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

Xue Zhou Jin

Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

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.

Keywords: DEMO safety, HCPB, LOCA, MELCOR.

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 (OB_4) 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). 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. The design data for OB_4 are: mass flow rate ($\dot{m}$) of 6.323 kg/s, temperature of 300 °C and pressure of 8 MPa at the blanket inlet, 500 °C at the blanket outlet, and thermal power of 6.572 MW. The cross section of the FW channel is 10 mm x 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) loop operated at a low pressure of 0.2 MPa.

A layout option of the PHTS is selected from [5], 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. In case of LOCA or loss of flow accident (LOFA) in one loop the FW cooling is still activated with 50% mass flow rate.

The free volume of the vacuum vessel (VV) is designed with 2243 m³ [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 m³ 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

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author's email: jin@kit.edu

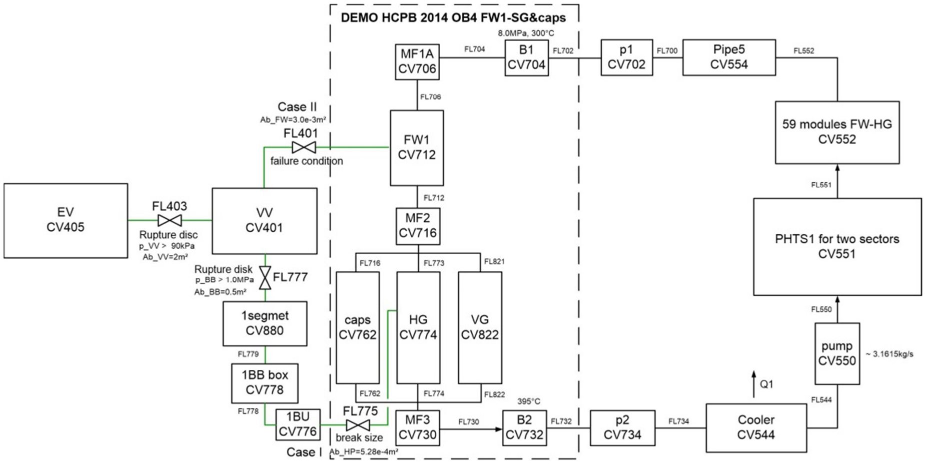
accidental sequences have been selected: case I in-box LOCA to the breeding blanket (BB) with failure of one HP in the SG; case II in-vessel LOCA with failure of 10 FW channels; and case III in-box LOCA to the PG system with failure of one CP in the BU.

4. MELCOR modelling, simulation and results

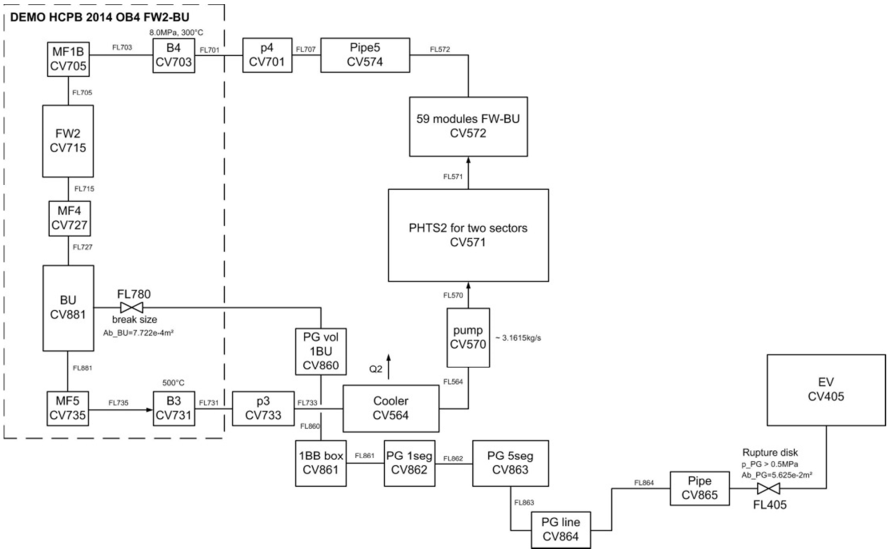
MELCOR 1.8.6 for fusion is selected for the LOCA simulation. It is improved against the previous MELCOR 1.8.2 with double precision and helium properties. Same to the previous version 1.8.2, helium as non-condensable gas is included as well.

4.1 Modelling and simulation

Fig. 1 shows MELCOR nodalization for case I / II (Fig. 1 (a)) and case III (Fig. 1 (b)). All components are modelled as control volumes (CVs) connected with flow path (FL). The affected blanket module OB_4 is started with its inlet piping (CV702 / CV701) and ended with the outlet piping (CV734 / CV733). Heat structures (HSs) are modelled for OB_4 regarding the manifolds (MFs), the FW, the HG, the VG, the caps and the BUs considering the pebble beds volume, the surface heat flux, the nuclear heating and the decay heat assumed as 1.7% of the full power. Helium flow is heated up due to the plasma surface heating and nuclear power in the blanket structures. A cooler is modelled at the downstream of OB_4 to cool down the flow to the module inlet temperature. A pump is modelled to control the pressure. PHTS1 for 2 sectors is modelled as one CV in Loop 1 with a volume of 133 m³ scaled from the selected layout in [5], and PHTS2 in Loop 2. Except the affected module all other modules are modelled in one CV, together with the CV for 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).



(a) Loop 1 for case I / II



(b) Loop 2 for case III

Fig. 1. MELCOR nodalization.

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. 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. 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 from one segment (CV880) in case I. In case III, 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 is opened.

The normal operation is achieved at the steady state of 1000 s. At this time three LOCA cases take place. They are simulated with a time step (dt) of 0.5 ms. The pump is assumed to be shut down in 3 s after the LOCA. A fast plasma shutdown (FPSS) is activated in 4 s after the LOCA based on the FW temperature behaviour studied in [6]. 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 and MELCOR versions comparison on case I. 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 m², and it is 6.0e-4 m² for the failure of two channels as case IIb. Using helium as non-condensable gas, case Ia with MELCOR 1.8.6 and case Ib with MELCOR 1.8.2 are simulated as well.

4.2 Steady state results

Table 1 shows the steady state results for Loop 1 and Loop 2 with respect to helium properties and MELCOR versions. 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/m³. However the PHTS part at the blanket outlet (500 °C and 7.6 MPa) has a lower density of ~5.46 kg/m³. Thus 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 (388.1 °C) and in Loop 2 from the BU (505.1 °C) have impact on components design in two separate cooling loops of the PHTS. EUROFER temperature in the FW exceeds the operating limit of 550 °C, which are higher than 502 °C using RELAP5-3D and 453 °C with CFX in [6] for the FW study. It may be caused by the simple HS modelling and rough power estimation in MELCOR. 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 due to missing design values. In the new HCPB design 2015 the SG is removed [1].

Comparing the results from helium as non-condensable gas with helium as working fluid, the inventory is increased by 18.4 kg, while the mass flow rate, pressure and helium temperature are well comparable. But the structure temperature more than 3700 °C in MELCOR 1.8.2 shows the problem of the HS model in this version.

Table 1. Steady state results.

Parameter			MELCOR 1.8.6			MELCOR 1.8.2
Loop Nr.			1	2	1	1
He	Flow		Working fluid		Non-condensable gas	
	Inventory (kg)		1016.7	988.6	1035.0	1035.1
FW	ṁ (kg/s)		3.1805	3.0707	3.2084	3.2096
	p_inlet (MPa)		7.84	7.93	7.85	7.88
	dp (kPa)		149.0	149.0	149.0	149.0
	T (°C)	inlet	294.2	296.7	294.5	296.8
		outlet	364.6	371.7	364.1	366.9
		EUROFER	621.8	818.7	621.1	*3721.3*
		PFC	661.1	862.0	660.4	*3765.0*
SG / BU	ṁ (kg/s)	HG / BU	1.7143	3.0707	1.7295	1.7301
		VG	0.6642	-	0.6701	0.6706
		Caps	0.8020	-	0.8087	0.8089
	T (°C)	He outlet	388.1	505.1	387.4	389.2
		Be	-	557.5	-	-
		Li_4SiO_4	-	635.6	-	-

4.3 Transient results

After the LOCA the flow path opens for the helium ingress into the VV or EV by exceeding the pressure limit: in case I helium ingress into the VV at 1 s and 37 s later into the EV; in case II at 7.9 s into the EV; and in case III at 1.4 s into the EV. The mass flow rate drops below 1 kg/s immediately after the LOCA in case I. case II with the largest break size makes the quickest pressure drop in the blanket module (Fig. 2). In the figure the start time is reset to 0.0. Small FW break size decelerates the helium loss speed, pressure drop, and temperature decrease in the affected module, and helium accumulation in the VV (case IIa and IIb). In case II helium mass in the VV reaches 279 kg within 400 s. The maximum helium mass in the EV is 921 kg in case III since the VV is absent. The PG pressure in the free Li_4SiO_4 pebble volume (CV860) reaches the first peak of 7.14 MPa at 0.5 s and the second peak of 7.234 MPa at 3.5 s. Then it drops below 1.0 MPa at 655 s. These pressure peaks may have impact on the BU design.

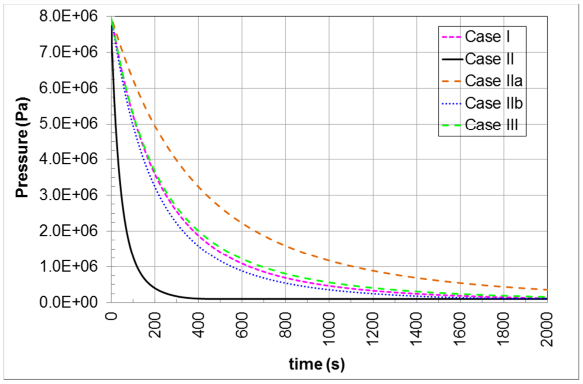


Fig. 2. Inlet pressure (CV706 / CV705)

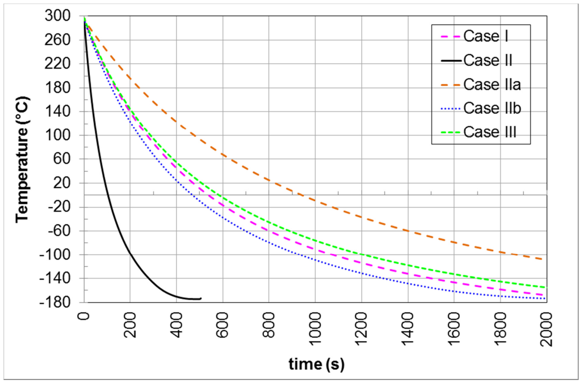


Fig. 3. Helium inlet temperature (CV704 / CV703)

The FPSS without plasma disruption makes temperature decrease in the fluid (Fig. 3) 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 OB_4 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.

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. 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. MELCOR 1.8.6 provides reliable results against MELCOR 1.8.2 due to the double precision. Helium properties produce precise results against helium as non-condensable gas. To avoid extreme low temperature due to adiabatic gas expansion in large volume all components and piping in the loop should be modelled with HSs. This is going to be investigated in EUROfusion safety program [7] using the updated design data for the PHTS and the HCPB blanket concept.

Acknowledgments

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