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SIMULATION OF WATER – LIQUID LEAD-BISMUTH EUTECTIC INTERACTION USING SIMMER-III CODE

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Abstract

During recent years heavy liquid metal-cooled (HLM) reactors have experienced increasing interest reflected in several European reactor projects, such as EFIT [1] and ELSY [2] LEADER [3] projects. The reactors with the focus on transmutation of Minor Actinides (MA), such as EFIT project, are usually designed with a two-loop system as the HLM does not react vigorously when coming into contact with water/steam or air. The two-loop layout bears however the risk that after a steam generator tube rupture (SGTR) event water and/or steam can be transported into the core which could lead to a reactivity insertion in case of a fast spectrum reactor. Based on this consideration, a series of numerical experiments was carried out in this paper to investigate the phenomenology and behaviour of thermal and hydraulic interactions between water/vapor and liquid LBE alloy using the code SIMMER-III [4]. The computational domain is a vessel, which was initially filled with molten LBE alloy. A pressurized water jet tube was immersed in the liquid LBE pool and injected vertically into the melt pool. Based on the EFIT steam generator idea, an orifice is arranged at the tube entrance to throttle the water/vapour mass flow in case of the pressurized water tube ruptures. The liquid LBE alloy temperature ranges from 400°C to 500°C, while the pressurized water temperature varies from 135°C to 335°C in an interval of 50°C. This research will focus on the water/steam penetration depth variation into the LBE pool influenced by the water and LBE temperatures.

Introduction

The increasing interest in heavy liquid metal reactors, based on either lead or lead-bismuth eutectic alloy coolants, raises the question of a possible interaction with water or steam. Some design proposals for heavy liquid metal coolant fast reactors and sub-critical transmutation systems, such as the European EFIT, ELSY projects, presently foresee the use of steam generation modules directly immersed in the hot leg of the primary HLM coolant pool for the economical reasons. In such a configuration a release of water/vapour into the primary coolant and transport into the core has to be assessed in case of a steam generator tube rupture (SGTR). In this accident scenario the pressurized coolant —— water or steam —— is discharged from the second loop and blasts into the primary heavy liquid metal coolant, which could trigger various transients and evoke structural risks. Steam could be dragged into the reactor core. A reason for this worry exists as the core void worth is in the same range or larger than the built-in subcriticality of the reactor core, such as the EFIT core, which has a positive void worth due to the actinide load of the fuel [5]. A thermal coolant-coolant interaction (CCI), similar to a fuel coolant interaction (FCI) could trigger a local voiding process, too. A CCI with a sudden vaporization of the discharged water could initiate a sloshing motion of the heavy primary coolant inducing strong impact loads which might challenge the vessel integrity. A severe pressure build-up could also lead to a core compaction process.

In the past years (collected papers of Nuclear Engineering and Design Vol. 155, 1995 [6]), interactions of a hot liquid with a cold volatile liquid has been intensively investigated through all stages from coarse mixing, triggering, propagation and expansion aiming to the fuel-coolant interaction in the context of nuclear reactor core accident scenario. In these investigations the focus is put on the hot liquid metal liquid (e.g. liquid corium) pouring into sub-cooled or saturated volatile liquid (e.g. water) to study its interaction. The boundary conditions of these investigations are different from the aforementioned steam generator tube rupture scenario.

While in the steam generator tube rupture (SGTR) scenario, the high pressurized water is discharged into the LBE pool. The LBE pool holds lower pressure and high temperature. Under this lower pressure and high temperature environment, the discharged water locally changes suddenly into super-saturated condition and subsequently into steam, the discharged water is undergoing a fast evaporation process, the water jet changes into a water-vapor two-phase jet injecting into the liquid LBE pool. This injection turns into a very complicated melt-water-vapor multiphase flow, which is different from afore mentioned fuel-coolant-interaction investigations.

The research on this steam generator safety issues and related phenomena is being actively pursued at a number of research centres, either through experiment or numerical simulation; see references of [7], [8], [9], [10].

In this paper, a series of numerical experiments with the code SIMMER-III was carried out to investigate the phenomenology and behaviour of thermal and hydraulic interactions between high pressurized water/vapor and liquid LBE, when the high pressurized water/vapour injects into LBE pool. Based on the EFIT steam generator idea, an orifice is arranged at the tube entrance in order to throttle the water/vapour mass flow in case of the water tube ruptures. It is believed that the numerical simulation of thermal-hydraulic phenomena of water/vapor-heavy liquid metal interactions is an essential approach to investigate these safety issues in heavy liquid metal coolant reactors, especially the penetration depth of water/vapour into LBE pool.

1. The SIMMER-III code and code improvements for heavy liquid metal flows

The SIMMER-III computer program published by Kondo [4], is a two-dimensional (2D)**,** multi-velocity-field, multi-phase, multi-component, Eulerian, fluid-dynamics code system with an integrated structure model including fuel-pins, hexcans and general structures, together with a space-, time- and energy-dependent neutron transport theory model. The SIMMER code family is currently developed by an international team (JAEA, KIT, CEA, ENEA, SCK.CEN, PSI and IRSN). The code is being used as one of the major tools for analyzing severe accidents for liquid metal cooled systems with fast neutron spectrum, both in critical and sub-critical configuration. An elaborate analytical equation-of-state (EOS) model is available in SIMMER-III code to close and complete the fluid-dynamics conservation equations. The EOS of SIMMER-III demands values for the solid, liquid and vapour state and within a wide temperature/pressure range from the melting point to the critical point and above. The default EOS function library has been extended to heavy liquid metal coolants, such as LBE and lead, published by Morita *et al.*[11], consistent with the most recent data and following to a wide extent the recommendations of the HLM handbook published by OECD [12]. The SIMMER-III EOS provides a good representation of the underlying experimental data.

Gas flows in heavy liquid metals have high liquid-to-gas density ratios, which are different from ordinary air-water systems. During experiments with nitrogen (N_2) gas rising in lead-bismuth, different shapes of bubbles were observed which affect the inter-phase drag in the bubbly flow regime. The original SIMMER-III momentum exchange model has been extended and refined by Suzuki *et al.* [13] to include this effect to adequately model the high liquid-to-gas density ratio multiphase flow.

2. Code Validation on Phenomena Related to the Heavy Liquid Metal Problem

The simulation of the interaction of heavy liquid metal with water problem comprises various complex phenomena. In LMFR severe accident scenarios fuel-coolant interactions (FCIs) have to simulated and SIMMER has therefore been subjected to extensive validation efforts in this area [14, 15]. Fuel materials to be simulated comprise UO_2 and a number of simulant materials. The experiments both cover sodium and water systems and premixing and propagation phases of an FCI. Based on the previous assessment efforts it can be stated that SIMMER-III is well applicable to integral multiphase thermal hydraulic problems including transient FCI phenomena.

2.1 Rapid depressurization of superheated water

During the SIMMER-III code assessment [14, 15], two experiments have already been recalculated that bear a substantial similarity in the initial discharge of a SGTR. In the experiments conducted by Edwards [16] and Bartak [17] super-heated water (70 bar, 242 °C, and 120 bar, 220/290°C, respectively) is rapidly depressurized with a rapid vapour generation accompanied by a shock wave travelling upstream and reflected at the pressure vessel, when the rupture disk is broken at the end of the tube. The SIMMER-III code could well predict the experimental data with the oscillatory behaviour of the single phase flow and the attenuation of the pressure wave in the two-phase zone.

2.2 Simulation of JAEA water-LBE interaction experiments

In order to qualify the SIMMER-III's ability to simulate the penetration of water jet into the hot melt, a suitable case found in literature [18] was recalculated and compared with the experimental data. The reference case is an experiment conducted at JAEA, in which subcooled water was injected into a molten LBE pool from top. The main objective of those experiments was to investigate the phenomenology and physics of thermal and hydraulic interactions between water and molten LBE alloy.

Fig. 1 shows the schematic view of the test apparatus. The test vessel has a 10-mm thick slice configuration with a semicircular closed bottom and a vented top to the atmosphere and is initially filled with molten LBE alloy to a height about 100 mm measured from the vessel bottom. A water jet was injected vertically onto the melt surface, through a 6-mm i. d. cylindrical nozzle, along the test section centreline from about 50 mm above the melt initial level.

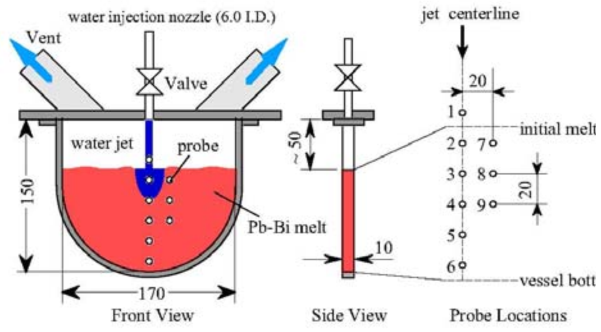


Fig. 1 Schematic view of test apparatus for water injection into LBE of [18].

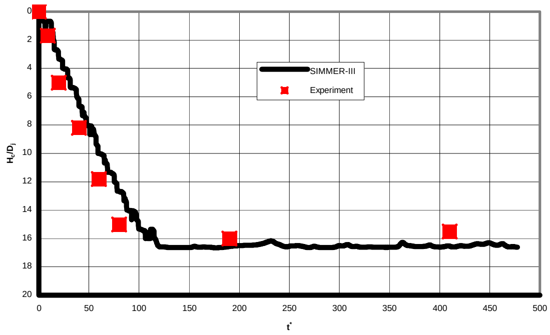


Fig. 2 Comparison between SIMMER-III calculations and experiment of run5 reported in [18].

Nine thermocouples, labelled with number 1 through 9 on Fig. 1, were used to measure the local fluid temperature and phase in such experiment, in order to assess the water jet depth.

An example of the experiment condition is as following: molten LBE alloy temperature T_m=530°C, water temperature T_j=80°C, and water injection velocity V_j=5.8 m/s. The experimental results of the water penetration depth were compared with the result of a numerical simulation with SIMMER-III performed in Karlsruhe Institute of Technology (KIT). The comparison shows that for the considered case the SIMMER-III code gives the satisfactory results.

3. SMMER-III Geometry Model and Simulation Conditions

In our previously research [19], the analysis concentrates on the EFIT steam generator engineering design, while in this current research the focus will be put on the impact of the water and LBE initial temperature on the water/vapour penetration depth through systematic variation of their temperatures.

The simulation region is a cylindrical geometry with the Z-axis of the SIMMER-III calculation domain setting on the axial centreline, see Fig. 3. The radius of the cylinder is 3.023m. The total height of the cylinder accounts for 8.6 meter. A steam generator tube postulated to fail is set vertically on the cylinder axial centreline and submerged in the LBE pool. The broken of the steam generator tube is supposed to be localized at the lowermost end of the tube, namely the tube rupture position immerses into LBE pool and accounts for 2.66m measured from the LBE pool surface. The jet outlet with 14.158 mm i.d., measured from cylindrical vessel bottom is 4.34 meter, which is practically enough deep by a preliminary test calculation, in order to avoid the penetration depth to reach to the vessel bottom.

The cylindrical geometry is initially filled with LBE melt to an elevation up to 7.0 meter measured from cylinder vessel bottom. Above the LBE melt pool is an air plenum available, which initially has a pressure of 1.0 bar to simulate the vessel upper plenum.

Molten LBE is used as the pool material. The melting point of the alloy is 125℃ and the density around the melting point is 10600 kg/m3. All the relevant physical properties are available, see reference [12].

In the SIMMER-III simulation the mesh points are 20 × 75 in radial and axial directions in a 2D cylindrical coordinate, respectively.

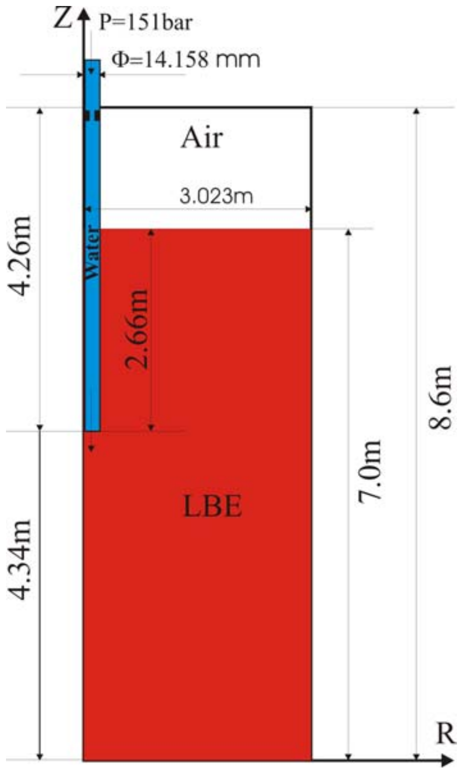


Fig. 3 SIMMER-III calculation domain geometry (not scaled)

The initial temperature of LBE pool ranges from 400°C to 500°C and is divided as three groups: the high melt temperature series (500°C, which is 50°C higher than the EFIT nominal LBE temperature), the low melt temperature series (400°C, which is 50°C lower than the nominal LBE temperature) and 450°C, which corresponding to the nominal LBE temperature, for a systematic investigation on the effects of the initial LBE temperatures

The water inlet temperature is changed from 135°C to 335°C in a 50°C interval. The simulation parameter matrix is shown in table 1.

Table 1. The simulation parameter matrix

parameters	LBE temperature °C		
	400	450	500
Water initial temperature °C	135	135	135
	185	185	185
	235	235	235
	285	285	285
	335	335	335

In the EFIT design [1], an orifice is arranged at the tube entrance in order to restrict water/vapour flow in case of steam generator tube rapture. According to this flow restrictor idea, in our current simulation, a flow restricting orifice is arranged at the tube inlet to limit the water/vapour flow rate, in order to avoid too much water/vapour pouring into the LBE pool in a short time.

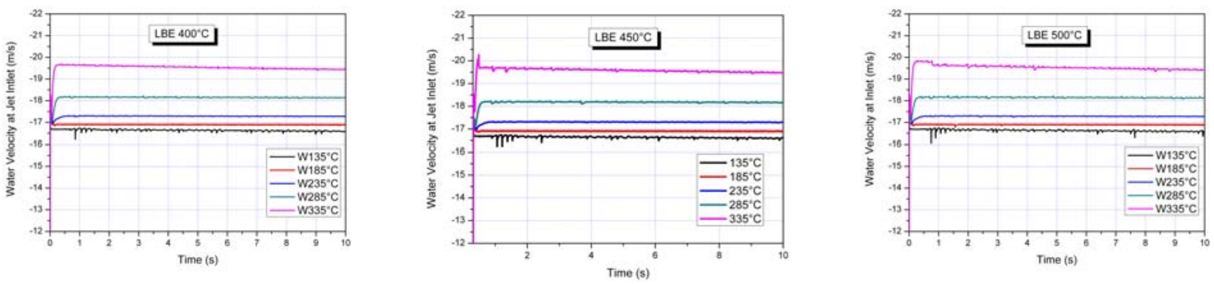
4. SIMMER Simulation and Results

During the simulation the water inlet pressure upstream the tube orifice, which is located at the tube inlet, is kept as constant as 151 bar, as illustrated in the Fig. 3. By means of adjusting the orifice coefficient, the pressure downstream the tube orifice gives the 147 bar when the tube doesn't rupture. This orifice coefficient is kept as unchanged for all the simulations. All simulations are performed for 10 seconds.

4.1 Water ingress velocity at tube entrance

The effect of the water inlet temperatures on the jet ingress velocities at the tube entrance can be observed from the Fig. 4(a)-(c). The water ingress velocity at the inlet increases with the water inlet temperature and the qausi-steady water velocities at the tube inlet are established almost immediately as the tube ruptures. It ranges between 16.5 m/s and 20m/s: at 135°C the water ingress velocity accounts for ~16.7m/s and at 335°C for ~19.6m/s.

The comparison of Fig. 4(a), 4(b) and 4(c), with different LBE pool temperatures, revealed no obvious evidence of the effect of the LBE pool temperature on the water ingress velocities at the tube inlet. This is to say, the water injection velocities depend only on the water inlet temperature, but not on the LBE pool temperatures.



(a) (b) (c)

Fig. 4. Water ingress velocity at tube entrance

4.2 Water discharge flow rate into the LBE pool

The inlet pressure is assigned as constant as 151 bar. With the increasing of the water temperature the water density decrease according to the equation of state of water, which is already embedded in the SIMMER code, Table 2 gives the water densities just upstream the tubes orifice for LBE temperature of 450°C. Since the water density at the tube entrance is independent on the LBE pool temperature. These water density values should have no changes for different LBE pool temperature.

Table 2. Water density at different inlet temperatures

Water temp. (°C)	135	185	235	285	335
Density (kg/m^3)	936.7	888.5	824.2	743.8	638.9

As a function of the water ingress velocity and the water density at the tube inlet, the water ingress mass flow rate is given as in Fig. 5.

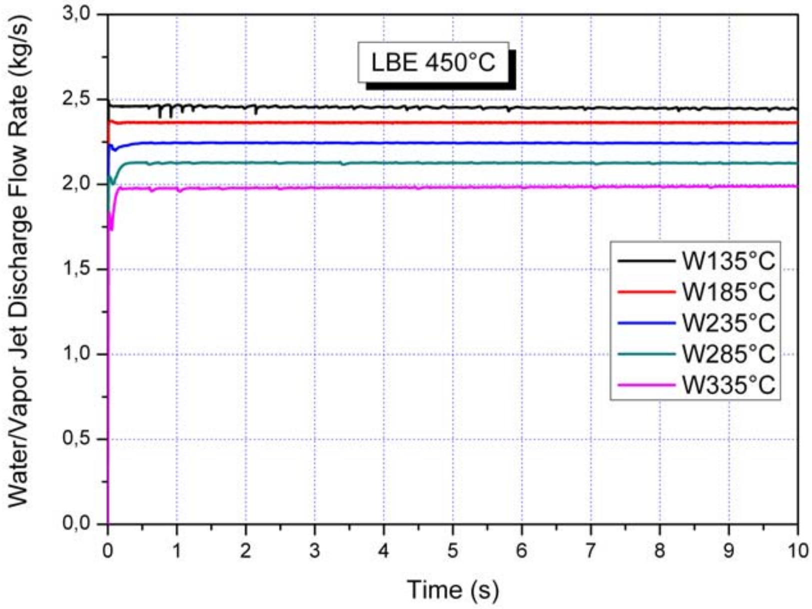


Fig. 5 Water/vapour jet discharge mass flow rate into the LBE pool (kg/s)

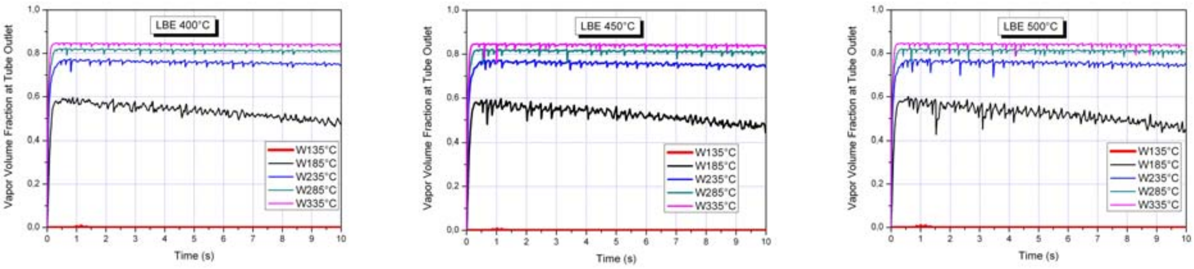
In this figure, the resulted water jet discharge mass flow rate into the LBE pool is given under the condition of LBE pool temperature as 450°C for different water temperatures. After a very short disturb phase until ~0.2s, the quasi-steady water jet mass flow rates are established when the steam generator tube ruptures. Under the water temperature of 135°C the injected water mass flow rate into the LBE pool accounts for ~2.46 kg/s. With the increase of the water temperature the discharged water mass flow rate decrease, e.g. at 335°C of the water inlet temperature the injected mass flow rate amounts to ~ 1.97 kg/s.

4.3 Water phase change at the tube exit

Under the ambient pressure condition near the tube exit of ~ 4bar (see section 4.5), the saturated water temperature accounts for ~ 140°C. The pressurized sub-cooled water (under ~ 150bar in the tube) undergoes an abrupt evaporating phase change when it flows out off the tube and is suddenly exposed to the tube exit environment, if the initial water temperature is higher than the local saturated water temperature. Fig. 6 gives the vapour volume fraction just at the tube outlet for different LBE and water initial temperatures for comparison. It is observed that the vapour volume fraction at the tube exit increases with the water inlet temperature. For water initial temperature of 135°C, because it is lower than the local saturated water temperature of ~ 140°C. The water doesn't undergo an abrupt evaporating phase change, as can be seen in Fig. 6. The vapour volume fraction at the tube exit keeps near zero for water initial temperature of 135°C during the simulation, (which overlaps on the time axis), while for water initial temperature of 335°C the vapour volume fraction at the tube exit is relative high and accounts for ~ 82%.

Fig. 7 shows the vapour mass fraction at the tube exit for LBE temperature of 450°C. The vapour mass fractions vary from 0 to 4% for different water inlet temperatures.

Compared the Fig. 6(b) with Fig. 7, it can be concluded that in case of water inlet temperature of 135°C, the jet is a sub-cooled water injection into the hot LBE pool, while in other cases the jet becomes a water/vapour two-phase flow injection into the LBE pool, which predominately consists of saturated vapour accompanied by a small volume fraction of liquid water. Though the vapour volume fraction of the water/vapour two-phase is high, but the corresponding mass fraction amounts to very small value, because of the quit difference of the liquid and vapour densities.



(a) (b) (c)

Fig. 6. Vapour volume fraction at the tube outlet

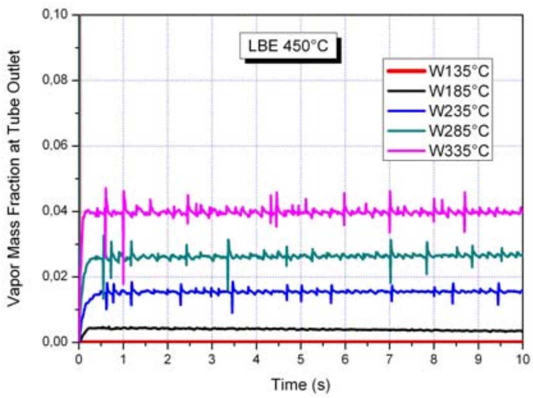


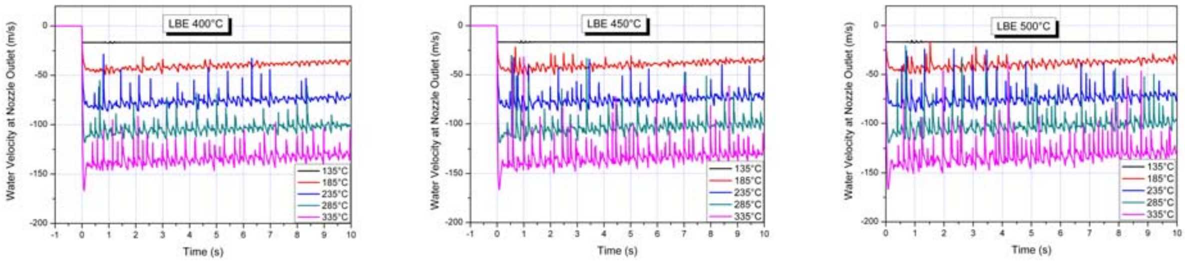
Fig. 7. Vapor mass fraction at the tube outlet for LBE temperature of 450°C.

To sum the conclusion up: in case of water inlet temperature of 135°C, the water jet is a sub-cooled injection into the LBE pool. For other cases, because water initial temperature is higher than the local saturated water temperature at the tube outlet, a part of water suddenly changes into vapour after the tube ruptures, and as a result the jet alters as water-vapour two phase flow injection into the LBE pool, which is different from the afore mentioned liquid injection into the hot metal pool in the literatures.

4.4 Water outflow velocities at tube exit

The water outflow velocity histories under different LBE pool and water inlet temperature at the tube exit can be seen from Fig. 8 (a), (b) and (c). The effect of the water vaporization or the phase change on the jet velocity at the tube exit is straightforward and understandable. Because of the high vapour volume fraction at the tube outlet, the water jet velocity was induced to very high, except the water initial temperature of 135°C. The water jet velocity at tube exit is consistent with the vapour volume fraction at the tube exit, as can be seen in figure 6(a), (b) and (c). From Fig. 8 it can be read that the water jet velocity at inlet temperature of 335°C accounts to ~ 140m/s and the at 185°C the water jet velocity becomes as ~45m/s. In the case of water temperature of 135°C, the water jet velocity accounts only for ~14m/s, because the water doesn’t undergo a sudden phase change at the tube exit.

Compared the curves for different LBE temperatures, LBE pool temperature has no effect on the water jet velocities at tube exit.



(a) (b) (c)

Fig. 8. The water outflow history at the tube exit.

4.5 Pressure development

Fig.9 gives the pressure evolution history just below the tube exit for water temperature of 135°C and 335°C under the LBE pool temperature of 450°C. The pressure pulses indicate that explosions are triggered locally due to the LBE-water interaction for 335°C. Compared the pressure pulse of water temperature of 335°C with one of 135°C, the pressure pulse denotes very higher amplitude with the high water temperature.

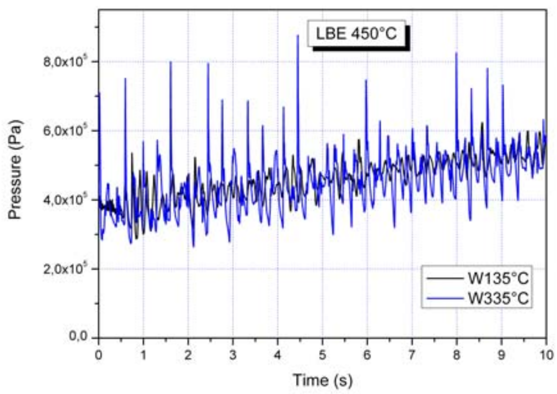


Fig. 9. Pressure evolution history at tube exit.

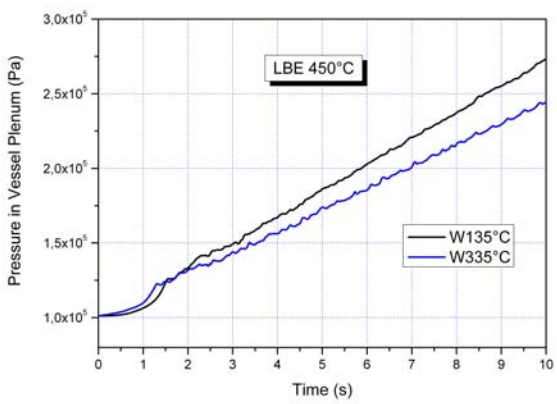
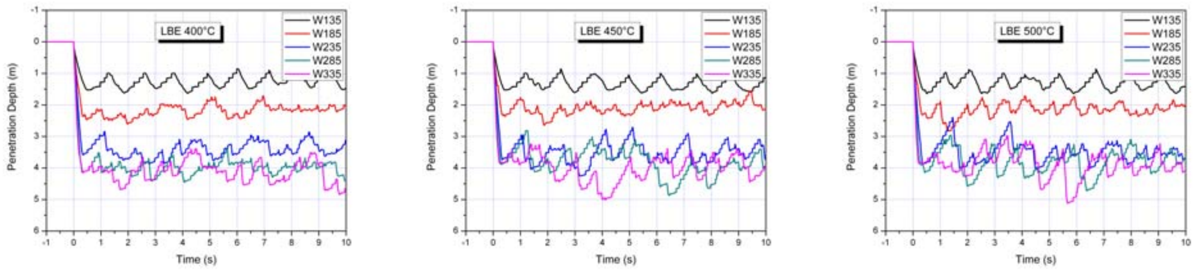


Fig.10. Pressure history in pool plenum.

The pressure evolution history in the pool upper plenum is shown in Fig. 10 for water temperatures of 135°C and 335°C, respectively, under the LBE pool temperature of 450°C. The pressure in the pool plenum increase roughly linearly and smoothly from 1.0bar to ~2.5bar. An abrupt pressure build-up in the plenum space is not observed and the LBE pressure hammer effect is excluded.

4.6 Water/Vapour penetration depth

Fig. 11(a), (b) and (c) give the water/vapour penetration depths for different LBE and water temperatures. The effect of the LBE temperature on the penetration depth can be deduced from comparing the penetration depth curves in figures 11(a) to 11(c) for the same water temperature. It can be found that the maximum penetration depths are roughly independent on the LBE temperature, e.g. when the water temperature is 235°C, the maximum penetration depth amounts to ~4m regardless of the LBE pool temperature.



(a) (b) (c)

Fig. 11. Water/vapour penetration depth into the LBE pool

The effect of the water initial temperature on the maximum penetration depth can be seen from these figures straightforward. All simulations indicate a consistent trend that the maximum depth increases with the water initial temperature.

The reason can be straightforward deduced from comparison of water outflow velocities at the nozzle outlet for different water and LBE temperatures in Fig. 8(a) to 8(c). The outflow water velocities at the nozzle outlet are consistent with what we observed in the penetration depth: the water outlet velocity depends solely on the water temperature, but not on the LBE temperature.

5. Conclusion

Within the European EFIT, ELSY or LEADER research projects, internal heat exchangers are immersed in the heavy liquid metal coolant. The secondary loop is designed as a pressurized water/vapour cycle that directly drives a steam turbine. The intermediate loop, typical for former sodium cooled fast reactors, is eliminated because of the supposed inertness of the HLM with water and air. In case of a steam generator tube rupture scenario high pressurized water/vapour could however be injected primary HLM coolant which could trigger various transients. Based on this consideration, a systematic simulation was carried out in this paper to study the water/vapour-liquid LBE interaction using the code SIMMER-III. The focus is put on the impact of the water and LBE initial temperature on the water/vapour penetration depth through systematic variation of their temperatures.

The water in the tube, initial under subcooled condition under the high pressure of 151 bar at tube inlet, is suddenly released into the hot LBE pool. The environmental pressure of broken position is of ~ 4 bar. The LBE pool temperature varies from 400°C to 500°C and the water inlet temperature is changed from 135°C to 335°C in a 50°C interval. The abruptly evaporated water leads the water outflow velocity at the tune exit to be changed very high. This velocity is mainly dependent on the water initial temperature, while the LBE pool temperature has little effect on the water velocity.

The calculation results show that a severe pressure build-up in the plenum space was not observed. The LBE temperature has no obvious effect on the jet penetration depth, while the water initial temperature has a great impaction on the penetration depth. The maximal penetration depth reaches to ~5 m measured from the tube rupture position. The safe LBE pool depth measured from the steam generator tube rupture location should be bigger than this value, in order to avoid the water/vapour to be dragged into the core.

6. Reference

[1] Ansaldo Nucleare, "Domain DM1 Design of IP-EUROTRANS: EFIT- Steam generator sizing", EU Contract FI6W-CT-2004-516520. 2005.

[2] EUROPEAN COMMISSION, "ELSY project", EU Contract FI6W-036439.

[3] LEADER- Lead cooled European Advanced DEmonstration Reactor, FP7 – 249668, Seventh Framework Programme, FP7-II.2.2 – Reactor Systems, 2010.

[4] Sa. Kondo, et. al., "SIMMER-III: An advanced computer program for LMFBR severe accident analysis", Proc. Int. Conference on Design and Safety of Advanced Nuclear Power Plants (ANP'92), No. 40-5, Tokyo, Japan, 1992, Oct. 25-29.

[5] W. Maschek et al., "Accelarator driven systems for transmutation: fuel development, design and safety", Progress in nuclear energy", Vol. 50, No. 2-6, 2008, pp.333-340.

[6] M. Akiyama, D. F. Fletcher, T. G. Theofanous, "collected papers of Nuclear Engineering and Design" 1995, Vol.155, No.1-2.

[7] Truc-Nam Dinh, "Multiphase Flow Phenomena of Steam Generator Tube Rupture in a Lead-Cooled Reactor System: A Scoping Analysis", Proceedings of ICAPP 2007, Nice, France, May 13-18, 200, Paper 7497

[8] S. Wang, M. Flad, W. Maschek, " Simulation of Subcooled Water – Heavy Liquid Metal Interaction using SIMMER-IV 3D Code and Its Verification", THIRS-Workshop, Forschungszentrum Karlsruhe, FTU, Karlsruhe, Germany, April 14-16, 2008.

[9] R. Sa, "Thermal interaction of lead-alloy droplet with subcooled water in pool water tank", ICONE 18, May, 17-21, Xi'an, China, 2010, paper ICONE18-29621.

[10] A. Ciampichetti, D. Pellini, P. Agostini, G. Benamati, N. Forgione, F. Oriolo, "Experimental and computational investigation of LBE–water interaction in LIFUS 5 facility", Nuclear Engineering and Design, Vol. 239, 2009, pp. 2468–2478.

[11] K. Morita, V. Sobolev, M. Flad, "Equation of state for heavy liquid metal targets", European Material Research Society, Spring meeting, Nice, France, 2006.

[12] OECD/NEA Nuclear Science Committee, "Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulivs and technologies", NEA No. 6195, 2007.

[13] T. Suzuki, Y. Tobita, Sa. Kondo, Y. Saito and K. Msihima, "Analyses of Gas-Liquid Metal Two-Phase Flows Using a Reactor Safety Analysis code SIMMER-III," *Nuclear Engineering and Design*, Vol. 220, 2003, pp. 207-223.

[14] Sa. Kondo, et al. "Phase 1 Code Assessment of SIMMER-III, A Computer Program for LMFR Core Disruptive Accident Analysis", PNC ZD0176 96-001, May 1996, Power Reactor and Nuclear Fuel Development Corporation, Japan.

[15] Sa. Kondo, et al. "Phase 2 Code Assessment of SIMMER-III, A Computer Program for LMFR Core Disruptive Accident Analysis", JNC TN9400 2000-105 Japan Nuclear Cycle Develop. Institute, September, 2000.

[16] Edwards, A.R., O'Brien, T.P. (1970), Studies of phenomena connected with the depressurization of water reactors, J. Br. Nucl. Energy Sci., 9, 125.

[17] J. Bartak, A study of the rapid depressurization of hot water and the dynamics of vapour bubble generation in superheated water", Int. J. Mult. Flow, vol.16, 1990, p.789.

[18] Y. Sibamotu, et. al., "Simultaneous measurement of fluid temperature and phase during water jet injection into high temperature melt", The 11th International Topical Meeting on Nuclear Thermal-Hydraulics, (NURETH-11), No. 181, Avigon, France, 2005, 2-6, Oct.

[19] S. Wang, et al. "Evaluation of a Steam Generator Tube Rupture Accident in an Accelerator Driven System with Lead Cooling", Progress in nuclear energy", Vol. 50, No. 2-6, 2008, pp.363-369.