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Modelling of integrated effect of volumetric heating and magnetic field on tritium transport in a U-bend flow as applied to HCLL blanket concept

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ABSTRACT

Under fusion reactor operational conditions, heat deposition might cause a complex buoyant liquid metal flow in the HCLL blanket, what has a direct influence on tritium permeation ratio. In order to characterise the nature of this flow, a simplified HCLL channel, including the U-bend near the reactor first wall, is analysed using a finite volume CFD code, based on OpenFOAM toolbox, following an electric potential based formulation. Code validation results for developed MHD flow and magneto-convective flow are exposed. The influence of the HCLL U-bend on the flow pattern is studied with the validated code, covering the range of possible Reynolds numbers in HCLL-ITER blanket, and considering either electrically insulating or perfectly conducting walls. It can be stated that, despite the very low velocities and the high Hartmann number, flow pattern is complex and unsteady vortices are formed by the action of buoyancy forces together with the influence of the U-bend. Through the analysis, the flow physics is decoupled in order to identify the exact origin of vortex formation. A simplified tritium transport analysis, considering tritium as a passive scalar, has been carried out including a study on boundary conditions influence and a sensitivity analysis of tritium permeation fluxes to diffusivity and solubility parameters. Results show the relevance of Sievert's coefficient uncertainties, which alters the permeation ratio by an order of magnitude.

1. Introduction

One of the key components, regarding heat transfer and tritium inventories, to be tested in ITER is the Test Blanket Module or TBM. It is located close to the first wall and, in its core, plasma neutrons interact with lithium generating tritium, the fusion reaction fuel. One of the Breeding Blanket designs to be tested in ITER is the HCLL (Helium Cooled Lead Lithium) blanket proposed by EU. This design uses the eutectic Pb–15.7Li as both tritium breeder material and neutron multiplier. Inside the HCLL channels, the liquid metal flows perpendicular to the toroidal magnetic field, experiencing a high pressure drop caused by Lorenz forces while absorbing the thermal load deposited by the high neutron flux. Heat is conveyed to cooling plates, located between liquid metal channels, which are cooled by circulated pressurised helium (see e.g. Salavy et al. [1]). Hence, the liquid metal undergoes, inside the liquid channels, a complex buoyant flow strongly affected by Lorentz forces. Tritium, generated in and transported by liquid metal, may eventually permeate through channel walls. The relevance of the detailed analysis of the flow for the proposed ITER blanket design lays basically on the need of accurately assessing tritium permeation.

A tritium system code was proposed on the basis of steady state flow process diagrams for HCLL DEMO by Gastaldi et al. [2]. A more detailed tritium model was implemented in TMAP7 1D tritium transport tool by Moreno and Sedano [3]. Future developments of such system codes are expected to implement, in a modular way, computational refinements at component channel level. In this direction, it will be necessary to include fluid interaction effects.

CFD codes are needed to take into account such fluid interactions, and models must include temperature and magnetic field couplings; in turn, the analysed system must be limited to a simplified blanket module for computational constrains. The magnetic coupling can be modelled following either the induced magnetic field formulation or the electric potential (ϕ) formulation [4], the latter involving less equations than the former. A comparison of both formulations for fully developed flows can

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Nomenclature

Acronyms

CFD	Computational Fluid Dynamics
CFL	Courant–Friedrich–Levy
DCLL	Dual Coolant Lead Lithium blanket
DEMO	DEMOnstration power plant
FSPM	Four Step Projection Method
HCLL	Helium Cooled Lead Lithium blanket
ITER	International Thermonuclear Experimental Reactor
LM	Lead Lithium
MHD	Magnetohydrodynamics
PISO	Pressure-Implicit Split-Operator
SM	Structural Material
TBM	Test Blanket Module
TPR	Tritium Permeation Ratio

Adimensional numbers

Ha	Hartmann number
Gr	Grashof number
N	Interaction parameter or Stuart number
Pe	Peclet number
Pr	Prandtl number
R_m	Magnetic Reynolds number
Re_{Din}	Reynolds number based on the hydraulic diameter
Re_{gap}	Reynolds number based on gap dimension
Sc	Schmidt number

Symbols

β	thermal expansion coefficient
ν	kinetic viscosity
$\vec{Bo}$	externally applied magnetic field vector
ϕ	electric potential
ρ	density
σ_m	electric conductivity
$\vec{j}$	electric current vector
$\vec{g}$	gravity vector
$\vec{v}$	velocity vector
C	tritium concentration
c_w	wall electric conductivity
D	tritium diffusivity
J_H	permeation through the Hartmann walls (%)
k	thermal conductivity
k_s	Sievert's coefficient for tritium
p_d	dynamic pressure (total pressure minus hydrostatic pressure)
$S_{thermal}$	thermal load
$S_{tritium}$	tritium generation
T	temperature
t	time
T_0	reference temperature

be found in Smolentsev and Tananaev [5], where authors concluded that the induced magnetic field formulation has a better convergence behaviour. In order to improve the ϕ-formulation, a new MHD algorithm conserving the electric current was proposed by Ni et al. [6]. An application of this algorithm to HCLL analysis can be found in Mistrangelo and Bühler [7], where the CFX code is adapted to analyse the influence of the electromagnetic coupling of several channels in the HCLL-TBM. Recently, a new MHD approach is analysed by Smolentsev et al. [8], where a $\vec{j}$-formulation based on the electric current as the main electromagnetic variable is introduced. Compared to the ϕ-formulation, the $\vec{j}$-formulation avoids some numerical errors potentially present at high Hartmann numbers but needs to solve a vectorial $\vec{j}$ equation instead of the scalar ϕ equation, requiring more computational time.

Modelling thermal coupling with MHD flow in the blanket is a complex issue and all the efforts done in this direction so far imply some flow or geometry simplifications. In addition, flow is assumed to be inductionless and the Boussinesq hypothesis is applied.

Garandet et al. [9] made an analytical study of a two-dimensional cavity with vertical magnetic field, considering both thermally insulated and conducting walls, and a fixed temperature gradient. In both cases, a one-dimensional velocity profile in the core, linear at high Ha numbers, and the classical exponential profile in the so called Hartmann layer of dimensionless thickness Ha^{-1} were obtained.

In Ozoe and Okada [10] the effect of the magnetic field orientation on the natural convection was numerically analysed for three-dimensional cubical enclosures. Later, the same authors carried out the corresponding experimental study [11].

A high Ha number asymptotic analysis was made by Alboussière et al. [12] considering the flow to be inertialess. Despite the analysis considers the driving force to be independent of the fluid velocity, which is not valid for buoyancy flows, the study shows the relevance of the nature of (electric) symmetry along magnetic field lines on the magnitude of the velocity. Later, Bühler [13] made an asymptotic analysis specifically for buoyant magnetohydrodynamic flows assuming that the flow remains laminar, is inertialess and the walls are electrically thin. Since the Peclet number is considered to be very small and the fluid to be an excellent conductor, the convective term in energy equation can be suppressed. In the study, high-velocity jets were observed for the first time along perfectly conducting side walls (parallel to the magnetic field). In this asymptotic analysis, and considering an imposed heat flux, the influence on the symmetry was highlighted. Moreover, it was shown that when uniform volumetric heating is considered, with cooled side walls, inverse side jets appear and a three-dimensional core velocity solution exists. For vertical enclosures with horizontal magnetic field, either perpendicular or parallel to the temperature gradient, numerical and experimental studies were carried out by Tagawa et al. [14] and Authié et al. [15]. In the latter, non-steady situations were analysed. The existence of the high velocity jets at the side boundary layers was deeply investigated by Molokov and Bühler [16], where it was stated that the amount of fluid carried out by these jets at the side boundary layer is proportional to the electric potential gradient between the layer and the core. Under some temperature distributions, the electric current lines are tangential to all walls and thus the induced jets are reduced drastically.

An application of the previous know-how to the HCLL blanket was made by Kharicha et al. [17], considering steady flows under strong magnetic field and low Peclet numbers. It was stated that in HCLL blanket buoyant convection may become as relevant as forced flow. In the same framework, a summary of critical HCLL issues was done by Reimann et al. [18], including MHD, multi-channel effect, and MHD natural convection.

More advanced numerical models can be found, for example, in Smolentsev et al. [19], where the 2D model for fully developed flow is coupled with the 3D model for heat transport, to study a front poloidal channel in the outboard module of a Dual Coolant Lead Lithium (DCLL) blanket with a SiC wall channel insert. A more recent example from the same research group can be found in Vetcha et al. [20], where a 2.5D code based on a pseudo-spectral method is applied to study the stability of the mixed convection in the poloidal flows of the DCLL blanket. Main conclusion of this latter study is that under DCLL blanket conditions all disturbances associated with buoyant flows in the front ducts will likely be damped by the strong toroidal magnetic field.