Fusion Engineering and Design 124 (2017) 1233–1236

Fusion Engineering and Design
journal homepage: www.elsevier.com/locate/fusengdes

Preliminary safety analysis of LOCAs in one EU DEMO HCPB blanket module

Xue Zhou Jin

Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

HIGHLIGHTS

- Three LOCA sequences in one EU HCPB blanket module (2014) have been investigated.
- MELCOR 1.8.6 for fusion is used for the simulation.
- Transient results for different LOCA scenarios have been discussed.

ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form 10 February 2017
Accepted 14 March 2017
Available online 27 March 2017

Keywords:
DEMO safety
HCPB
LOCA
MELCOR

ABSTRACT

Safety analysis for the design basis accident (DBA) is essential to support DEMO blanket concept design. It is necessary to study the pressure behaviour in the blanket and the connected systems during the loss of coolant accident (LOCA) in a blanket module, as well as the temperature evolution in the coolant flow and the associated structures. For the Helium Cooled Pebble Bed (HCPB) blanket concept (version 2014) three representative accidental sequences of LOCA have been simulated using system code MELCOR 1.8.6 for fusion. The LOCA is identified to be the failure of cooling channels in the stiffening grid, in the FW or in the breeder unit. Simulation results are discussed in this paper.

1. Introduction

Helium Cooled Pebble Bed (HCPB) blanket concept is one of the DEMO (Demonstration Power Plant) blanket concepts running for the final design selection. It is necessary to study the pressure behaviour in the blanket and the connected systems during the loss of coolant accident (LOCA) in a blanket module, as well as the temperature evolution in the coolant flow and the associated structures. Three representative accidental sequences for the design basis accident (DBA) have been selected. The HCPB design version 2014 is adopted as the reference design [1]. MELCOR 1.8.6 for fusion is used for the LOCA simulation [2]. For the cooling circuit redundancy of the primary heat transfer system (PHTS) two separate cooling loops are modelled. The accident is initialized during the normal operation at the steady state. Steady state and transient results are presented in this paper. Impact of MELCOR versions and the break size of the FW cooling channels are discussed as well.

2. Relevant design for the LOCA analysis

For DEMO design 2014 with 16 toroidal fields and a fusion power of 1572 MW [3] the whole HCPB blanket system is subdivided into 16 sectors [1]. Each blanket sector comprises three outboard (OB) and two inboard (IB) segments, leading to a total number of 48 OB and 32 IB segments respectively. Each IB or OB segment contains 6 blanket modules; hence one sector has totally 30 blanket modules. The equatorial module in the OB (OB4) is selected as the affected reference module for the LOCA analysis. It has an ITER-like HCPB TBM design with modular breeder unit (BU) embedded in the stiffening grids (SGs) that consist of horizontal grids (HGs) and vertical grids (VGs) (Fig. 1). The top and bottom of the module is covered by caps. A set of BUs for tritium production is located behind the first wall (FW), containing lithium orthosilicate (Li_4SiO_4) as breeding material and Be as neutron multiplier in form of pebble beds. The FW has to absorb high heat fluxes from the plasma and it is cooled down with helium in counter flow for the redundancy. After the FW one flow goes to the SG and caps, while another flow goes to the BUs separately. If one cooling circuit fails due to the LOCA or loss of flow accidents (LOFA), the half of the FW is still cooled by another one to avoid rapid temperature increase on the FW. The

---

E-mail address: jin@kit.edu

http://dx.doi.org/10.1016/j.fusengdes.2017.03.082

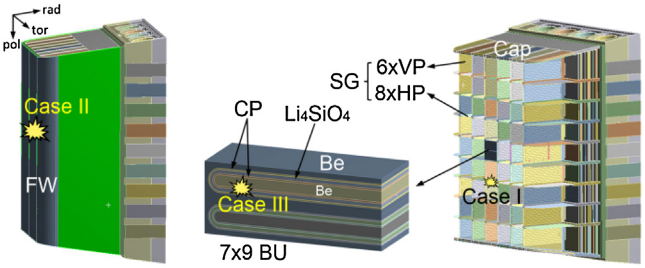


Fig. 1. OB4 of HCPB 2014 and LOCA locations.

design data for OB4 are: mass flow rate (ṁ) of 6.323 kg/s, temperature of 300 °C and pressure of 8 MPa at the blanket inlet, 500 °C at the blanket outlet, the surface heat flux of 500 kW/m^2, and the thermal power of 6.572 MW. The cross section of the FW channel is 10 mm × 15 mm. EUROFER is used as structural material and tungsten as plasma facing component (PFC) with a thickness of 2 mm. The produced tritium is purged away from Li_4SiO_4 pebble beds in a separate helium purge gas (PG) system operated at a low pressure of 0.2 MPa.

A layout option of the PHTS is selected from [6], for which each cooling train is an independent system serving two of 16 sectors. Therefore each cooling loop has a cooling ability for 60 blanket modules and each sector is supplied by two separate cooling loops for the cooling circuit redundancy.

The free volume of the vacuum vessel (VV) is designed with 2243 m^3 [3,5]. The VV-PHTS using water as coolant is not considered in this study for the temperature behaviour of the VV. An expansion volume (EV) is required in use of gas coolant in the PHTS to assure the VV integrity. It is defined at the environment temperature of 20 °C, the subatmospheric pressure of 0.09 MPa, and the volume of 9.1e4 m^3 in [4]. Temperature of the VV, PHTS and PG are assumed to be the same as the blanket inlet temperature of 300 °C.

3. LOCA scenarios

A LOCA can be caused by rupture/leak of sealing weld or cooling channels inside the blanket box. Concerning cooling channel locations in the HCPB blanket design, which are identified as the FW, the horizontal and vertical plates (HP, VP) of the SG, and the cooling plate (CP) of the BU, three representative accidental sequences have been selected (Fig. 1): case I in-box LOCA to the breeding blanket (BB) with failure of one HP in the SG; case II in-vessel LOCA with failure of 10 FW channels; and case III in-box LOCA to the PG system with failure of one CP in the BU.

4. MELCOR modelling, simulation and results

MELCOR 1.8.6 for fusion is selected for the LOCA simulation. It is improved against the previous MELCOR 1.8.2 with double precision and helium properties.

4.1. Modelling and simulation

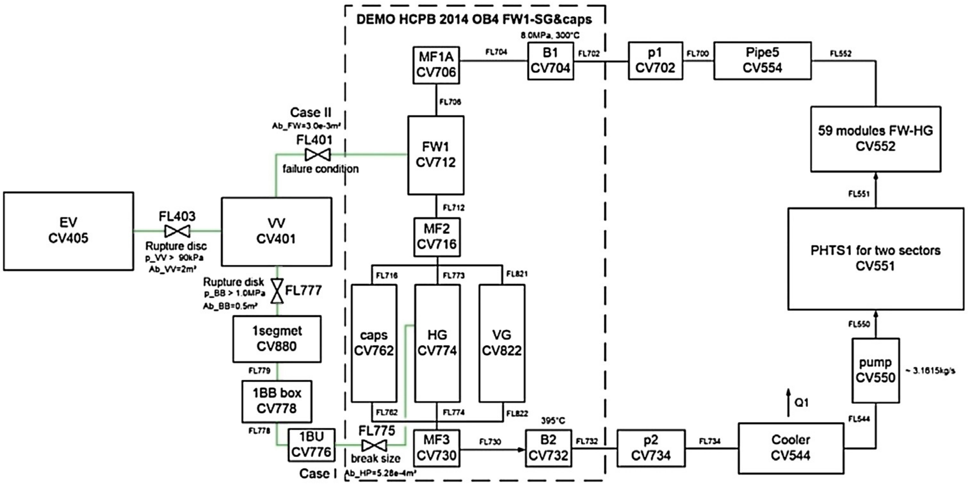
Fig. 2 shows MELCOR nodalization for case I/II (Fig. 2(a)) and case III (Fig. 2(b)). All components are modelled as control volumes (CVs) connected with flow path (FL). The affected blanket module OB4 is started with its inlet pipe CV702 or CV701 and ended with the outlet pipe CV734 or CV733. 95 cooling channels of the FW are divided in 47 channels as FW1 (CV712) and 48 channels as FW2 (CV715). Caps, HG and VG are modelled with CV762, CV774 and CV822 respectively in Loop 1, while CV881 models the BU in Loop 2. Heat structures (HSs) are modelled for OB4 components such as the manifolds (MFs), the FW, the HG, the VG, the caps and the BUs considering the pebble beds volume. Convective boundary condition is applied with the heat transfer coefficient (HTC) calculated by the HS package. To avoid high FW temperature on the plasma side due to the simplified 1D-HS modelling, heat exchange to other HSs between cooling channels and on the FW rear side is modelled with MELCOR function as well. The surface heat flux is multiplied with the FW surface area facing the plasma to be surface power source of the HS. The nuclear heating [5] and the decay heat are the internal power source of the HS. The decay heat is assumed to be 1.7% of the full power. A cooler is modelled at the downstream of OB4 to remove enthalpy source that the flow is cooled down to the module inlet temperature. A pump is modelled with QUICK-CF pump model to evaluate its pressure boost. PHTS1 for 2 sectors is simplified as one CV in Loop 1 (CV551) with a volume of 133 m^3 scaled from the selected layout in [6], and PHTS2 in Loop 2 (CV571). Except the affected module all other modules are modelled in one CV (CV552 or CV572), together with the CV for the PHTS, the total helium inventory can be estimated. The roughness in FL is assumed to be 20 μm. Proper energy loss coefficients are assumed for pressure loss. Double pipe break is considered for the break size (Ab).

If LOCA occurs, helium ingresses into the blanket box, into the VV or into the PG system in case I, case II or case III respectively. In case I, failure of one HP is modelled with FL775. For the design option of the blanket box with the pressure limit of 1.0 MPa, a pressure relief system allows helium ingress into the VV (FL777) from one segment (CV880). It is assumed that if the VV pressure exceeds 90 kPa, which is below the VV pressure limit of 200 kPa, the rupture disc to the EV is opened (FL403). In case II, failure of the FW is modelled with FL401. It is assumed that all 10 FW channels fail in one flow direction. In case III, failure of the one CP in the BU is modelled with FL780. Helium flows into the free Li_4SiO_4 pebble volume of one BU firstly (CV860); then into the whole free volume of the module filled with PG (CV861); after that into one segment with 6 modules (CV862). It is assumed that the PG from 5 segments is collected in a header (CV863) which is connected to the EV via PG line and pipe in a total length of 40 m. If the PG pipe (CV865) exceeds the pressure limit of 0.5 MPa, the rupture disk to the EV (FL405) is opened.

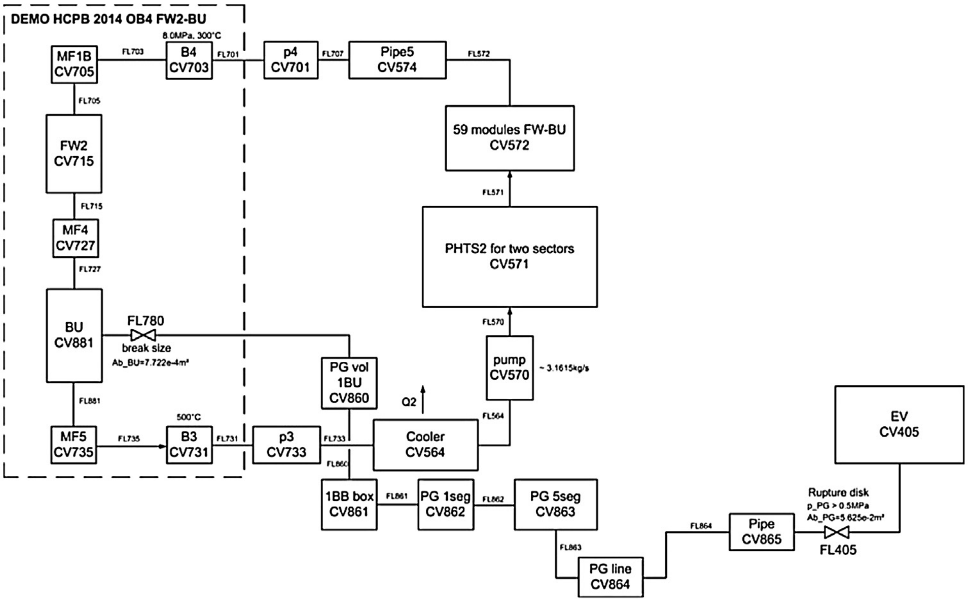
The normal operation is achieved at the steady state of 1000 s. At that time the LOCA takes place and it is simulated with a time step (dt) of 0.5 ms. The pump is assumed to be shut down in 3 s after the LOCA, while a fast plasma shutdown (FPSS) is activated in 4 s based on the FW temperature behaviour studied in [7]. A plasma disruption following the FPSS is not considered, since the plasma disruption time and the plasma surface heat flux during the disruption are not yet available in DEMO. Simulations are also carried out for different break sizes of the FW on case II. The assumed FW break size is ~6 times larger than the HP break size in case I and ~4 times larger than the CP break size in case III. In order to compare pressure and temperature behaviour with equivalent break size, scenarios with a break of one or two FW channels are simulated as well. For the failure of one channel as case IIa the break size is 3.0e-4 m^2, and it is 6.0e-4 m^2 for the failure of two channels as case IIb.

4.2. Steady state results

Table 1 shows the steady state results for Loop 1 and Loop 2. Helium inventories for the PHTS and the associated 60 modules are conservatively estimated to be 1016.7 kg in Loop 1 and 998.6 kg in Loop 2, because CV551 for PHTS1 and CV571 for PHTS2 are assumed at the blanket inlet (300 °C and 8 MPa) with helium density of ~6.63 kg/m^3. However the PHTS part at the blanket outlet (500 °C and 7.6 MPa) has a lower density of ~5.46 kg/m^3. Thus



(a) Loop 1 for case I / II



(b) Loop 2 for case III

Fig. 2. MELCOR nodalization.

Table 1
Steady state results.

Parameter			Steady state	
Loop			1	2
Inventory (kg)			1016.7	988.6
FW	Inventory (kg)		3.1617	3.1615
	$\dot{m}$ (kg/s)		7.89	8.00
	p_inlet (MPa)		172.0	89.0
	T (°C)	inlet	295.7	300.7
		outlet	364.0	372.7
		EUROFER	522.2	558.4
		PFC	564.0	592.8
SG/BU	$\dot{m}$ (kg/s)	HG/BU	1.7042	3.1615
		VG	0.6602	–
		Caps	0.7972	–
	T (°C)	He outlet	387.6	503.1
		Be	–	554.7
		Li_4SiO_4	–	632.7

the real inventory will be less than the simulation results. Detailed PHTS design is required to determine the exact helium inventory.

Different helium outlet temperatures in Loop 1 from the SG (387.6 °C) and in Loop 2 from the BU (503.1 °C) have impact on components design in two separate cooling loops of the PHTS. The FW temperature of Loop 1 (522 °C) is higher than 502 °C using RELAP5-3D and 453 °C with CFX in [7] due to low HTC calculated by MELCOR. The temperature exceeds the operating limit of 550 °C in Loop 2 (558.4 °C), because the coupling of two loops for the heat exchange of the counter flow is not investigated. Taking a packing factor of 63% for the pebble beds, beryllium and Li_4SiO_4 temperatures are controlled below their design limits of 650 °C and 920 °C respectively. For more detailed modelling the HS for single pebble should be considered.

The mass flow rate in the HG is much more than it in the VG or caps. However the mass flow distribution will not be assessed since the SG design is not optimised. In the new HCPB design 2015 the SG is removed [1].

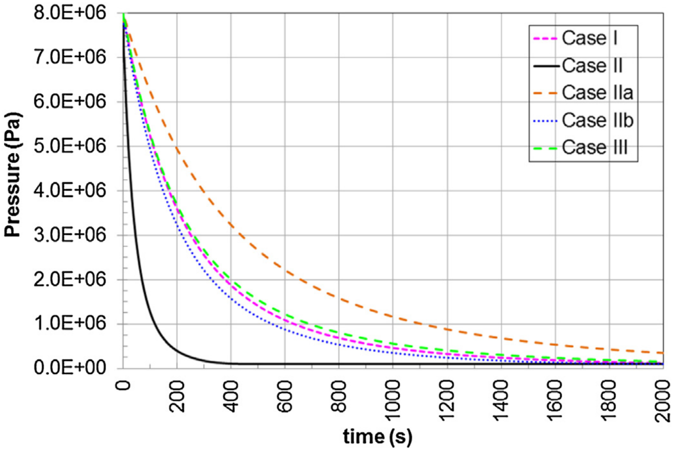


Fig. 3. Inlet pressure (CV706/CV705).

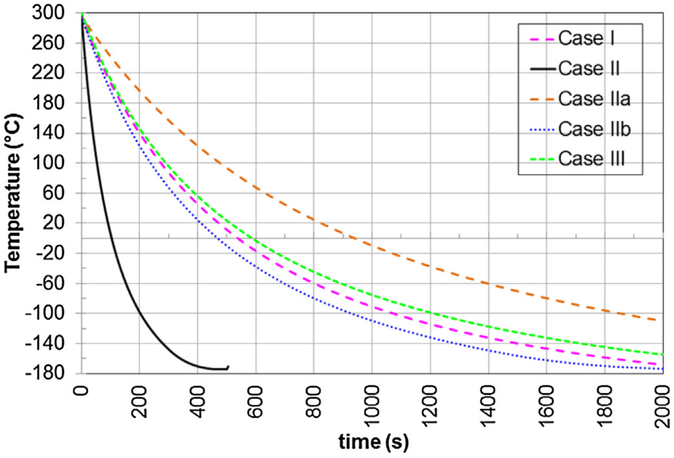


Fig. 4. Helium inlet temperature (CV704/CV703).

4.3. Transient results

Case I: the mass flow rate drops below 1 kg/s after the pump shut down. Helium ingresses into the VV at 1 s, which means that the blanket box exceeds the pressure limit of 1.0 MPa immediately. Then 37 s later helium ingresses into the EV. The FW inlet pressure drops to 1.0 MPa at 630 s and to 0.116 MPa at 2000 s (Fig. 3). The start time in Fig. 3 is reset to 0.0 for the transient. At 2000 s helium mass reaches 260 kg in the VV and 678 kg in the EV.

Case II: helium ingresses into the EV at 7.9 s. The largest break size makes the quickest pressure drop in the blanket module (Fig. 3). Small FW break size decelerates the helium loss speed, pressure drop, and temperature decrease in the affected module, and helium accumulation in the VV. Within 400 s Helium mass in the VV reaches 173 kg, 209 kg and 281 kg in case IIa, case IIb and case II respectively.

Case III: without the VV, helium ingresses into the EV at 1.4 s. The FW inlet pressure drops to 1.0 MPa at 690 s and to 0.155 MPa at 2000 s (Fig. 3). At that time helium mass in the EV is 899 kg. The PG pressure in the free Li_4SiO_4 pebble volume (CV860) reaches the first peak of 7.18 MPa at 0.5 s and the second peak of 7.284 MPa at 3.5 s. Then it drops below 1.0 MPa at 650 s These pressure peaks may have impact on the BU design.

The FPSS without plasma disruption makes temperature decrease in the fluid (Fig. 4) and structure. The largest temperature gradient is found in case II due to the quickest gas expansion. Temperature drops to very low value of −180 °C, since the HS are modelled for the affected module OB4 only. The remaining components in the loop are considered as adiabatic due to missing design data so that their heat storage in the structure does not take into account. Therefore at this stage the temperature value is not credible for the safety assessment.

5. Conclusions

The DBA analysis for LOCAs in one EU DEMO HCPB blanket module (2014) has been studied for three representative accidental sequences. Helium inventory has been estimated at ~1000 kg in one loop. Small FW break size decelerates the helium loss speed, pressure drop, and temperature decrease in the affected module, and helium accumulation in the VV. The FPSS without plasma disruption makes temperature decrease in the fluid and structure. Pressure increase in the free Li_4SiO_4 pebble volume over 7.1 MPa may have impact on the BU design. To avoid extreme low temperature due to adiabatic gas expansion in large volume all components and piping in the loop should be modelled with detailed HSs, which is being investigated in EUROfusion safety program [8] with the updated design data for the HCPB blanket concept and the associated PHTS.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] L.V. Boccaccini, et al., Objectives and status of EUROfusion DEMO blanket studies, Fusion Eng. Des. 109–111 (2016) 1199–1206.
[2] B.J. Merrill, et al., Recent development and application of a new safety analysis code for fusion reactors, Fusion Eng. Des. 109–111 (2016) 970–974.
[3] C. Bachmann, Plant Description Document, EUROfusion EFDA_D_2KVWQZ version 1.2, 2014.
[4] M.T. Porfiri, G. Mazzini, DEMO BB Safety Data List (SDL), EUROfusion EFDA_D_2MF8KU, 2015.
[5] U. Fischer, et al., Neutronic performance issues of the breeding blanket options for the European DEMO fusion power plant, Fusion Eng. Des. 109–111 (2016) 1458–1463.
[6] D. Carloni, et al., LOCA accident for the DEMO helium cooled blanket, Fusion Sci. Technol. 68 (2) (2015) 353–357.
[7] X. Jin, et al., LOFA analysis for the FW of DEMO HCPB blanket concept, in: 1st IAEA TM on the Safety, Design and Technology of Fusion Power Plants, Vienna Austria, 3–5 May, 2016.
[8] N. Taylor, et al., Resolving safety issues for a demonstration fusion power plant, these proceedings, SOFT (2016).