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

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Abstract: 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.

1. Introduction

In the constant search for new power sources, thermonuclear fusion could be the ideal solution to satisfy world's energetic needs for the next centuries. 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 device, the DEMOnstration power plant that will demonstrate the production of electrical power and tritium fuel self-sufficiency [1]. 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 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.

2. The Tokamak configuration and the breeding blanket

In a Tokamak [2] 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 (Figure 1). The toroidal magnetic field and the poloidal field must be generated by superconducting magnets with a magnetic field up to 13T.

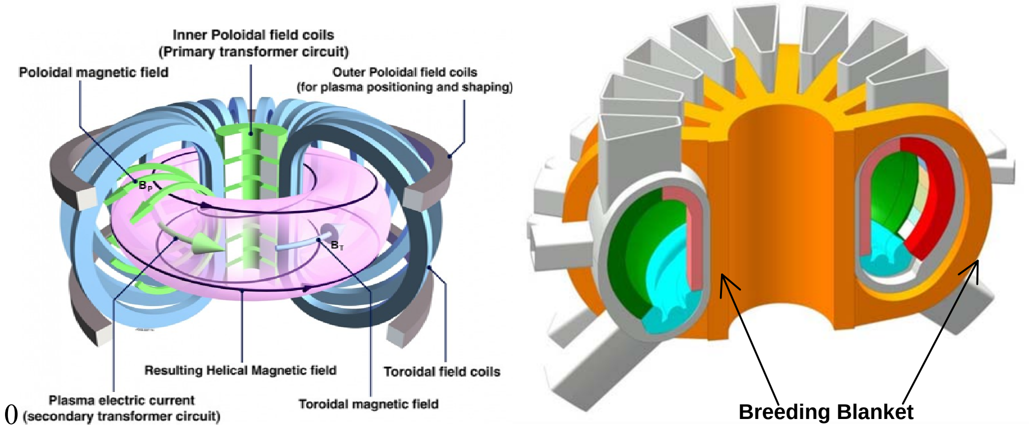

Figure 1: The tokamak concept and the breeding blanket.

The most suitable reaction for practical exploitation of nuclear fusion is the one between deuterium and tritium: $^{2}D+^{3}T \rightarrow ^{4}He + n$. 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 (Figure 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.

Among liquid breeders, the eutectic alloy PbLi 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.

3. Critical MHD issues in fusion blankets

Critical issues related to MHD interactions of the moving PbLi with the magnetic field are due to occurrence of increased pressure drops and special flow distributions. A review of MHD issues can be found for instance in [3]. 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 ($Ha \geq 10^4$) 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 system performance is concept-specific. Of the four blanket concepts presently studied in the EU [4], 3 are based on the use of the PbLi eutectic (Figure 2): the Helium Cooled Lithium Lead (HCLL), the Dual Coolant Lithium Lead (DCLL) and the Water Cooled Lithium Lead (WCLL).

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

Table 1 Main MHD issues for proposed blanket concepts

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 minimum current density is achieved. This explains why MHD pressure drop reduction is obtained by electrically decoupling walls and fluid by means of suitable insulation.

For $Ha >> 1$ and $N >> 1$ 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 conducting channels high-velocity jets are present in layers parallel to B. In turns, this may affect corrosion of the structural materials [5]. A slug flow is instead expected in insulated ducts.

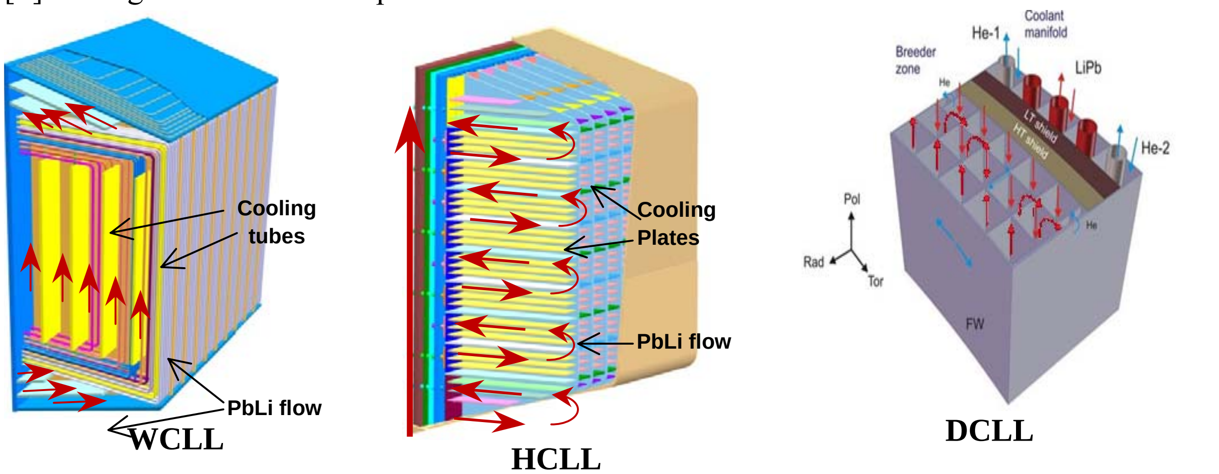

Figure 2: Blanket concepts based on the use of Pb15.7Li

4. Concept specific MHD issues in EU blankets

The 3 EU blanket concepts 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 3 designs can be classified by the increasing difficulties and advantages they present. The WCLL uses water in pressurized water reactor (PWR) conditions (285-325°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 higher coolant temperatures and enhanced efficiencies of the power conversion cycle. The DCLL concept uses He but also PbLi as coolant which permits achieving even higher temperatures (≥ 700°C).

4.1 Water Cooled Lithium Lead (WCLL) blanket. In the WCLL blanket [6] the PbLi enters from the rear of the module in the bottom part, it flows 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 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 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 MHD pressure drop and velocity distribution.

4.2. Helium cooled Lithium Lead (HCLL) blanket. In the HCLL blanket concept [7] 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 wall electric conductivity, flow direction and orientation of B. Electric flow coupling can be exploited for supporting uniform flow partitioning in BUs [8]. It has been shown experimentally that pressure drop in BUs is not an issue due to the small velocities. Results have been extrapolated to ITER TBM and a total pressure drop lower than 0.3MPa has been estimated [9]. 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 showed also that natural convection can be intense resulting in large fluid recirculation and convective instabilities [10,11,12].

4.3. Dual coolant Lithium Lead (DCLL) blanket. In the DCLL blanket [13] the PbLi flows poloidally in the channels defined by the stiffening grid without any additional cooling. In order to reduce pressure drop caused by MHD interactions, poloidal Pb-Li channels are insulated by flow channel inserts (FCIs) made of sandwiched ceramic materials or SiC_f/SiC that ensure the electrical decoupling of the liquid metal from the channel walls. However, the impact of 3D MHD effects on 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 [14], in non-uniform magnetic fields, at junctions between FCIs [15], near gaps or holes for pressure equalization [16], close to possible cracks [17]. In [14] MHD pressure drop in a DEMO DCLL blanket were estimated. It was highlighted that available empirical formulations used for 3D MHD pressure drops Δp_{3D} were not derived for geometries comparable to the manifold design. Therefore the contribution of the 3D flow to Δp_{3D} in this component remained the main uncertainty. Further studies are needed [18]. Due to imperfect insulation provided by FCI higher velocities are present in parallel boundary layers which can be destabilized leading to occurrence of turbulence. Recent calculations show the importance of mixed magneto-convection in the DCLL blanket [19]. FCI thermal and electrical properties and thickness have strong influence on MHD pressure drop, velocity profile and thermal blanket efficiency. Thus, the correct design of such FCI is of crucial interest [16].

5. Conclusions

MHD phenomena in PbLi-based fusion blankets change heat-transfer characteristics, pressure drop and the required pumping power for circulating the liquid metal. They also influence mass transport characteristics, affecting in turns tritium permeation and corrosion kinetics. Considerable efforts, both in modeling and experiments, have been 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 electro-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.

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