V European Conference on Computational Fluid Dynamics
ECCOMAS CFD 2010
J. C. F. Pereira and A. Sequeira (Eds)
Lisbon, Portugal,14-17 June 2010

FLOW ANALYSIS IN THE HCLL-TBM ITER CHANNELS INCLUDING MHD AND HEAT TRANSFER

E. Mas de les Valls*, J. Fradera† and L. Batet†

*Technical University of Catalonia (UPC), GREENER, Technology for Fusion (T4F),
Dept. of Heat Engines, Av. Diagonal 647, 08028 Barcelona, Spain
e-mail: elisabet.masdelesvalls@gits.ws
†Dept. of Physics and Nuclear Engineering, Av. Diagonal 647, 08028 Barcelona, Spain

Key words: MHD, heat transfer, Breeding Blanket

Abstract. *One of the key components regarding heat transfer and tritium inventories in deuterium-tritium nuclear fusion reactors is the (tritium) Breeding Blanket, called Test Blanket Module or TBM in ITER experiment. Several designs are going to be tested in ITER, one of those is the HCLL (Helium Cooled Lithium Lead) design. Before being tested, it is of major interest to predict in detail several flow parameters such as pressure drop, tritium inventories and tritium permeation rates through walls.*

The goal of the present study is to analyze the flow near the gap region (close to the first wall) in the HCLL-TBM so as to quantify tritium inventories and permeation fluxes. To do so, simplified C-shaped channels are simulated under ITER specifications. The flow appears to be very complex and, in order to get the origin of this complexity, the phenomenon physics are decoupled. First, the pure hydrodynamic case is simulated; obtaining that the critical Reynolds number is around TBM/ITER specifications. Second, the MHD flow with perfectly insulating walls is studied and, as expected due to the high Hartmann number, hydrodynamic instabilities disappear. Finally, when heat transfer is introduced, vorticity is generated due to Rayleigh-Bénard instabilities at the channel inlet and, as the flow travels through the channel, faster vortices appear in the gap region and in the outlet channel. These vortices originate high tritium concentration zones. Hence, the existence of vortices is of crucial interest for tritium inventories prediction and HCLL design.

1 INTRODUCTION

One of the key components regarding heat transfer and tritium inventories in ITER nuclear fusion reactor 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 TBM designs that is going to be tested in ITER is the HCLL (Helium Cooled Lithium Lead). Inside the HCLL, the eutectic Pb-15.7Li flows perpendicular to the toroidal magnetic field and, while tritium is generated, the fluid experiences a huge thermal load. The relevance of the detailed analysis of the flow in the TBM lays basically on the need of getting the exact value of tritium permeation through the TBM walls, for safety reasons. This detailed analysis is also necessary for the final definition of the HCLL design, which is still evolving.

Numerical TBM studies nowadays are mainly carried out with the algorithm proposed by Ni et al. (2007) [1], where the isothermal MHD algorithm is electric current conservative. Following this algorithm, Mistrangelo (2009) [2] analyzes the influence of the electromagnetic coupling of several channels in the HCLL-TBM, in the isothermal case. Few authors have studied the heat transfer in the HCLL; one example is Gabriel et al. (2007) [3] where the channel is simplified to a 2.5D case without bends, the flow is considered at steady state and the Boussinesq hypothesis is applied.

The goal of the present study is to analyze the flow near the gap region (close to the first wall) in the HCLL-TBM, in order to quantify tritium permeation rates. The OpenFOAM toolbox [4] has been used for algorithm implementation, following the electric current conservative scheme proposed in Ni et al. (2007) [1]. In a first approach, Boussinesq hypothesis has been considered for the thermal coupling. Some code details are analyzed in section 1.1.

For computational reasons HCLL-TBM geometry has been simplified. The studied system is defined in section 2, and results for different flow conditions are discussed in sections 3, 4 and 5.

1.1 Code details

The algorithm proposed by Ni et al. in [1] includes Navier-Stokes, Maxwell and energy equations. Since liquid metals have a very low magnetic Reynolds number ($Rm \sim 10^{-6}$), the induced magnetic field can be considered negligible so that coupling between magnetic field and velocity field is unidirectional and can be calculated by means of the explicit introduction of the Lorentz force term in the momentum equation [5]. Therefore, the magnetic field can be considered constant in time and equal to the externally applied magnetic field $\overrightarrow{Bo}$.

The algorithm has been implemented in a sequential form following the Four Step Projection Method [1]. An internal loop for each time step is implemented in order to account for real transient simulations. The algorithm has been validated for Shercliff and Hunt's flow. More details can be found in [6][7][8].

For tritium transport modelling, a passive scalar transport equation has been implemented. Hence, tritium does not alters liquid metal properties nor flow behavior.

Being tritium permeation through walls a critical parameter for Breeding Blanket performance, a post-process measuring the total amount of tritium generated G_C, the permeation through Hartmann walls J_H, the permeation through side walls J_S, the outcoming tritium J_{out} and the tritium mean concentration in the outlet C_{out} has been built. This way, the fraction of permeated tritium can be defined as $\frac{J_H+J_S}{G_C}$. Due to the relevance of this parameter, the obtained permeation rate is also used to quantify mesh errors.

2 SIMPLIFIED TBM C-SHAPED CHANNEL

The detailed simulation of the complete TBM is not affordable nowadays due to computational limits. The available alternative is to simplify the geometry according to the studied phenomena. In the present work, the effect of the u-bend in the TBM module is to be analyzed. Hence, a simplified 3D channel corresponding to an inlet channel, the 180 degrees bend (gap between the stiffening plates and the first wall) and an outlet channel, both between the stiffening plate and two cooling plates, is analyzed. For more details on the complete HCLL-TBM geometry see G. Rampal et al. (2006) [9]. Geometry and dimensions are sketched in figure 1.

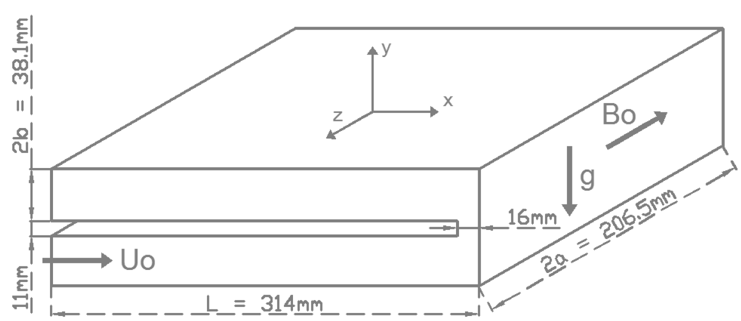


Figure 1: Geometry and dimensions for the simplified channel

The fluid is the eutectic Pb-15.7Li which flows under a toroidal magnetic field of 7 T. According to Pb-15.7Li data base [10] and HCLL-ITER specifications [9], adimensional numbers for the HCLL-TBM can be obtained. The Reynolds number at the inlet is $Re_{D_{in}} = 480$, the Hartmann number $Ha_a = 1740$ and the interaction parameter or Stuart number is $N_a = 3935$. Here, subindex indicate the chosen characteristic dimension. For Grashof number evaluation, the temperature gradient is calculated from the heat deposition, obtaining $\Delta T_L = 2.51$ and $Gr_L = 5.21 \cdot 10^9$. For tritium transport, the Scmidth number is $Sc = 134.2$.

Setting the boundary conditions is a main concern. As the simplified geometry (figure 1) is just part of the whole TBM, boundary conditions in a single channel can not be physically exact without simulating the whole system. In the present study, and as a first approach, velocity is chosen to be known and uniform at the inlet, walls are non-slip and a free outlet with fixed pressure is imposed. Temperature is uniformly fixed at inlet and at walls (at 450 C), this later representing idealized helium cooling plates. In order to get the worst scenario with maximum permeation, tritium concentration at walls is set to zero.

Both source terms, heat deposition and tritium generation, are chosen to follow the specifications in [9], where exponential correlations in radial direction (x axis in figure 1) are obtained.

Simulation results can be strongly mesh dependent; hence, the corresponding errors must be quantified. To this aim, three different meshes have been defined depending on the number of nodes in Hartmann boundary layers (of depth a/Ha) and side boundary layers (of depth $2a/Ha^{1/2}$). The finest one, called mesh 2, is the one considered reasonably adequate for MHD simulations, that is, with 4 nodes in Hartmann boundary layers and 10 in side boundary layers, with 777600 nodes for the whole channel. The coarsest mesh, called mesh 0, has only 2 nodes in the Hartmann boundary layer and 5 in the side one, with a total amount of 92784 nodes. Mesh 1 is an intermediate mesh between mesh 0 and mesh 2 with 291168 nodes in total.

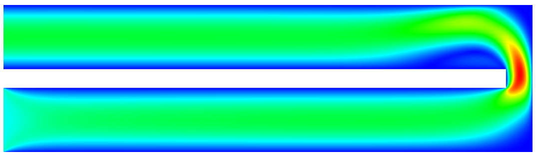
3 PURE HYDRODYNAMICS

In the pure hydrodynamic analysis, there do not exist neither a magnetic field nor temperature gradients in the system. So, flow can be characterized by the Reynolds number. The hydrodynamic analysis is essential for a better understanding of the phenomena that appear in more complex flow situations, but also provides the correct escenario for the first ITER phases (without plasma) and for some real transients.

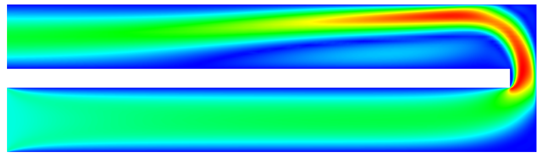
The system has been simulated for different Reynolds numbers using mesh 2 (defined in section 2) without time step inner convergence (pseudo-transient simulation), although meeting the CFL constraint. Results are shown in figure 2. It can be seen that under HCLL-TBM specifications (case d) a periodic flow developes due to the 180 degrees bend. Such oscilations could affect the structure of the module.

Mesh influence is analysed for $Re_{in} = 48$ (corresponding to case a of figure 2). Temporal evolution and velocity profiles obtained using the three meshes are similar, with an average 19.9 % difference meshes 0 and 2 (9.0 % between meshes 1 and 2). These errors may indicate that the correct mesh 'in terms of accurate flow profiles' would be finer than mesh 2; however, in order to evaluate the influence of this mesh error on tritium permeation fluxes, the scope of the analysis, the tritium post-process has been applied to the existing results.

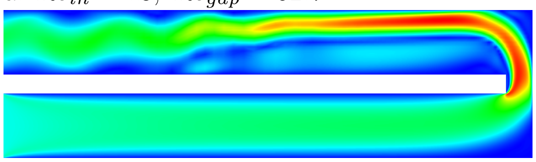
The obtained tritium concentration profiles, for each mesh (figure 3), may indicate that a finer mesh in the core channel is needed for a detailed tritium profile. Comparing each profile, the average relative error between meshes 0 and 2 is 9.7 % and between meshes 1 and 2 is 6.3 %. When tritium concentration in boundary layers is compared, by means of tritium permeation through walls (table 1), the permeation fluxes are accurate enough even for mesh 0. Thus, if permeation flux is the critical aspect to be quantified, mesh 0



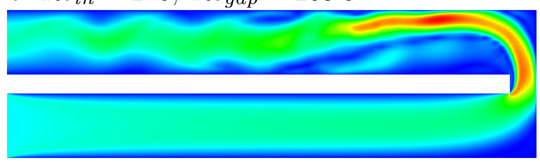
a: $Re_{in} = 48,\ Re_{gap} = 52.7$



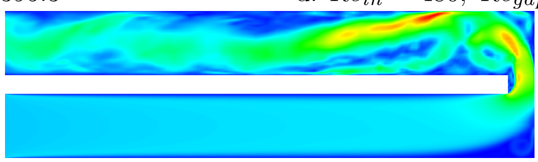
b: $Re_{in} = 240,\ Re_{gap} = 263.6$



c: $Re_{in} = 360,\ Re_{gap} = 395.3$



d: $Re_{in} = 480,\ Re_{gap} = 527.1$



e: $Re_{in} = 4795,\ Re_{gap} = 5271$

Figure 2: Velocity maps as a function of Reynolds number. Under HCLL-TBM specifications, corresponding to case *d*, the pure hydrodynamic flow is unstable. Simulated with mesh 2.

is fine enough. These results support the use of mesh 0 for further analysis.

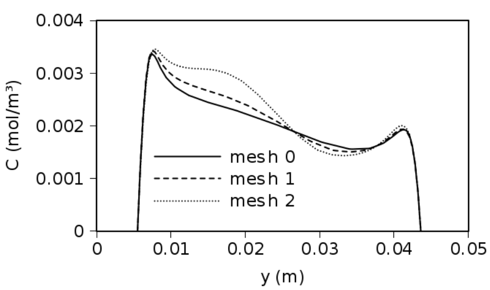


Figure 3: Tritium concentration in y axis in the middle of the outlet channel. $Re_{in} = 48$

Parameter	mesh 0	mesh 1	mesh 2
$G_C\ [mol/s]$	$9.3 \cdot 10^{-9}$	$9.3 \cdot 10^{-9}$	$9.3 \cdot 10^{-9}$
$J_H\ [mol/s]$	$1.2 \cdot 10^{-10}$	$1.3 \cdot 10^{-10}$	$1.3 \cdot 10^{-10}$
$J_S\ [mol/s]$	$7.5 \cdot 10^{-10}$	$7.5 \cdot 10^{-10}$	$7.6 \cdot 10^{-10}$
$J_{out}\ [mol/s]$	$8.5 \cdot 10^{-9}$	$8.5 \cdot 10^{-9}$	$8.4 \cdot 10^{-9}$
$C_{out}\ [mol/m^3]$	$2.3 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$
$\frac{J_H+J_S}{G_C}$	9.3 %	9.4 %	9.5 %

Table 1: Tritium permeation for the pure hydrodynamic simulation. $Re_{in} = 48$

All the abovementioned results have been obtained by means of pseudo-transient simulations, what is only correct if a steady solution is known to exist. In case of instabilities, oscilations or turbulence, the full transient simulation (converged at each time step) is required. Hence, both pseudo-transient and full transient simulations have been compared for the channel at $Re_{in} = 480$ (case *d* of figure 2) and mesh 0. Results show that both the periodic nature of the solution and the order of magnitude of velocity are conserved for each simulation, but the period of the oscillation is modified. Thus, for a detailed quantification of the period of the oscilation and hence, the vibrations that the flow provides to the structure, a full transient simulation would be required.

4 MHD WITH ELECTRICALLY INSULATED WALLS

In HCLL/ITER channels, walls are slightly electrically conductive. In CFD calculations, if a finite conducting wall has to be considered, as the thin boundary layer theory [11] is not valid in bends, the coupling of fluid and solid regions has to be implemented. At present, the code does not account for fluid-solid coupling and the most conservative hypothesis of perfectly insulating walls is considered. This hypothesis is the most conservative one in terms of tritium permeation fluxes as the fluid velocity in boundary layers is smaller than with conductive walls and, correspondingly, tritium concentration and permeation are higher.

Under HCLL/ITER specifications ($Ha_a = 1740$) and considering perfectly insulated walls, simulation results show how the Lorentz force is able to stabilize the oscillating flow obtained at $Re_{in} = 480$. The stabilized flow is 2D except for Hartmann boundary layers. Convergence evolution for different simulation strategies show that mesh 1 with pseudo-transient simulation is able to obtain accurate results, with less than 1.6 % error in velocity profiles.

When tritium concentration is analyzed at steady state (figure 4), it seems necessary to refine the mesh in side boundary layers if peak concentration has to be determined accurately. Inaccuracy in calculating the peak value affects directly permeation flux values as shown in table 2, where obtained permeation fluxes are 6.0 % for mesh 0 and 6.5 % for mesh 2. However, the maximum relative error between meshes 0 and 2 is 3.6 % and between meshes 1 and 2 is 1.8 %, which are sufficiently small values to consider solution with mesh 0 as acceptable.

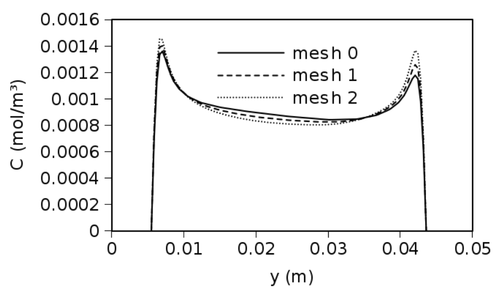


Figure 4: Tritium concentration in y axis in the middle of the outlet channel. MHD with $Re_{in} = 480$

Parameter	mesh 0	mesh 1	mesh 2
G_C $[mol/s]$	$9.3 \cdot 10^{-9}$	$9.3 \cdot 10^{-9}$	$9.3 \cdot 10^{-9}$
J_H $[mol/s]$	$5.5 \cdot 10^{-11}$	$5.6 \cdot 10^{-11}$	$5.6 \cdot 10^{-11}$
J_S $[mol/s]$	$5.1 \cdot 10^{-10}$	$5.3 \cdot 10^{-10}$	$5.5 \cdot 10^{-10}$
J_{out} $[mol/s]$	$8.8 \cdot 10^{-9}$	$8.8 \cdot 10^{-9}$	$8.7 \cdot 10^{-9}$
C_{out} $[mol/m^3]$	$1.1 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$
$\frac{J_H+J_S}{G_C}$	6.0 %	6.3 %	6.5 %

Table 2: Tritium permeation for MHD case, $Re_{in} = 480$

5 HEAT TRANSFER MHD

Based on previous results, all MHD thermofluid simulations have been carried out with mesh 0 and using a full transient treatment.

As a preliminary study and in order to see the thermal source effect on temperature field, the case with zero heat expansion coefficient is analyzed. Temperature field shows two hot spots next to the bend, one in the inlet channel and the other in the outlet channel.

Parameter	mesh 0
G_C $[mol/s]$	$9.3 \cdot 10^{-9}$
J_H $[mol/s]$	$6.7 \cdot 10^{-11}$
J_S $[mol/s]$	$5.7 \cdot 10^{-10}$
J_{out} $[mol/s]$	$8.7 \cdot 10^{-9}$
C_{out} $[mol/m^3]$	$1.2 \cdot 10^{-3}$
$\frac{J_H+J_S}{G_C}$	6.8 %

Table 3: Tritium permeation for heat transfer MHD case. $Re_{in} = 480$

The maximum temperature difference is about 3.5 degrees, which is in accordance with the temperature difference evaluated using the thermal source term. The temperature results are clearly 3D.

Once the estimated temperature gradient is known, next step is the complete coupling with heat deposition, hence with $Gr_r = 5.21 \cdot 10^9$. The solution shows vortex production in the inlet due to Rayleigh-Bénard instability, and steady vortex in the bend and outlet, as shown in figure 5. The temperature field is clearly 3D while vortex are stretched in z axis, along magnetic field lines.

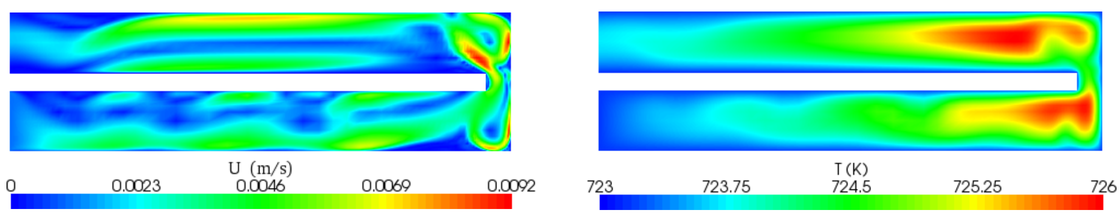


Figure 5: Velocity and temperature field for MHD case with $Re_{in} = 480$ and heat deposition. Results obtained with mesh 0 and Boussinesq hypothesis.

When tritium concentration is analyzed, results show a high concentration zone in the outlet channel, corresponding to the existing vortex. The existance of this high concentration zone increases tritium inventories in HCLL channels.

Obtained tritium permeation values exposed in table 3 do not differ substantially from the ones obtained without heat deposition (table 2). Nevertheless, for a deep insight more advanced heat boundary conditions in the wall should be analyzed as, for example, variable heat flux or the influence of fluid-solid coupling.

6 CONCLUSIONS

In the present work, simplified C-shaped channels are simulated under HCLL-ITER specifications.The flow appears to be very complex and, in order to get the origin of this complexity, the phenomenon physics has been decoupled and analyzed.

When the pure hydrodynamic case is studied, a periodic flow is observed in the outlet channel. The origin of such oscillations is the jet produced in the bend and its corresponding boundary layer detachment. This result is relevant for module structure design considering the first phase of ITER experiment and also some real transients.

Under ITER magnetic field conditions, with $Ha_a \sim 1740$, the resulting MHD flow is steady. However, when thermal deposition is considered, the Rayleigh-Bénard instability generates vorticity at the inlet channel and, as the flow travels through the simplified module, faster vortices appear in the gap region and in the outlet channel due to buoyancy forces. All vortices are stretched through magnetic field lines. The existence of these vortices is of crucial interest for tritium inventories prediction and HCLL design.

REFERENCES

[1] M-J. Ni, R. Munipalli, P. Huang, N.B. Morley, and M.A. Abdou. A current density conservative scheme for incompressible MHD flows at low magnetic Reynolds number. Part II: On an arbitrary collocated mesh. *Journal of Computational Physics*, 227(1):205–228, 2007.

[2] C. Mistrangelo and L. Bühler. Influence of helium cooling channels on magnetohydrodynamic flows in the HCLL blanket. *Fusion Engineering and Design*, 84:1323–1328, 2009.

[3] F. Gabriel, Y. Escuriol, F. Dabbene, O. Gastaldi, J.F. Salavy, and L. Giancarli. A 2D finite element modelling of tritium permeation for HCLL DEMO blanket module. *Fusion Engineering and Design*, 82:2204–2211, 2007.

[4] OpenCFD Ltd. *http://www.openfoam.org*, 2004.

[5] P.A. Davidson. *An introduction to magnetohydrodynamics*. Cambridge texts in applied mathematics, 2001.

[6] E. Mas de les Valls and L. Batet. Transient algorithm for low magnetic Reynolds numbers. Validation. *MHD workshop: MHD fundamentals, from liquid-metals to astrophysics*, Brussels, 14-16 April 2008.

[7] E. Mas de les Valls, F. Gabriel, C. Moreno, J.A: Jiménez, L. Batet, and L.A. Sedano. Boundary layer analisys for coupled mixed convection and MHD flow on tritium permeation in ITER HCLL TBM c-shaped channels. *25th Symposium on Fusion Technology (SOFT 2008)*, Rostock, September 2008.

[8] E. Mas de les Valls, J. Fradera, L. Batet, and L.A. Sedano. Desarrollo de herramientas computacionales de simulación acoplada de la MHD y el transporte de tritio en los canales de ITER HCLL. *34 Reunión Anual de la Sociedad Nuclear Española*, Murcia, Octubre 2008.

[9] G. Rampal and G. Aiello. Design and analyses of the HCLL TBM including design of supporting system and instrumentation integration. report DM2S,

SEMT/BCCR/RT/06-004/A. Technical report, CEA, Direction de l'nergie Nuclaire, 2006.

[10] E. Mas de les Valls, L.A. Sedano, L. Batet, I. Ricapito, A. Aiello, O. Gastaldi, and F. Gabrfiel. Lead-lithium eutectit material database for nuclear fusion technology. *Journal of Nuclear Materials*, 376(3):353–357, 2008.

[11] U. Müller and L. Bühler. *Magnetofluiddynamics in Channels and Containers*. Springer, 2001.