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Dynamic thermal-hydraulic modelling of the EU DEMO HCPB breeding blanket cooling loops

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A B S T R A C T

A global, system-level thermal-hydraulic model of the EU DEMO tokamak fusion reactor is currently under development and implementation in a suitable software at Politecnico di Torino, including the relevant heat transfer and fluid dynamics phenomena, which affect the performance of the different cooling circuits and components and their integration in a consistent design. The model is based on an object-oriented approach using the Modelica language, which easily allows to preserve the high modularity required at this stage of the design. The first module of the global model will simulate the blanket cooling system and will be able to investigate different coolant options and different cooling schemes, to be adapted to the different blanket systems currently under development in the Breeding Blanket (BB) project. The paper presents the Helium-Cooled Pebble Bed (HCPB) module of the EU DEMO blanket cooling loops system model. The model is used to compare different schemes for the cooling of the different components of the HCPB BB, and to suggest improvements aimed at optimizing the pumping power required by the cooling system. The model is then used to analyse a pulsed scenario, characteristic of the EU DEMO operation.

1. Introduction

Within the framework of the Horizon 2020 EU fusion roadmap (Romanelli et al., 2012), the conceptual design of a European Demonstration Fusion Power Reactor (EU DEMO) is under development. After ITER, this device shall demonstrate the operation in a closed fuel cycle (i.e. tritium self-sufficiency) and the production of net electricity. The development of a global thermal-hydraulic model of the EU DEMO tokamak has been launched by the EUROfusion Project Management Unit (PMU) to simulate the cooling loops of the main in-vessel components, including the ex-tokamak parts. The model shall be based on an object-oriented approach, in order to be sufficiently modular to follow-up the design development.

The development of this model, which will be the first system-level thermal-hydraulic model to be developed for the power cycle of DEMO, has started in 2015 in the Energy Department at Politecnico di Torino. Up to now, engineering modelling efforts for DEMO mainly focused on other kind of system-level analyses (e.g. global thermal analysis (Costa Garrido et al., 2015)), or on component-level CFD analyses, see e.g. (Arbeiter et al., 2016). For ITER, some system-level analyses have been carried on for the BB cooling system and related to safety studies for the EU (Boccaccini et al., 2007), Korean (Ahn et al., 2009) and Chinese (Wang et al., 2013) Test Blanket Modules (TBMs), as well as analyses of the thermal-hydraulics of other systems (e.g. the superconducting magnet system (Savoldi Richard et al., 2010),); also for ITER, of course, extensive component-level CFD analyses were performed (Zanino et al., 2014; Savoldi Richard et al., 2013).

The first module of the global model will allow the transient simulation of the BB cooling system, which has to remove ~80% of the total thermal power produced in the reactor and to integrate it into a power generation system. This model shall be able to investigate different coolant options and different cooling schemes, in order to simulate the different blanket systems currently under development in the EUROfusion Breeding Blanket Work Package (WPBB), determining the resulting thermal-hydraulic and thermodynamic performances, depending on different heat load distributions on the plasma facing components.

In this paper we present the development and first application of a version of the first module of the code, devoted to the Helium-

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Nomenclature

A	Area of channel cross section [m^2]
c_v	Specific heat at constant volume [J/(kg K)]
D_h	Hydraulic diameter [m]
e	Specific energy [J/kg]
f	Fanning friction factor
h	Specific enthalpy [J/kg]
K	Localized pressure loss coefficient
l	Length [m]
$\dot{m}$, dm/dt	Mass flow rate [kg/s]
Nu	Nusselt number
p	Pressure [Pa]
Δp	Pressure drop [Pa]
Pr	Prandtl number
$\dot{Q}$	Heat load [W]
Re	Reynolds number
T	Temperature [K]
t	Time [s]
V	Volume [m^3]
v	Velocity [m/s]

Greek

γ	Heat transfer coefficient [W/(m^2 K)]
ρ	Density [kg/m^3]

Subscripts

i	Volume index
m	Metal structures
in	Inlet
out	Outlet

Acronyms

BB	Breeding Blanket
BC	Boundary Condition
BM	Breeding Module
BSS	Back Supporting Structure
BZ	Breeding Zone
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CP	Cooling Plate
DIV	Divertor
EU DEMO	European Demonstration Fusion Power Reactor
FV	Finite Volume
FW	First Wall
HCPB	Helium-Cooled Pebble Bed
HCPB-D	HCPB-Detached
HCPB-I	HCPB-Integrated
HCPB-S	HCPB-Separated
HIP	Hot Isostatic Pressing
HTC	Heat Transfer Coefficient
HX	Heat eXchanger
IB	Inboard
OB	Outboard
OOP	Object-oriented programming
PHTS	Primary Heat Transfer System
PMU	Project Management Unit
SG	Steam Generator
TBM	Test Blanket Module
WCLL	Water-Cooled Lithium Lead
WPBB	Work Package Breeding Blanket

Cooled Pebble Bed (HCPB) BB concept. Another version, devoted to the Water-Cooled Lithium Lead BB concept, is currently under development.

2. The HCPB cooling circuit

For the development of this model, the 2014 design of the HCPB BB (Norajitra et al., 2015), which is shortly described in the following, has been considered; anyway, thanks to the modular

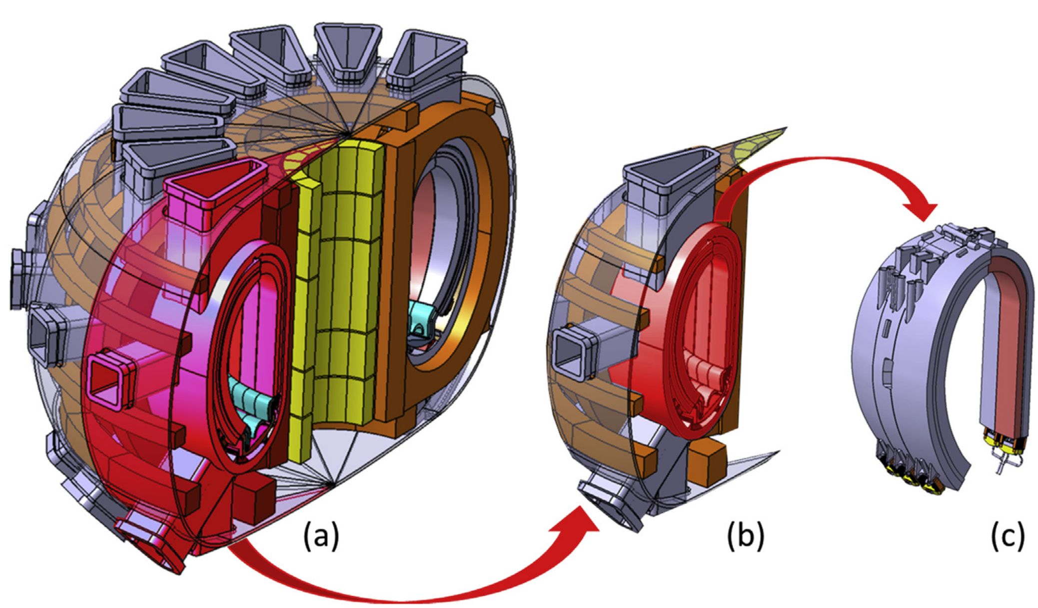

Fig. 1. (a) Sketch of half of the 2014 EU DEMO tokamak, divided in 8 sectors; (b) single sector, (c) 5 blanket segments, three outboard and two inboard, constituting the single sector. Adapted from (Boccaccini, 2014).