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COMPUTATIONAL MAGNETOHYDRODYNAMICS CODES FOR THE DEVELOPMENT OF LIQUID METAL BREEDING BLANKETS IN MAGNETIC FUSION REACTORS

Alessandro Tassone*, Lorenzo Melchiorri, Sonia Pignatiello, Simone Siriano, Gianfranco Caruso

Nuclear Engineering Research Group, DIAEE - Sapienza University of Rome, Corso Vittorio Emanuele II 244, 00186 Rome, Italy

1. ABSTRACT

Liquid metal (LM) system and components are investigated in nuclear fusion R&D programmes worldwide for near-term implementation in technological demonstrators. Unique challenges are posed to the development of this technology in magnetic fusion reactors due to the onset of magnetohydrodynamic (MHD) effects. The role of numerical tools for the prediction of LM MHD flows is discussed and so its impact in the development of breeding blanket concepts. Results achieved with computational fluid dynamics and system thermal-hydraulic codes at Sapienza University of Rome are described.

2. INTRODUCTION

A pivotal component in a magnetic confinement fusion power plant is anticipated to be the breeding blanket (BB), which envelopes the plasma chamber and serves three primary roles: extracting heat from the plasma, shielding the rest of the plant from plasma radiation, and breeding tritium to ensure a self-sustaining fuel cycle. Several BB concepts utilize liquid metals (LMs) as their working fluids, owing to their good cooling and breeding capabilities. However, these electrically conductive fluids interact with the intense external magnetic field required to confine the plasma and, as a result, their motion must be described by magnetohydrodynamics (MHD) to properly characterize the component performance. A MHD flow regime distinguishes itself from the ordinary hydrodynamic (OHD) one in the same conditions since mass, momentum, and heat transport are profoundly affected, for instance, by alterations in the velocity profile, staggering increase in pressure drop and decrease in heat transfer coefficients [1]. Owing to the huge cost and complexity entailed in the design and experimental demonstration of LM technology in a fusion-relevant environment, computational MHD (CMHD) codes play an important role in guiding the pre-conceptual and conceptual development of LM system and components [1].

In this contribution, we discuss the use of CMHD tools able to resolve different scales to aid and support the design of LM BB concepts. We focus on activities carried out at Sapienza University of Rome on the Water-Cooled Lead Lithium (WCLL) BB. Computational fluid dynamics (CFD) codes based on the finite volume method (ANSYS CFX and OpenFOAM) are adopted to gather insights about flow features and transport coefficients at local scale. A custom version of the system thermal-hydraulic (STH) code RELAP5/mod3.3 (REDMaHD) is used to model MHD effects at system-level scale.

3. METHODOLOGY

The internal flow of an electrically conductive fluid in the presence of a static and uniform applied magnetic field is described by the MHD governing equations [1]. Working under the assumption of a very low magnetic Reynolds number, these may be written for an incompressible and Newtonian fluid following the dimensionless formulation based on the electric potential

$$\frac{\mathrm{Re}}{\mathrm{Ha}^2}\left[\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\mathbf{v}\right]=-\nabla p+\frac{1}{\mathrm{Ha}^2}\nabla^2\mathbf{v}+\boldsymbol{j}\times\boldsymbol{B}-\frac{\mathrm{Gr}}{\mathrm{Ha}^2\mathrm{Re}}\boldsymbol{g}\quad \text{with } \nabla\cdot\mathbf{v}=\mathbf{0} \tag{1}$$

$$\mathrm{Pe}\left[\frac{\partial T}{\partial t}+(\mathbf{v}\cdot\nabla)T\right]=\nabla^2 T+q''' \tag{2}$$

*Corresponding Author: alessandro.tassone@uniroma1.it

$$\nabla^2\phi = \nabla\cdot(\mathbf{v}\times\boldsymbol{B}) \quad (3)$$
$$\boldsymbol{j} = \sigma(-\nabla\phi + \mathbf{v}\times\boldsymbol{B}) \text{ with } \nabla\cdot\boldsymbol{j} = 0 \quad (4)$$

Where the symbols $p, \phi, T, \mathbf{v}, \boldsymbol{j}, \boldsymbol{B}, \boldsymbol{g}$ stand for the pressure, electric potential, temperature, velocity, current density, applied magnetic field, and gravitational acceleration. In Eq (1), the Boussinesq approximation is adopted to represent the buoyancy term in the momentum conservation equation and thermoelectric effects are neglected in Eq (3). The Reynolds number, defined as $\mathrm{Re} = v_0 L/\nu$, is the relative ratio between inertial forces due to forced convection and viscous forces calculated adopting the half-width of the channel in the direction of the magnetic field as length scale (L) and the mean velocity (v_0), with ν standing for the kinematic viscosity. The Hartmann number, $\mathrm{Ha} = B_0 L\sqrt{\sigma/\rho\nu}$, is the square root of the ratio between Lorentz and viscous forces calculated considering the intensity of the applied magnetic field (B_0), with σ and ρ standing for electrical conductivity of the fluid and density. The Grashof number, $\mathrm{Gr} = g\beta\Delta T L^3/\nu^2$, represents the relative ratio between inertial forces due to buoyancy and viscous forces, in which ΔT and β are the characteristic temperature difference of coefficient of volumetric expansion. In Eq (2), Pe stands for the Péclet number, ratio of advective to diffusive heat transfer that, for a mixed convection case, takes the form $\mathrm{Pe} = \mathrm{GrPr}/\mathrm{Ha}^2$, in which Pr stands for the molecular Prandtl number. In Eq (2), the symbol q''' stands for the volumetric heating due to interaction of the liquid metal with the neutrons flowing from the reaction chamber, whereas we neglect the contribution of Ohmic heating.

The set of Eqs (1)-(4) is then solved numerically given the appropriate kinematic, thermal and electrical boundary conditions. It is important to distinguish between cases that require different formulation for the latter ones by introducing the wall conductance ratio, $c = \sigma_w t_w/\sigma L$. If $c \ll \mathrm{Ha}^{-1}$, Eq (3) can be solved only in the fluid with imposing $\partial\phi/\partial n = 0$ at the fluid/solid interface. Conversely, if $\mathrm{Ha}^{-1} \ll c < 1$, the solution of Eqs (3) and (4) is a conjugated problem with $\phi_w = \phi$, $\boldsymbol{j_n} = \boldsymbol{j_{n,w}}$ at the fluid/solid interface. In the wall, Eq (3) is modified into $\nabla^2\phi_w = 0$ and $\partial\phi/\partial n = 0$ is imposed on the external surface, assuming a dielectric surrounding medium.

4. RESULTS

The use of CMHD tools to predict LM BB performances is presently restricted to the operation in nominal conditions and it falls in three categories: pressure drop estimates, heat transfer prediction, and calculation of mass transfer rates (tritium permeation and corrosion). We restrict the discussion to the first two examples, since the third is sharing many similarities, relying on prediction of velocity and temperature distribution.

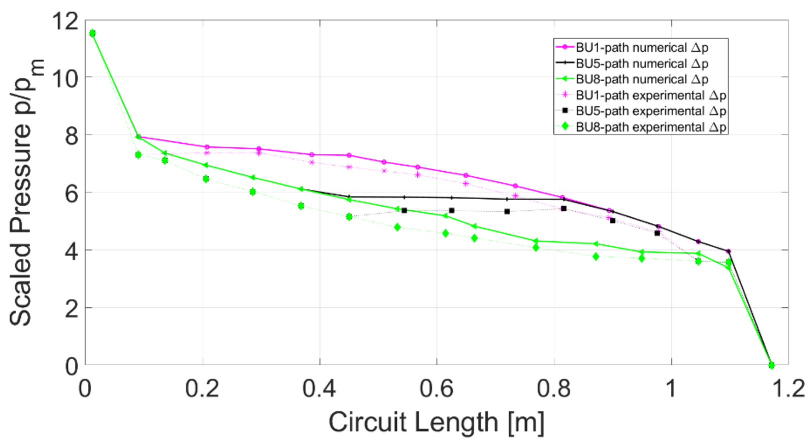

Fig. 1 REDMaHD prediction of the MHD pressure drop in the WCLL Test Blanket Module mock-up versus experimental data for Ha = 3000 and Re =300 [3]

MHD pressure drop can exceed by several orders of magnitude the OHD ones and, thus, its accurate prediction is relevant, at local scale, to determine the flow distribution across elementary flow paths and, at system scale, for the design of the LM pumping system. Engineering correlations are available to evaluate pressure losses for fully developed flows in rectangular and circular pipes but it is significantly more difficult to predict them for developing flows where both velocity (bends, cross-section variation, etc.) and electromagnetic gradients (non-uniform magnetic field) may be present. CFD tools are favoured for the simulation of 3D MHD flows since they are able to resolve the inertial-viscous-electromagnetic force balance existing therein and calculate the local pressure loss [2]. The necessity to resolve thin wall-attached and internal boundary layers ($\delta \propto \mathrm{Ha}^{-1}$) leads to high computational cost that limits almost exclusively the applicability of these methods to local scale simulations [2]. Even if examples of CFD system-scale simulations exist, a more cost-effective alternative is provided by STH like REDMaHD that predict MHD pressure drops at system-level scale through reduced order models (ROM) that have been demonstrated, as in Fig. 1, to be accurate for blanket-like geometry and governing parameters.

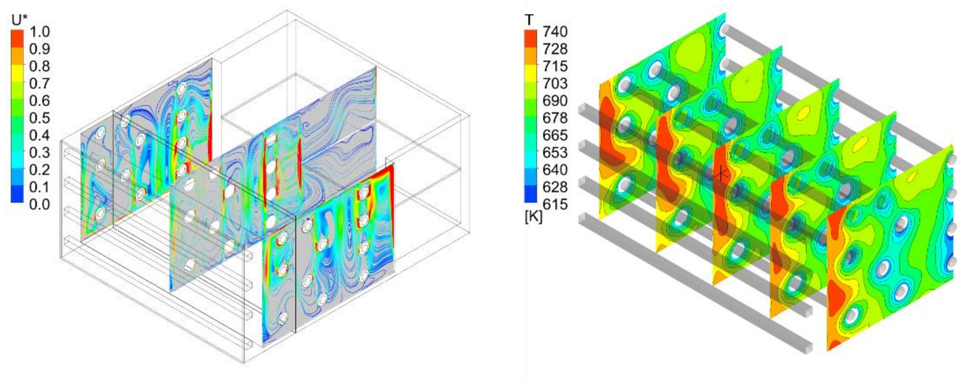

Fig. 2 CFD simulation of the magnetoconvection regime in the WCLL elementary cell. Left: Velocity streamlines. Right: Temperature distribution

Accurate estimate of heat transfer is important to guarantee the operation in the temperature window of the structural material (T < 823 K) and to predict the reactor thermodynamic efficiency. It tends to be starkly degraded in LM BB due to turbulence damping and laminarization by the magnetic field through Ohmic dissipation. In BB concepts in which the power extraction is accomplished with a secondary non-electrically conductive fluid, LM velocity is kept at <1 mm/s to minimize MHD pressure drop and heat transfer is almost completely diffusive. Nevertheless, the existence of strong temperature gradients give rise to magnetically-affected free convection regimes (magnetoconvection) in the LM that alter the temperature distribution compared with pure conduction. Magnetoconvective simulations are possible only with CFD tools and face similar challenges to those described for isothermal computations but, in general, tend also to rely on a less solid database of validation data. It is often excruciatingly difficult to generate a suitable computational grid for these cases due to the presence of immersed obstacles that feature a complicated geometry (U-pipes, helical pipes, etc.). As such, CFD system-scale analyses are limited and are mostly restricted to simpler configurations composed by rectangular ducts with no internal obstacles or simplified cooling pipe geometry.

Development of MHD heat transfer ROM for STH codes is at a lower level of maturity compared with isothermal flows. The state-of-the-art is restricted to ideal configurations, e.g. forced convection in insulated pipes, and often relies on analytical solutions due to the scarcity of experimental results; a problem even more accentuated for BB-scale configurations. Verification and Validation is thus performed on isolated flow elements, like pipes with uniform heating, whereas we are restricted for fusion-relevant test cases to code-to-code comparison.

Lastly, MHD two-phase and multi-phase flows may occur in BB during normal operation or as consequence of accidental transients. For instance, CFD analyses are performed to investigate the transport of helium bubbles in the LM [4]. Helium is a by-product of tritium breeding and coalescing bubbles may affect the component performances by degrading fuel generation efficiency and causing the formation of hotspots. Ingress of water in the LM due to a Loss-Of-Coolant Accident is also a concern in the WCLL BB due to the pressure transient and potential for explosion hazard due to the production of hydrogen. Numerical models based on the 1D Method Of Characteristics are used to assess MHD effects on the evolution of pressure waves in the BB.

5. CONCLUSIONS

CFD and STH codes are used to predict MHD flows in LM BB concepts in nominal conditions. Simulation of isothermal flows has reached a satisfactory level of maturity and it is now routinely used to predict MHD pressure losses at local and system-level scale. Conversely, validation efforts are still ongoing to demonstrate the confidence for heat transfer predictions, especially for buoyant flows. MHD effects for off-normal transients and multiphase flows are currently underexplored, even if relevant for reactor safety.

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