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Modelling an In-Vessel Loss of Coolant Accident in the EU DEMO WCLL Breeding Blanket with the GETTHEM Code

Antonio Froio[a], Andrea Bertinetti[a], Sergio Ciattaglia[b], Fabio Cismondi[b], Laura Savoldi[a] and Roberto Zanino[a]

[a]*NEMO group, Dipartimento Energia, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy*
[b]*EUROfusion Consortium, Boltzmanstr. 2, 85748 Garching bei München, Germany*

One of the accidents to be analyzed for the operation of the EU DEMO tokamak reactor is the in-vessel Loss-Of-Coolant Accident (LOCA), in which a postulated rupture in the First Wall causes a rapid pressurization of the Vacuum Vessel (VV). To avoid rupture of the VV, a VV Pressure Suppression System (VVPSS) is used, which is aimed at removing the coolant from the VV, preserving its integrity and safely storing the coolant together with the radioactive products contained therein. A system-level tool for the analysis of thermal-hydraulic transients in tokamak fusion reactors, called GEneral Tokamak THErmal-hydraulic Model (GETTHEM), is under development at Politecnico di Torino. This paper presents the GETTHEM module developed for the description of the EU DEMO VVPSS, in the case of a water-cooled Breeding Blanket concept; the code validation against experimental data coming from the Inlet Coolant Event campaign performed in Japan is shown. The tool is then applied to a parametric analysis relevant for an EU DEMO in-VV LOCA, and the results are presented and discussed.

Keywords: DEMO, in-vessel LOCA, Vacuum Vessel, VVPSS, WCLL

1. Introduction

Within the framework of the EU DEMO pre-conceptual design there is a strong need for fast computational codes, which would allow parametric analyses to identify the system response to different inputs at the global level in a reasonable time. For this reason, the EUROfusion Programme Management Unit is supporting the development of a system-level thermal-hydraulic code, the GEneral Tokamak THErmal-hydraulic Model (GETTHEM), which is being developed since 2015 at Politecnico di Torino using Modelica®, an object-oriented declarative modelling language. The code has been successfully applied to the optimization of the coolant flow path in the Helium-Cooled Pebble Bed (HCPB) Breeding Blanket (BB) [1] and verified against CFD for the Water-Cooled Lithium-Lead (WCLL) BB [2]. More recently, the code was applied to analyze the hot-spot temperature distribution in the HCPB structural material [3] and, for the first time, also to the analysis of an accidental transient in a helium-cooled BB [4].

In the present work, the development of a simplified GETTHEM model for the in-vessel Loss-Of-Coolant Accident (in-VV LOCA), i.e. a release of coolant inside the VV following a failure of the First Wall (FW), for the WCLL BB is presented. Such model allows analyzing the pressure transient in the EU DEMO Vacuum Vessel (VV), following an in-VV LOCA. In fact, in order to have plasma, vacuum conditions have to be maintained inside the VV, which thus normally operates at pressure of the order of some millipascals. On the other hand, the BB coolant is usually at much higher pressures (15.5 MPa for WCLL), so if the coolant is released the VV pressure increases. As the VV is also the primary confinement barrier against the release of radioactive materials (tritium, activated dust, activated corrosion products), its integrity must be preserved; hence, to avoid overpressures, it is connected to a VV Pressure Suppression System (VVPSS), which must intervene (through passive components) to keep the pressure below the limit, which, for the EU DEMO, is currently foreseen to be 0.2 MPa (same as ITER). The code is initially validated against experimental results, and then applied to parametrically analyze different break sizes, to identify the maximum tolerable accident for a fixed design of the mitigation system, which would allow keeping the VV pressure below its design limit.

Some analyses with different computational tools have been made in the past in this sense. Among the others, in [5], a parametric analysis is performed for the JET tokamak using CATHARE, with a FW break in the range 1 m² – 50 m², assuming also failure of different safety systems and a variable number of relief lines. However, considering the very different dimensions and coolant inventory of JET and EU DEMO, it is hard to extrapolate results from the first to the latter. Similar conclusions apply to the experimental and numerical studies carried out by JAERI [6] with the TRAC code on the Ingress of Coolant Event (ICE) test facility [7], whose dimensions are scaled down from ITER. A set of studies relevant for the Japanese DEMO have been performed by Nakamura et al. using MELCOR [8] [9]; these works however exploit a detailed 1D nodalization, which causes a relatively large computational cost limiting the parameter space to analyze. The present work, instead, is based on a fully-0D model, which allows solving an entire LOCA transient in <0.1 s (~6000× faster than realtime) on a Intel® Core™ i7-4810 MQ @ 2.80 GHz, sweeping a very large range of the parameter space.

author's email: antonio.froio@polito.it

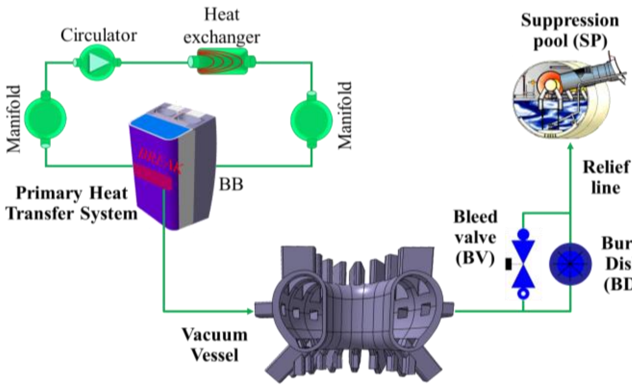

Fig. 1. The EU DEMO VVPSS system layout for a water-cooled BB.

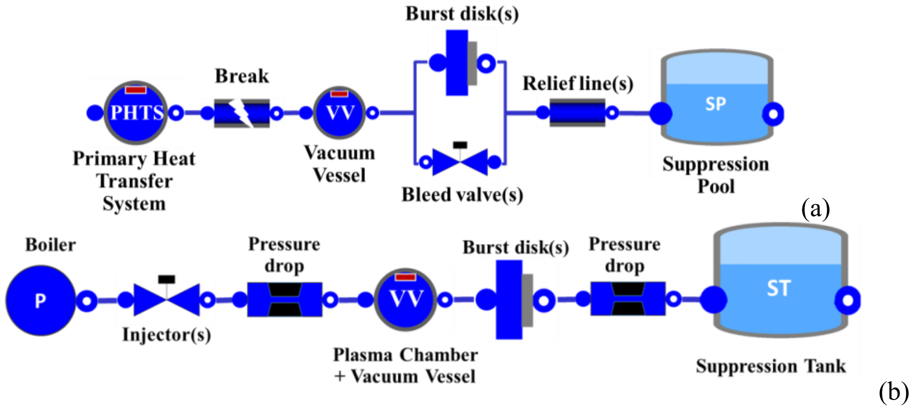

Fig. 2. GETTHEM model of the EU DEMO VVPSS for a water-cooled BB (a) and of the ICE facility (b).

2. The EU DEMO VVPSS layout for water-cooled BBs

The layout of the EU DEMO VVPSS is shown in Fig. 1. The domain considered in the present analysis starts from the Primary Heat Transfer System (PHTS), which extracts the heat from the BB (contained inside the VV) and brings it to the secondary systems. The VVPSS is composed by a Suppression Pool (SP), which keeps the pressure constant by condensing water (as it is done in Boiling Water Reactors); the SP is connected to the VV by means of one or more Relief Lines (RLs), equipped with Burst Disks (BDs). In addition, other smaller lines (Bleed Lines, BLs), equipped with actively operated valves (Bleed Valves, BVs), are used to bypass the BD, to avoid unnecessary BD ruptures in case of small leakages: in fact, whenever a BD is ruptured, its substitution requires the intervention of the Remote Handling system, which would then increase the machine unavailability.

3. The GETTHEM VVPSS model for water-cooled BBs

The GETTHEM model of the EU DEMO VVPSS is sketched in Fig. 2a. All the components are modelled as 0D objects (but the relief line, which is modelled as a 1D pipe), which are directly taken or adapted from the widely used and validated ThermoPower Modelica library [10] [11]; the water properties are taken from the Modelica.Media library, which uses the universally adopted IAPWS IF97 standard [12].

3.1 PHTS and VV models

The PHTS and VV are modelled as constant volume tanks in which conservation of mass and energy for an open system are imposed, according to equations 1 and 2, respectively:

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} = V\left(\left.\frac{\partial \rho}{\partial p}\right|_h \frac{dp}{dt} + \left.\frac{\partial \rho}{\partial h}\right|_p \frac{dh}{dt}\right) \qquad (1)$$

$$\frac{dE}{dt} = h\frac{dm}{dt} + m\frac{dh}{dt} - V\frac{dp}{dt} = \\ = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + \gamma S(T_m - T) + Q_{ext} \qquad (2)$$

where m is the mass inside the volume, t is the time, $\dot{m}_{in(out)}$ is the inlet (outlet) mass flow rate, V is the volume of the tank, ρ is the fluid density, p is the pressure inside the volume, h is the fluid enthalpy inside the volume, E is the internal energy inside the volume, $h_{in(out)}$ is the enthalpy of the fluid entering (exiting) the volume, γ is the heat transfer coefficient between the tank walls and the fluid, S is the internal surface of the tank, T_m and T are the temperature of the tank walls and the fluid, respectively, and Q_{ext} is the thermal power exchanged with the environment (positive if entering); the partial derivatives of the density are computed from the IF97 water properties.

The energy conservation in the tank wall is modelled according to equation 3, where C_m is the heat capacity of the solid:

$$C_m \frac{dT_m}{dt} = \gamma \, S\left(T - T_m\right) \quad (3)$$

The fluid quality is evaluated as the ratio between the enthalpy difference between the mixture and the saturated liquid enthalpy h_l, and the latent heat of vaporization h_{lv} at the same pressure, see equation 4:

$$x = \frac{h - h_l}{h_{lv}} \quad (4)$$

3.2 Break, BV and BD models

The break in the BB is modelled as a valve, the model of which takes into account flashing phenomena, followed by a localized pressure drop (see section 3.3 below). BDs and BVs are modeled as valves that open if the pressure difference across the component is higher than a threshold value.

All the valves are modelled according to the ANSI/ISA-75.01 standard, in which the mass flow rate is defined by equation 5, where A is the valve cross section and Δp_{eff} is the effective pressure drop across the component, computed accounting for flashing and choked flow according to equations 6-8 [13]:

$$\dot{m} = A\sqrt{\rho \Delta p_{eff}} \quad (5)$$

$$\Delta p_{eff} = \begin{cases} p_{in} - p_{out} & if \quad \left(p_{in} - p_{out}\right) \le \Delta p_{ch} \\ \Delta p_{ch} & if \quad \left(p_{in} - p_{out}\right) > \Delta p_{ch} \end{cases} \quad (6)$$

$$\Delta p_{ch} = 0.81\left(p_{in} - F_F \, p_v\right) \quad (7)$$

$$F_F = 0.96 - 0.28\sqrt{\frac{p_v}{p_c}} \quad (8)$$

where p_{in} is the pressure at the inlet of the valve, Δp_{ch} is the choked pressure drop, F_F is the liquid critical pressure ratio factor, p_v is the vapor pressure of the liquid at inlet temperature and p_c is the critical pressure of the water (22.1 MPa).

3.3 Pressure drop model

The localized pressure drop, connected downstream the valve in the break model, solves the following equation:

$$\dot{m} = A\sqrt{K\rho\Delta p} \quad (9)$$

where K is the localized pressure loss coefficient and Δp is the pressure drop across the component.

3.4 SP model

The SP is modelled as a 0D constant volume tank containing a two-phase mixture always in equilibrium conditions (i.e., the temperature of the coolant inside is always the saturation temperature) in which conservation of mass (equation 10) and energy (equation 11) are imposed, where $V_{l(v)}$ is the volume occupied by the liquid (vapor) phase, $\rho_{l(v)}$ is the density of the saturated liquid (vapor), $m_{l(v)}$ is the mass of the liquid (vapor) phase and $h_{l(v)}$ is the enthalpy of the saturated liquid (vapor):

$$\dot{m} = \frac{dV_l}{dt}\rho_l + V_l\frac{d\rho_l}{dp}\frac{dp}{dt} + \frac{dV_v}{dt}\rho_v + V_v\frac{d\rho_v}{dp}\frac{dp}{dt} \quad (10)$$

$$\dot{m}_{in}h_{in} + Q_{ext} = m_l\frac{\partial h_l}{\partial p}\frac{dp}{dt} + \frac{dm_l}{dt}h_l + $$
$$+ m_v\frac{\partial h_v}{\partial p}\frac{dp}{dt} + \frac{dm_v}{dt}h_v \quad (11)$$

The vapor quality is computed as the ratio between the vapor mass inside the volume and the total mass (vapor and liquid), following equation 12:

$$x = \frac{m_v}{m_v + m_l} \quad (12)$$

4. Model validation

The validation of the GETTEM VVPSS model is performed against data from the experimental campaign lead in Japan between March 2000 and November 2001 at the mentioned ICE test facility.

The ICE facility simulates the PHTS by an electric boiler with a volume of 0.63 m^3 in which the coolant inside can be pressurized by N_2. The boiler is connected to two tanks (V_{tot} = 0.63 m^3) representing different regions of the VV, which in the GETTHEM model are lumped in a single 0D volume (this assumption is reasonable as the two tanks always have the same pressure [7]). The VV is connected by three relief lines (diameter 35.5 mm) to the Suppression Tank (ST), with a volume of 0.93 m^3 and a maximum water storage of 0.5 m^3 [6] [7]. Fig. 2b shows the GHETTEM model of the ICE test facility. The case 4 of the 2000 ICE experimental test campaign [7] is considered to validate the GETTHEM code. The pressure evolution in the boiler is imposed equal to the experimental scenario.

The comparison between ICE experimental results (solid lines) and GETTHEM computed results (dashed lines) is reported in terms of mass flow rates injected from the boiler to the VV (Fig. 3) and pressure inside the VV and ST (Fig. 4), showing an excellent agreement of the computed results against the experimental data. In particular, the computed mass flow rate reproduces the evolution in the ICE facility with an error always smaller than 4 % (average error below 0.4 %); the error on the total discharged mass is instead 1 %. It should also be noted that, even if the mass flow rate is slightly underestimated during most of the transient, this has a negligible effect on the safety-relevant quantity, i.e. the VV peak pressure, which is also (conservatively) overestimated by ~20 kPa (less than 5 %). The computed final pressure in the VV at the end of the transient is underestimated by ~7 kPa. Also, the pressure evolution in the ST is very well reproduced by the GETTHEM model, with a pressure value reached at the end of the transient ~ 6 kPa higher than the experimental one. It is anyway important to note that, while GETTHEM reached the same value of pressure at the end of the transient for the two connected volumes VV and ST. The experimental data differ in fact by ~13 kPa, which we consider to be the experimental accuracy. The GETTHEM result is, however, between the two values, so it can be safely considered correct within the experimental accuracy.

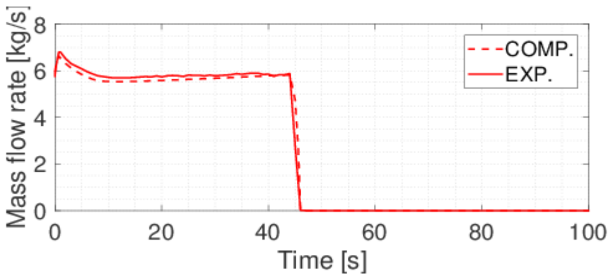

Fig. 3. Model validation: comparison of the experimental (solid) and computed (dashed) mass flow rate injected from the boiler to the VV.

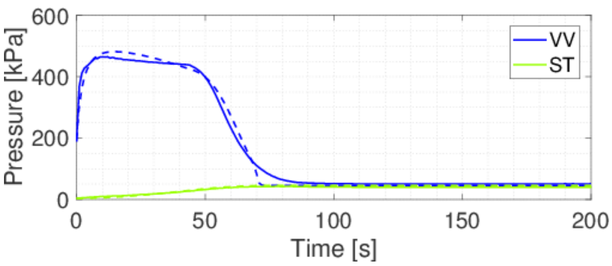

Fig. 4. Model validation: comparison of the experimental (solid) and computed (dashed) pressure evolution inside the VV (dark-colored lines) and ST (light-colored lines).

5. Parametric analysis results on EU DEMO layout

The GETTHEM model is then applied to the EU DEMO, in order to parametrically analyze the pressure evolution in the VV during the accident, investigating the effect of the break size. All the simulations are performed also investigating parametrically the number of RLs connecting the VV to the SP, while all the other parameters are maintained unchanged, see Table 1.

Exploiting the above-mentioned code speed, 44 different break sizes have been identified and simulated; these have been obtained considering different dimensions of FW failures and computing the number of FW cooling channels involved [17]; as mentioned, all the simulations have been performed considering two different RL options, respectively. For the sake of clarity, only the five most relevant results are shown in this work, corresponding to the break sizes reported in Table 2. The pressure evolution inside the VV is reported in Fig. 5, where the horizontal line represents the pressure limit of the VV (0.2 MPa). As the figure shows, the pressure limit is overcome in all the considered cases, except when a FW failure below 1 m² is considered: in these cases, the pressure buildup is so slow that the intervention of BVs is sufficient to mitigate the accident, without the need for the intervention of the BDs. Note, however, that the computed pressure is an average value, so in principle this result does not exclude the possibility that somewhere locally in the VV the pressure overcomes the limit, calling for a detailed (at least) 2D analysis of the first phase of the transient, when large non-uniformity in the VV could be present. On the other hand, when the FW failure is above or equal to 2 m², the pressure increase is too fast for the mitigation system to operate effectively, causing the pressure peak to go above the limit (even up to ~0.8 MPa) in a few seconds. This is strongly mitigated when three relief lines are used, but still not effectively enough to respect the limit.

Case 3, with a FW failure of 1 m², is exactly in the middle: in fact, in this case, if two RLs are used, the pressure slightly overcomes the limit, whereas if three RLs are used the limit is satisfied, albeit marginally. These results are summarized in Table 2, where also the time instants when BVs and BDs open are reported. The equilibrium pressure at the end of the transient is ~17 kPa, regardless of the considered scenario, as it depends only on the total volume.

As a side remark, the results obtained in Cases 3-5 compare very well with the results obtained by Nakamura et al. in [8] in the leak size range 0.02 m² – 0.1 m², with a much more detailed nodalization using the well-known MELCOR code. Such comparison can anyway be qualitative only, as the parameters of the VVPSS are slightly different; nevertheless, it proves the reliability of GETTHEM predictions, despite the simplifications.

Table 1. Parameter used in the EU DEMO LOCA analyses.

Component	Parameter	Value	Ref.
PHTS	Volume	138 m³	[14]
	Initial pressure	15.5 MPa	[14]
	Initial temperature	325 °C	[14]
VV	Volume	3000 m³	[15]
	Initial pressure	1 kPa	[a]
SP	Volume	2000 m³	[16]
	Initial pressure	4.2 kPa	[b]
	Initial water level	50 %	[16]
BD	Cross section	0.49 m²	[c] [16]
BV	Cross section	0.1 m²	[d]
RL	Length	54 m	[d]
Break	Localized pressure loss coefficient	5	

[a] Minimum value allowed by IF97 water properties model.
[b] Saturation pressure @ 25 °C.
[c] Space available through each Neutral Beam Injector port.
[d] Same as ITER.

Table 2. Results of the parametric analysis.

Case	FW break size [m²]	Leak size [m²]	t_{open} BV [s]	t_{open} BD [s]	p_{max} [kPa] 2RLs/3RLs
1	0.01	~2.9×10^{-4}	~275	-	94/94
2	0.1	~2.6×10^{-3}	~30	-	136/97
3	1	~2.6×10^{-2}	~3	~6.5	264/193
4	2	~5.1×10^{-2}	~1.6	~3	441/329
5	5	~1.3×10^{-1}	~0.63	~1.2	770/619

To have an idea of what is the driver of this different behavior, Fig. 6 reports the evolution of the mass flow rates from PHTS to VV and from VV to SP for cases 3 and 5. Here it is evident that, in case 5, immediately after the intervention of the BDs the mass flow rate removed from the VV is a small fraction of that entering the same volume, causing the pressure to continue increasing, whereas in case 3 the two values are similar (thanks to the smaller leak size) and the overpressure mitigation is more effective. In addition, from this plot it is clear that the BVs are negligibly contributing to the overpressure mitigation, as the mass flow rate flowing through them is always negligible with respect to that entering the VV through the break.

As a final remark, the water inside the VV is always two-phase; in this case, it may become important to consider the stratification of the coolant in future 2D/3D analyses, which would allow a more effective overpressure mitigation by draining the liquid water from the bottom of the VV.

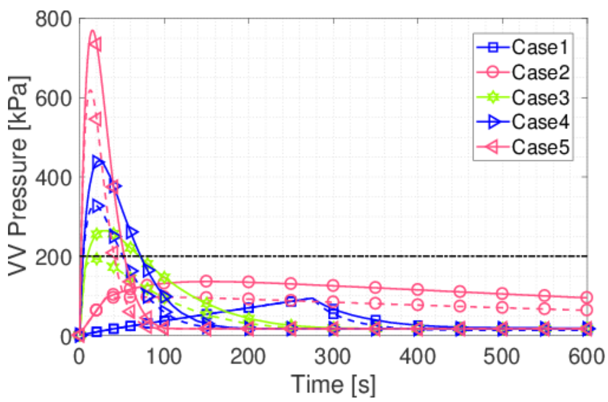

Fig. 5. Computed pressure evolution inside the VV for different break size dimension, computed considering two (solid) or three (dashed) RLs, respectively.

6. Conclusions and perspective

A simplified thermal-hydraulic model of the EU DEMO VVPSS has been developed and included in the GETTHEM library, allowing the evaluation of accidental transients following an in-VV LOCA for water-cooled BBs.

The model has been validated against the experimental campaign performed at the ICE facility in Japan in year 2000, showing an excellent agreement for all the global variables of interest.

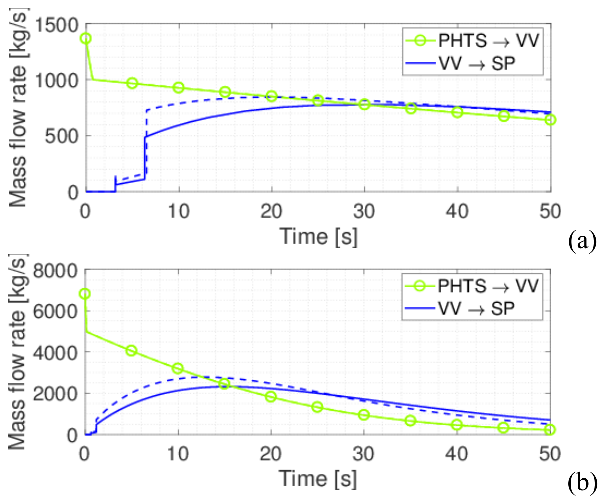

Fig. 6. Evolution of the computed mass flow rate from PHTS to VV and from VV to SP, for cases 3 (a) and 5 (b), considering two (solid) or three (dashed) RLs.

The GETTHEM model has then been applied to the analysis of an in-VV LOCA for the EU DEMO. Taking advantage of the reduced computational weight of the model, several simulations have been performed varying the dimension of the break size, and the effect of different number of RLs has been assessed. It has been shown that any FW break larger than 1 m² would cause the VV to be pressurized above its limit with the current VVPSS parameters, calling for a revised design of the mitigation system if such accident cannot be avoided. Nevertheless, the presence of three RLs instead of two allows reducing sensibly the pressure peak inside the VV, and consequently an increase of number of lines can be considered as one of the most important action to mitigate the effect of in-LOCA on VV pressure peak.

In perspective, the GETTHEM VVPSS model will be linked to the 1D model of the PHTS, already present in the GETTHEM library, to evaluate the effects of this transient also on the cooling system. Moreover, a 2D analysis of the VV cross section will be carried out, to check the representativeness of an average pressure in the early stage of the LOCA transients, as well as to evaluate the effect of the coolant stratification.

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