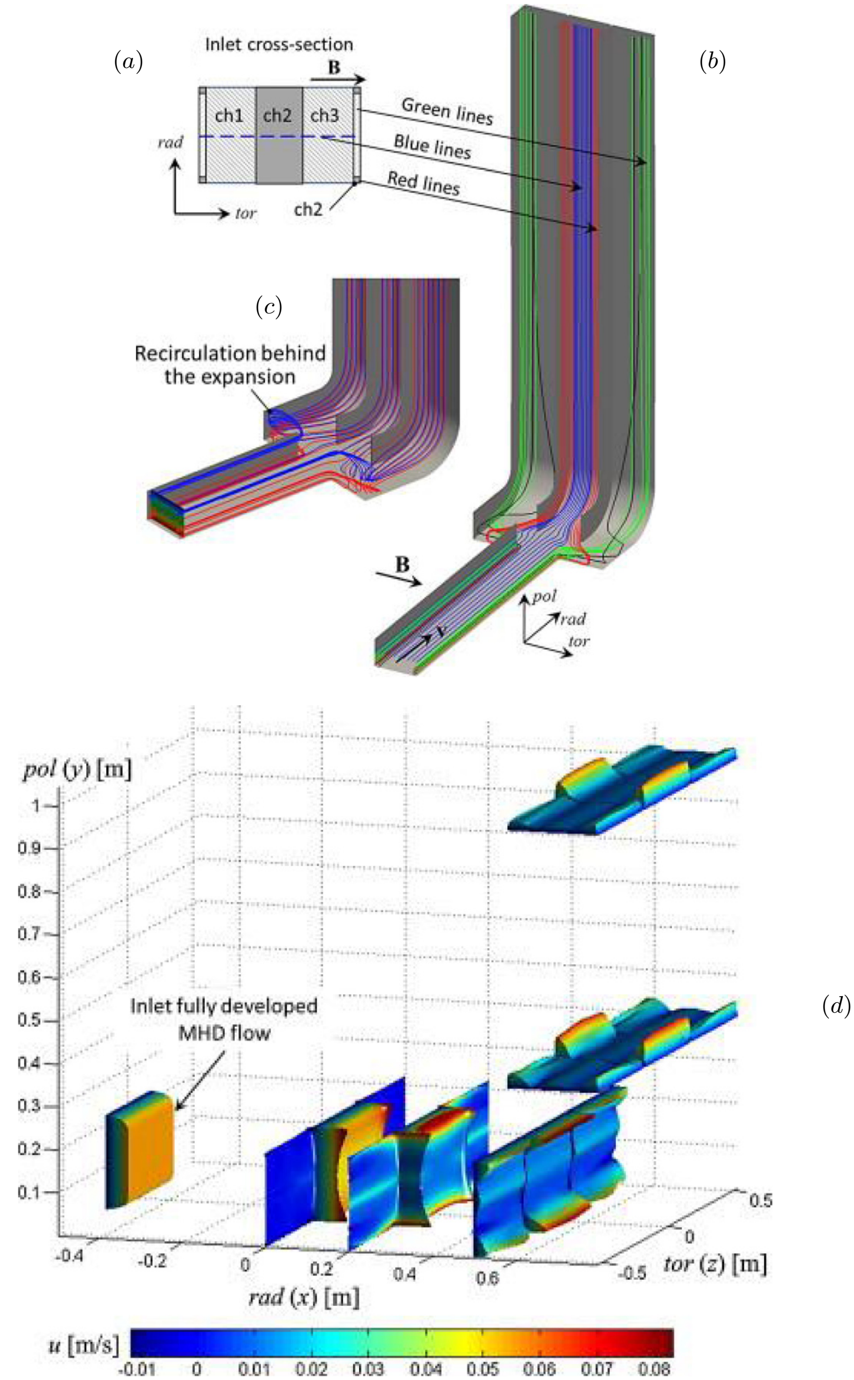


Fig. 5. MHD flows in a DCLL manifold: (*a*) approximate map on the inlet cross-section indicating the outlet channel; (*b*) velocity streamlines originating from different areas of the inlet cross-section; (*c*) streamlines show the recirculation behind the expansion; (*d*) axial velocity distribution at different cross-sections for the flow at Ha = 1000.

4. Conclusions. MHD phenomena in PbLi-based fusion blankets change the heat-transfer characteristics, pressure drop and the required pumping power for circulating the liquid metal. They also influence the mass transport characteristics, affecting, in turn, tritium permeation and corrosion kinetics. Considerable efforts, both in modeling and in experiments, were made in the past years to investigate MHD issues in liquid metal blankets. Further efforts should be directed to enlarging our knowledge of MHD and heat transfer phenomena in channels of complex geometry, but also in straight channels with perfect and non-perfect electrically insulated walls. In parallel, the use of dedicated experimental facilities and the development of more sophisticated predictive capability tools to perform fully coupled 3D numerical simulations should be pursued.

Acknowledgments. This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1] M. Gasparotto. Present status of fusion research: the next-step tokamak (ITER) and the demonstration reactor (DEMO). *Applied Radiation and Isotopes*, vol. 46 (1995), issues 6–7.

[2] R. Andreani, M. Gasparotto. Overview of fusion nuclear technology in Europe. *Fusion Engineering and Design*, vols. 61–62 (2002).

[3] Y. Poitevin, L.V. Boccaccini, M. Zmitko *et al.* Tritium breeder blankets design and technologies in Europe: Development status of ITER test blanket modules, test and qualification strategy and roadmap towards DEMO. *Fusion Engineering and Design*, vol. 85 (2010), issues 10–12.

[4] F. Romanelli *et al.* *Fusion Electricity: A Roadmap to the Realization of Fusion Energy* (EFDA, 2012).

[5] J. Wesson. *Tokamaks* (Oxford Science Publications, 2004).

[6] S. Smolentsev, R. Moreau, L. Bühler and C. Mistrangelo. MHD thermofluid issues of liquid-metal blankets: Phenomena and advances. *Fusion Engineering and Design*, vol. 85 (2010), pp. 1196–1205.

[7] A. Li-Puma *et al.* Design and development of DEMO blanket concepts in Europe (*to be published in Fus. Eng. and Des.*).

[8] R. Moreau, Y. Bréchet, L. Maniguet. Eurofer corrosion by the flow of the eutectic alloy PbLi in the presence of a strong magnetic field. *Fusion Engineering and Design*, vol. 86 (2011), issue 1, pp. 106–120.

[9] J. Aubert, G. Aiello, N. Jonqures, A. Li-Puma, A. Morin, G. Rampal. Development of the water cooled lithium lead blanket for DEMO (*to be published in Fusion Engineering and Design*).

[10] G. Aiello, J. Aubert, N. Jonqures, A. Li-Puma, A. Morin, G. Rampal. Development of the helium cooled lithium lead blanket for DEMO (*to be published in Fusion Engineering and Design*).

[11] C. Mistrangelo and L. Bühler. Electric flow coupling in the HCLL blanket concept. *Fusion Engineering and Design*, vol. 83 (2008), pp. 1232–1237.

[12] C. Mistrangelo and L. Bühler. MHD mock-up experiments for studying pressured distribution in a helium cooled liquid-metal blanket. *IEEE Transactions on Plasma Science*, vol. 38 (2010), no. 3, pp. 254–258.

[13] C. Mistrangelo and L. Bühler. Magneto-convective flows in electrically and thermally coupled channels. *Fusion Engineering and Design*, vol. 88 (2013), issues 9–10, pp. 2323–2327.

[14] E. Mas de les Valls, L. Batet, V. de Medina, J. Fradera and L.A. Sedano. Modelling of integrated effect of volumetric heating and magnetic field on tritium transport in a U-bend flow as applied to HCLL blanket concept. *Fusion Engineering and Design*, vol. 86 (2011), pp. 341–356.

[15] E. Mas de les Valls, L. Batet, V. de Medina and L.A. Sedano. MHD thermofluid flow simulation of channels with uniform thermal load as applied to HCLL breeding blankets for fusion technology. *Magnetohydrodynamics*, vol. 48 (2012), no. 1, pp. 157–168.

[16] L. Bühler and P. Norajitra. *Magnetohydrodynamic Flow in the Dual Coolant Blanket* (Forschungszentrum Karlsruhe FZKA 6802, 2003).

[17] L. Bühler and C. Mistrangelo. Influence of non-insulated gaps between flow channel inserts in ducts of DCLL blankets. *Proc. the 25th Symposium on Fusion Engineering* (June 11–14, San Francisco, 2013).

[18] S. Smolentsev, N.B. Morley and M. Abdou. Magnetohydrodynamic and thermal issues of the SiCf/SiC flow channel insert. *Fusion Science and Technology*, vol. 50 (2006), no. 1, pp. 107–119.

[19] L. Bühler. The influence of small cracks in insulating coatings on the flow structure and pressure drop in MHD channel flow. *Fusion Engineering and Design*, vol. 27 (1995), pp. 650–658.

[20] L. Bühler and P. Norajitra. *Magnetohydrodynamic Flow in the Dual Coolant Blanket* (Forschungszentrum Karlsruhe FZKA 6802, 2003).

[21] C. Mistrangelo and L. Bühler. Liquid metal magnetohydrodynamic flows in manifolds of dual coolant lead lithium blankets. *Proc. the 11th International Symposium on Fusion Nuclear Technology* (16–20 September, Barcelona, 2013).

[22] S. Smolentsev, N. Vetcha and R. Moreau. Study of instabilities and transitions for a family of quasi-two-dimensional magnetohydrodynamic flows based on a parametrical model. *Physics of Fluids*, vol. 24 (2012), p. 024101.

[23] E. Mas de les Valls, L. Batet, V. de Medina, J. Fradera, M. Sanmartí and L.A. Sedano. Influence of thermal performance on design parameters of a He/LiPb dual coolant DEMO concept blanket design. *Fusion Engineering and Design*, vol. 87 (2012), pp. 969–973.

Received 31.10.2014