RESEARCH IN PLASMA PHYSICS AND FUSION NUCLEAR TECHNOLOGY IN THE DEPARTMENT OF PHYSICS OF UPC

Activities of Advanced Nuclear Technologies (ANT) Research Group of Universitat Politècnica de Catalunya (UPC) in the field of Nuclear Fusion include Plasma Physics and Magneto-Hydrodynamics (MHD), MHD of liquid metals, diverse applications of Computational Fluid-Dynamics (CFD) (among them, those related to tritium transport modelling), development of ad-hoc one-dimensional tritium migration modelling tools (aimed at inventory control) and the use of thermal-hydraulic system codes to model the Balance-of-Plant. Most of these activities are framed within the EUROFusion program, and are carried out in collaboration with Spanish and international research institutions and experimental fusion devices, also with ITER.

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Advanced Nuclear Technologies (ANT) Research Group of Universitat Politècnica de Catalunya (UPC) has diverse fields of activity; research lines in the field of Nuclear Fusion are summarized in this article. Activities of ANT group in this field encompass from Plasma Physics to Control Engineering, including studies of plasma instabilities, fluid-dynamics and heat and mass transfer analyses; and relate to a variety of subsystems, from the plasma itself to the ancillary systems, including the plasma facing components and the Breeding Blankets. Breeding Blankets are complex components that perform three functions in a fusion reactor: shielding the magnets, recovering the heat produced in the plasma, and producing tritium, which is one of the fuels of fusion. Most of ANT group activities are framed within the EUROFusion program (www.euro-fusion.org), in close collaboration with existing experimental fusion devices and with ITER, the large international R&D fusion project (www.iter.org).

PLASMA PHYSICS AND MHD

Fusion nuclear reactions keep Sun shining and radiating energy. One possible way to achieve sustained nuclear fusion on the Earth is to confine a plasma formed by very high temperature ionized particles by means of a magnetic field. Magnetic confinement is essential, because no material can withstand the high temperatures reached in a fusion plasma. A toroidal configuration called 'Tokamak', where the magnetic field has a torus (doughnut-shape) structure in order to close the magnetic field lines, has been adopted in the furthest developed magnetic confinement devices.

Fusion on Earth is feasible; however, it is a demanding task to achieve a sufficiently good confinement for a 'burning plasma' due to various kinds of plasma instabilities. One of the critical unresolved problems is MHD (Magneto-Hydro-Dynamics) instabilities at the plasma boundary, called Edge Localized Modes (ELMs). ELMs are equivalent to solar flares. Both, solar flares and ELMs, which erupt (the former) from the surface of the Sun or (the latter) from magnetically confined plasma, release large quantities of energy (relatively speaking). These ELM eruptions are potentially harmful since they could damage the plasma facing components (reactor walls). One of the methods of ELM mitigation is the injection of small pellets (deuterium ice cubes) to induce small ELMs before large ELM occurs. The technique is experimentally proved, but the theoretical understanding of it needs further progress. To better understand the physical processes involved in ELM control by pellet injection, the three-dimensional non-linear MHD simulation code JOREK (www.jorek.eu) is being used in order to improve the physics basis for the application of this ELM control method for fusion plasmas.

JOREK [Huysmans 2007, Czarny 2008] is the unique code that has the capability to perform the non-linear 3D MHD simulations required to carry out the research. The code takes into account the region between the

INVESTIGACIÓN EN FÍSICA DE PLASMA Y TECNOLOGÍA NUCLEAR DE FUSIÓN EN EL DEPARTAMENTO DE FÍSICA DE LA UPC

Las actividades del Grupo de Investigación en Tecnologías Nucleares Avanzadas (ANT) de la Universitat Politècnica de Catalunya (UPC) en el campo de la Fusión Nuclear incluyen Física y Magneto-Hidrodinámica (MHD) del Plasma, MHD de metales líquidos, varias aplicaciones de la Fluido-Dinámica Computacional (incluyendo el modelado del transporte de tritio), el desarrollo de herramientas unidimensionales ad-hoc para modelar la migración de tritio (dirigidasal control de inventario) y el uso de códigos termohidráulicos de sistema para modelar el Balance de Planta. Muchas de estas actividades se enmarcan en el programa EUROFusion, y se realizan en colaboración con instituciones de investigación, españolas e internacionales, e instalaciones de fusión experimentales, también con ITER.

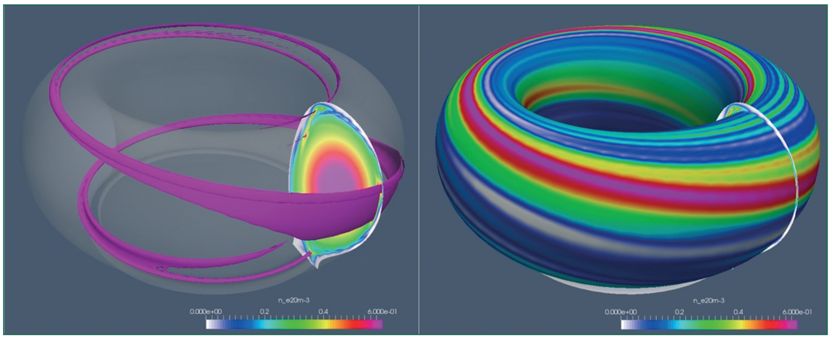

Figure 1. (Left panel) The plasma perturbation profile caused by a pellet injection in a tokamak plasma. (Right panel) The density profile on the separatrix during the pellet triggered ELM.

main plasma and the wall with its specific magnetic geometry, which is not easy to manage. This part of the plasma geometry is essential for the simulation of ELMs. The pellet ablation modelling which has been implemented in JOREK [Futatani 2014] is realistic, i.e. moving pellet, time-varying, toroidally and poloidally localized, adiabatic density source. The interaction of the physics governing pellet ablation and the nonlinear three-dimensional MHD dynamics is very complex, as shown in Figure 1. The JOREK code, which solves this complex physics self-consistently, has been used in a first instance to model experiments at the DIII-D tokamak (San Diego, US) in which pellet injection was successfully applied to trigger ELMs [Futatani 2014]. This allowed the identification of the key physical processes and the estimation of the power flux to the materials surrounding the plasma.

In parallel, theoretical research of stellarator plasmas via 3D non-linear MHD pellet modelling is carried out. Stellarator is another type of fusion device which exploits strangely-shaped magnets that is hard to build but potentially easier to operate. Realistic pellet modelling has been implemented by S. Futatani in the MEGA code [Todo 2010, Ichiguchi 2015, Futatani 2018]. Figure 2 shows the pellet particle propagation in a stellarator plasma.

FLUID DYNAMICS APPLIED TO THE BREEDING BLANKETS

In a fusion reactor, Magneto-Hydro-Dynamics is not only present in plasmas. One of the Breading Blanket designs proposed for DEMO within the EUROFusion program is the Dual Coolant Lithium Lead (DCLL) [Rapisarda 2016], where the system is cooled by pressurized helium and a liquid metal (LiPb) which, being electrically conductive, presents MHD effects.

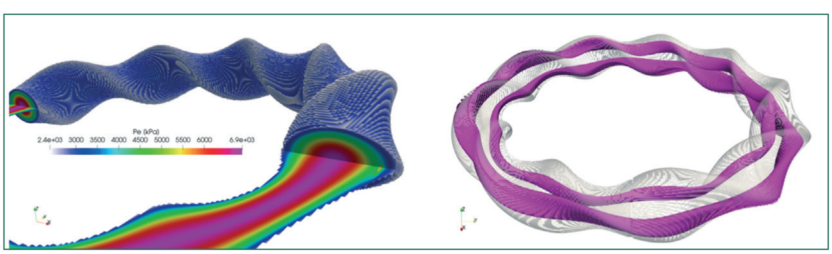

Figure 2. (Left panel) The plasma pressure profile in a stellarator plasma. (Right panel) The pressure perturbation profile caused by a pellet injection in a stellarator.

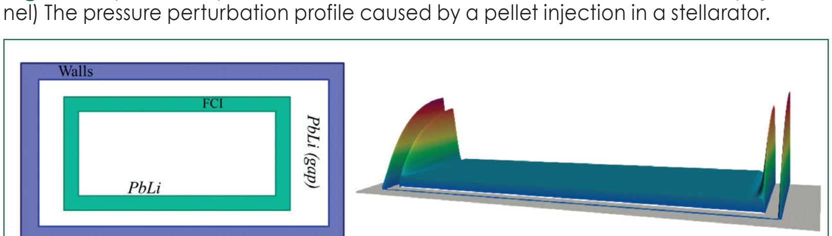

Figure 3. (Left panel) Sketch of the cross-section of a DCLL channel with FCI (not to scale). (Right panel) Corresponding velocity profile for Hartmann number Ha=3000 (this number is the ratio of magnetic to viscuos forces). The complex MHD flow profile can be observed: velocity jets appear at both sides of the FCI aligned with the magnetic field, whereas an almost uniform velocity exists in the bulk region.

ANT group uses OpenFOAM (www.openfoam.com) to understand the behaviour of this kind of systems. OpenFOAM is an open source Computational Fluid-Dynamics (CFD) software, which has been successfully used by ANT in the past to model this kind of systems after implementing MHD capabilities on it [Mas de les Valls 2011] [Mas de les Valls 2012].

As an example of application, a channel of the DCLL has been analysed with a model that includes the fluid, the metallic wall surrounding it and the so-called flow channel insert (FCI), made of insulating material. Pressure loses in the lithium lead flow due to MHD effects increase with the velocity of the fluid. Moreover, when the fluid is surrounded by conducting walls, the electric currents can flow easily through these walls yielding to even higher MHD pressure loses. FCI allows to separate the bulk of the fluid from the conducting walls, greatly reducing the pressure losses and improving the circulation of the coolant. Figure 3 shows the effect of the FCI on the velocity profile. The analyses done permit to find out what are the effects of a FCI deformation on the pressure drop, or what are the critical aspects (e.g. temperature hotspots) of a possible FCI rupture or perforation, allowing for a short-circuit between the bulk flow in the channel and the flow in the gap between the FCI and the channel walls.

Fluid-dynamic analyses do not limit to the MHD inside the breeding blanket channels: e.g. OpenFOAM has been applied as well to quantify the pressure drop and the flow distribution imbalances in DCLL manifolds.

Of special interest is the analysis of tritium migration within the several fluids and through the structural materials. Tritium transport modelling features have been added to OpenFOAM. Tritium is modelled as a passive scalar, i.e. its presence can be understood as not affecting other parameters like temperatures and velocities (because its concentration is relatively low), but on the contrary, temperatures and velocities affect tritium concentration, as implemented in the model.

TRITIUM INVENTORY CONTROL

Viability of Nuclear Fusion as a sustainable source of energy depends, among other conditions, on the capability of tritium breeding. Tritium will be formed in the blanket surrounding the plasma by means of neutron-lithium reactions. Radiation protection requirements will pose strong limitations to the environmental emissions of tritium, which in turn obliges, both, to keep a low tritium inventory within the fusion plant internals and ancillary systems (in order to minimize migration outwards), and to maintain a precise inventory control.

ANT group at UPC is working towards the development of a dynamic inventory control strategy which relies on the achievement (within the next decade) of an active tritium sensor, combined with validated predictive modelling tools. ITER will operate with a static tritium control scheme, i.e. time-to-time mass balance checks in devoted measuring systems, where tritium will be conveyed.

The robustness of the dynamic control of the tritium inventory will rest in three pillars; the first two have already been introduced above: first, the availability of probes able to measure in a continuous form and with sufficient accuracy the tritium concentration is streams and atmospheres; second, the ability of the available numerical tools to perform precise tritium migration predictions. The third pillar is an adequate Control, Data Access and Communication (CODAC) system.

Main activity ongoing at UPC in this context so far has been the development of transport models for tritium and other hydrogenated species, both for CFD tools like OpenFOAM and for ad-hoc one-dimensional codes. These tools help understand the relative importance of the various migration phenomena that tritium undergoes, under different chemical forms, in the plant's subsystems and in their respective enveloping enclosures.

Tritium sensors are being developed at the Institut Quimic de Sarrià (IQS) [Llivina 2014a, Llivina 2014b]. with whom ANT group maintains a close collaboration.

As a first step towards the development of a control system, simple migration models (similar to transfer functions) describing system parts and sensors are being tested, using more sophisticated models as a benchmark. The ultimate goal is to dispose of a monitoring system able to track the tritium concentration in the plant by means of overlapping system-wide predictions with localized measurements.

ENERGY CONVERSION

Among the possible options to convert thermal to electric power in a commercial Fusion Nuclear Plant, a supercritical CO_2 Brayton cycle is being designed for DEMO plant by Comillas Pontifical University [Linares 2018], with whom UPC is partnering within EUROFusion. This type of cycle is the most efficient for the ranges of temperature to be found in the primary coolant of future fusion reactors.

ANT group is exploring the capabilities of RELAP5-3D to model this kind of circuits (i.e., helium and liquid metal primary loops, CO_2 power cycle and water) in order to design a control strategy for the eventual operation of a power plant. RELAP5-3D (relap53d.inl.gov) is a system code allowing the dynamic simulation of thermal-hydraulic systems (in this case including compressors, turbine and special heat-exchangers), which is useful to characterize the timely response of a system in front of perturbations. A number of control features have been designed for the simulated plant: flow, pressure and temperature controllers, for instance. The robustness of the code makes it suitable for sensitivity analyses that can be used to adjust control parameters (e.g. valve opening speed) and other design features. The final goal is to maximize the electric output of the plant while assuring that all the parameters (pressures, temperatures) are within tolerances.

FUTURE WORK

The research of ELM control will be continued to apply other existing and/or future fusion reactors, such as JET (EU machine located in UK), ASDEX Upgrade (Germany), JT-60SA (Japan) and ITER. The physics model will be improved to be able to compare with experimental results not only in qualitative but also in quantitative manner. This step is important to predict the plasma events for the fusion reactor operation.

MHD research for stellarator will be also expanded and will be applied to TJ-II (Spain), LHD (Japan) and Wendelstein 7-X (Germany).

Breeding blanket liquid metal MHD effects studies will continue in order to enhance the understanding of 3D geometric singularities' effect on pressure drop. Sensitivity of tritium migration phenomena to different flow regime conditions will be studied as well.

As for tritium inventory control modelling, an Industrial Doctorate has been launched recently with the company Inprocess, which is expected to represent a significant step forward in order to prove the feasibility of the proposed dynamic control strategy.

Finally, within EUROFusion program, UPC will upgrade the compressor model it has been using so far, using data generated by Comillas; and will continue updating the RELAP5-3D models developed so far to account for recent layout improvements.

In summary, ANT research group has a variety of activities, in the field of nuclear physics and engineering, with a good projection into the future in collaboration with Spanish and international research institutions and experimental laboratories. ■

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