# Identification of key MHD thermofluid issues and associated R&D for the next generation liquid blankets

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Using Li-containing liquids in fusion blankets as a breeder/coolant is a very attractive option due to potentially higher blanket thermal efficiency (>40%) compared to solid breeder blankets. Besides utilization of different breeders (either molten salts Flibe or Flinabe, or liquid metals PbLi or pure Li), liquid blankets can vary in many other ways depending, for instance, on: (i) cooling the breeder zone (helium-cooled, dual-coolant, or self-cooled blankets); (ii) basic flow direction (toroidal, poloidal or radial blankets); (iii) usage of insulating and structural materials, *etc*. Typical examples of liquid blankets are DCLL (dual-coolant lead-lithium), HCLL (helium-cooled lead-lithium), and self-cooled lithium/vanadium blankets. In spite of their attractiveness, liquid blankets have many feasibility issues associated with the nature of liquid breeders, including their high chemical activity, and interaction with the plasma-confining magnetic field that may result in various magnetohydrodynamic (MHD) effects. The MHD effects, being coupled with heat and mass transfer, have a profound impact on the blanket performance, operation and safety, which can be either positive or negative depending on the specific issue. If MHD effects on blanket operation are better understood and predicted in normal and off-normal conditions, fusion blanket designs can be significantly improved. The main goal of this paper is therefore to identify key MHD thermofluid issues and associated R&D for the next generation liquid blankets including those for ITER and beyond. Based on that, a new R&D initiative is proposed, aiming at development of new predictive capability tools for complex MHD thermofluid phenomena in the variety of breeding blankets that utilize liquids as the work fluid.

***Traditional MHD thermofluid issues.*** The most important MHD flow issues for blanket applications are traditionally related to: high MHD pressure drop and flow balancing; electrical and thermal insulation of blanket channels; flows in 3-D blanket elements, such as manifolds, bends, contractions and expansions; flows in a fringing field; and electromagnetic coupling between flows in neighboring channels (Madarame effect). In turn, significant changes in the flow field due to the MHD interaction may have a significant effect on temperature distribution, tritium transport and corrosion/deposition processes that occur at the solid-liquid interfaces. In the recent past, these processes were analyzed using simplified MHD models, starting from a slug-flow approximation, followed by a more advanced but still limited “core flow” approach, in which viscous and inertia forces in the flow bulk were neglected compared to the Lorentz force and pressure gradients. These limited approaches are still used for “envelope” calculations but as a rule are too rough to be used in practice for accurate flow predictions. Presently, more sophisticated numerical approaches based on the full set of the 3-D Navier-Stokes/Maxwell equations are being developed but their applicability to the real blanket flows is still limited by the complexity of the flow geometry and/or the magnetic field strength.

***Blanket optimization.*** The key parameters associated with the flows in a blanket, which need optimization, are the magnetohydrodynamic (MHD) pressure drop, interface temperatures, heat losses into helium flows (for DCLL), secondary stresses in structural elements and insulating flow inserts. Satisfying all the requirements and increasing the blanket efficiency at the same time is extremely challenging. Optimizations may require special flow routing, tailoring the MHD flows, and development of lower thermal stress flow channel inserts. Also, both molten salts and liquid metals allow for the active flow control by applying an electric current. All these require good understanding of the MHD phenomena and adequate predictive capability tools.

***Inboard (IB) versus outboard (OB) blankets.*** Characteristic features of any IB versus OB blanket are related to the restricted available space, lower heat loads, long poloidal path of the liquid flows, and a significantly higher magnetic field: 10-12 T against ~ 4 T at the OB. The strong magnetic field and its associated gradients are the main factors resulting in higher MHD pressure drops. The ultimate goal for any liquid blanket design is to keep the overall MHD pressure drop ΔP below 2 MPa. For OB blankets, ΔP typically does not exceed 0.3-0.5 MPa (*e.g.,* DCLL). Extrapolating the OB data to the IB blanket conditions suggests ΔP 3-10 times higher, which can be intolerable. Thus using effective electrical insulation and optimized flow schemes are necessary for IB blankets.

***Mass transfer.*** Mass transfer includes tritium transport in the liquid and its diffusion through the solid walls into the surroundings, and corrosion of the solid structure and transport of corrosion products including their deposition in the cold section of the loop. An excessive amount of corrosion products may cause clogging of small cross-sectional area elements, *e.g.* valves, and should be avoided. The critical parameter for corrosion is the interfacial temperature between the liquid and solid, which has not been accurately evaluated yet for the variety of blankets. All mass transfer processes are strongly affected by MHD effects and temperature distribution in the blanket and thus mass transfer phenomena should be analyzed in parallel with MHD flows and heat transfer.

***Effect of liquid flows on the magnetic field.*** The flow of a conducting liquid in a plasma-containing magnetic field $B_0$ induces its own magnetic field $B'$ so that the resultant magnetic field is $B = B_0 + B'$. Generally in order to avoid any distortions in the plasma confinement, it is necessary to provide $B_0 >> B'$, which requires $Re_m << 1$ ($Re_m = \mu\sigma LU$ is the magnetic Reynolds number). This is not necessarily true if the blanket duct are not perfectly insulating as the characteristic length becomes comparable with the chamber size. In these conditions (for liquid metals), $Re_m \sim 1$ suggesting that distortions of the magnetic field due to the liquid metal flows are not negligible.

***New trends.*** Recent studies of MHD flows under liquid blanket conditions have indicated a number of physical phenomena not taken into account in the existing MHD thermofluid models but most likely having a pronounced effect on blanket performance and operation. First of all, unlike the traditional belief that a strong reactor magnetic field leads to the flow laminarization, the liquid metal MHD flows in dual-coolant or self-cooled blankets as well as molten salt flows are seen to be turbulent. Second, the blanket flows are expected to be dominated by buoyancy effects associated with the high-intensity volumetric heat generation. The most dramatic effect associated with buoyancy is formation of reverse or stagnant zones in the poloidal flows where the buoyancy force strongly opposes the forced flow. This may cause local “hot spots” at the walls as well as tritium accumulation. Third, due to impurities in the liquid metal (e.g., corrosion products), possible helium bubbles formation, and stratification (for PbLi), the liquid metal flows can hardly be considered using a single-phase model. Associated modeling thus requires more sophisticated approaches. Fourth, the interfacial phenomena between the flowing liquid and the solid boundary seems to be another potential issue for the thermofluid modeling as a poor-wetting phenomenon and an associated interfacial slip is another important factor that needs to be accounted for.

Taking into account the importance of MHD thermodluid phenomena for liquid blankets along with all the uncertainties and shortages of the existing approaches used for their prediction, the present initiative suggests a new complex study of MHD thermofluid phenomena under conditions of a liquid blanket including experiments, theory, and numerical modeling. The ultimate goal of the proposed work is the development of adequate high-efficiency computational tools suited for MHD flows in a liquid blanket and its coupling with heat and mass transfer phenomena. In line with this goal, three programs (campaigns) have been identified.

***Experiment***. The main role of the experimental campaign is to deliver necessary knowledge and to create a physical database, which can be used at the later stages to formulate proper boundary conditions and to construct closing relations, especially for turbulent flow regimes. The experimental data can also be used for validating new physical models and benchmarking numerical codes. An important element of this campaign is construction of new experimental MHD facilities with advanced capabilities, including bigger space, stronger magnetic fields, and usage of surrogate liquids (KOH, GaInSn, Hg, Ga) as well as “real” liquids (Li, PbLi, Flibe, Flinabe). The experiments will also be performed with ITER TBM and, at the later stages, in CTF allowing for volumetric heating.

***Theory.*** To cover basic transport mechanisms, adequate physical models for the flow bulk as well as interfacial phenomena are needed. The new physical models should range from laminar to turbulent flows and address specific electromagnetic processes typical to high electrical conductivity liquid metals as well as lower conductivity molten salts.

***Numerical modeling.*** A computer code (codes) will culminate the experimental and theoretical efforts. The main requirements on the new computational tools are: wide parameter range capability, efficiency and accuracy. The new codes can be used for interpretation of the experimental data, planning new experiments in lab facilities, ITER and CTF, and as a design and optimization tool to develop new and improve existing liquid blanket designs.