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A modular approach to lead-cooled reactors modelling

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A B S T R A C T

After an overview of the lego plant simulation tools (LegoPST), the paper gives some details about the ongoing LegoPST extension for modelling lead fast reactor plants. It refers to a simple mathematical model of the liquid lead channel dynamic process and shows the preliminary results of its application in dynamic simulation of the BREST 300 liquid lead steam generator. Steady state results agree with reference data [IAEA-TECDOC 1531, Fast Reactor Database, 2006 Update] both for water and lead.

1. Introduction

In the field of real time power plant dynamic simulation, CESI RICERCA specialists developed an integrated software environment, named 'lego plant simulation tools' (LegoPST), able to model the whole plant, from the field (plant process and machinery) to the Human Machine Interface [1,2]. LegoPST was successfully used to build dynamic plant simulators both in nuclear (LWR) [3,4] and conventional field [5–7] to verify plant control and automation system, for plant operation transient analysis and plant operators training.

In the frame of the European Project ELSY, the extension of the LegoPST capability to lead fast reactor plants simulation is ongoing in order to study and verify plant control strategy during normal and abnormal plant operational transients. The first step of this activity consists in the extension of the coolant physical properties to liquid lead and in the development of a simple liquid lead channel mathematical model. The performances of the updated computational model have been provisionally tested by simulating a steam generator of the russian reactor design BREST 300.

2. Lego plant simulation tools

The LegoPST suite consists in different integrated tools covering all plant simulator building steps, from the design to the final simulator including debugging, monitoring and configuration:

Lego Process CAD (LegoPC) for process models development and test.
Lego Automation CAD (LegoAC) that allows full graphic editing of automation schemes.
LegoHMI for Plant Display and Operating Window building and configuration.

The EXECUTIVE which manages the running of the whole simulator, created connecting process, automation and HMI multiple models.

2.1. Process CAD

The process model builder LegoPC is a modular and open system: a model is built by assembling instances of general purpose models taken from expandable libraries. The default library include the models of many power plants components (valves, pipes, pumps, drums, evaporators, etc.) referred to water, air and flue gas as process fluids.

It covers and sequences all the phases of process building and testing: models topology build-up, input assignment, steady state and transient calculation and output analysis.

The plant section model is built by selecting the component model (valve, header,...) from a graphical library and drawing the plant section on a graphical page (see Fig. 1) linking the components input–output physical terminals. That is translated into a global differential and algebraic equation non-linear system (Fig. 2) solved via a Newton–Raphson iterative method.

2.2. Liquid lead physical properties

To solve the equation system derived from the power plant process modelling, the fluid-dynamic mechanism (heat transfer, head loss, etc.) and fluid physical properties correlations (density, thermal conductivity, etc.), as well as state equations, are to be coupled. This way, the LegoPC library of fluid physical properties was extended to liquid lead to perform lead fast reactors simulation, as reported in the followings.

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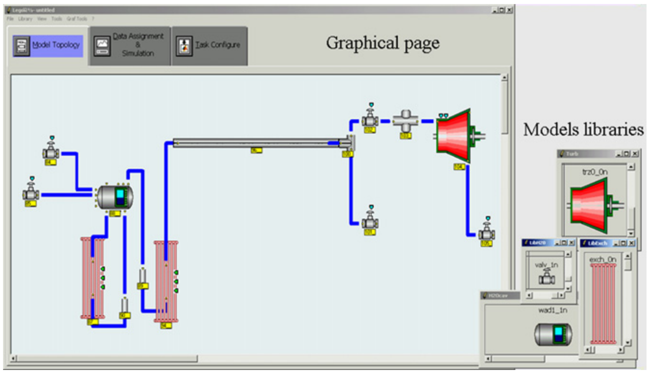

Fig. 1. LegoPC graphical interface.

Lead temperature T [K] as function of specific enthalpy H [J kg^{-1}] [8]:

$$T = 19.66X^4 - 152.47X^3 + 362.5X^2 + 1101.25X - 7.24X^{-1} + 235.14, \quad (1)$$

$X = H/200\,000$; [64.5 kJ kg^{-1} < H < 494.3 kJ kg^{-1}].

Heat capacity $\mathbf{C_p}$ [J kg^{-1} K^{-1}] [8], density ρ [kg m^{-3}] [9], thermal conductivity κ [W m^{-1} K^{-1}] [9] and dynamic viscosity μ [Pa s] [9]:

$$\mathbf{C_p} = (36.287 - 10.28 \times 10^{-3}T^{-3} - 3.158 \times 10^5 T^{-2} + 4.113 \times 10^{-6}T^2 - 4.35 \times 10^{-10}T^3)/207.2 \times 10^{-3}, \quad (2)$$

[600.65 K < T < 3600 K].

$$\rho = 8.6 \times 10^{-5}(T - 600.65)^2 - 1.246T + 10.61 \times 10^3 \quad [600.65\ \mathrm{K} < T < 1823\ \mathrm{K}], \quad (3)$$

$$\kappa = 15.0 + 0.75 \times 10^{-2}(T - 600.65) \quad [600.65\ \mathrm{K} < T < 1326\ \mathrm{K}], \quad (4)$$

$$\mu = 0.412 \times 10^{-3} \exp(1167.84T^{-1}) \quad [600.65\ \mathrm{K} < T < 1400\ \mathrm{K}]. \quad (5)$$

2.3. Liquid lead steam generator model

To build the model of a liquid lead circuit, it was also needed to extend the LegoPC components library. A one-dimensional dynamic model of a liquid was firstly developed in a lumped parameter approach lead pipe, applying the mass, momentum and energy (in the enthalpy form) conservation equations for an incompressible fluid to a generic volume of a long pipe. Then, the developed model was characterized to simulate the shell side of a lead steam generator.

According to the mathematical model, the tubes external temperature is a boundary condition, while lead bulk temperature and lead-tubes heat transfer coefficient are calculated variables, that is a relevant characteristic that allows to build a complete model of a lead steam generator (Fig. 3) linking together multiple blocks of lead shell model and a pre-existing water–steam tubes bundle model.

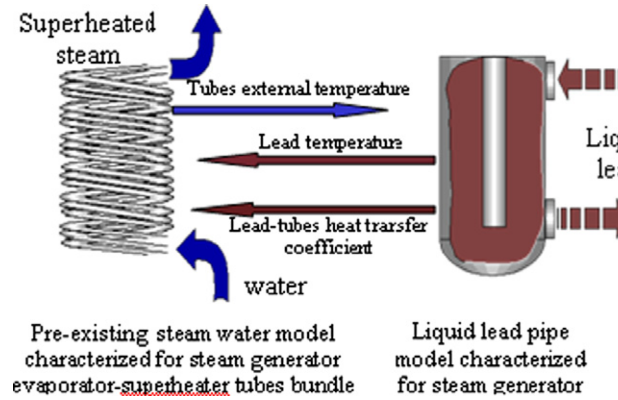

Fig. 3. LegoPC liquid lead steam generator model.

3. BREST 300 steam generator model

The BREST 300 (Fig. 4), one of the most advanced LFR projects, has four once-through steam generators working in supercritical

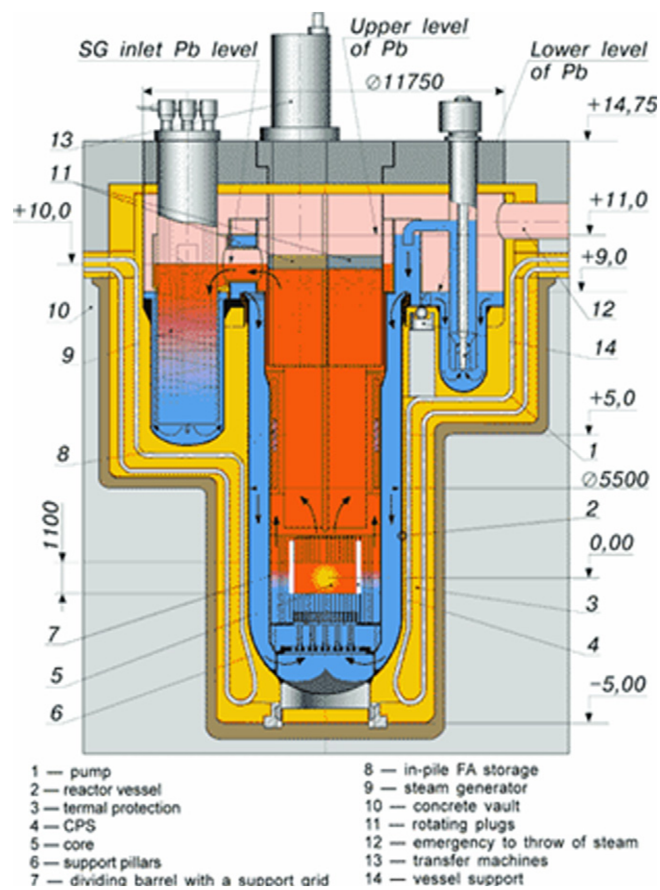

Fig. 4. LFR BREST 300 – vertical section.

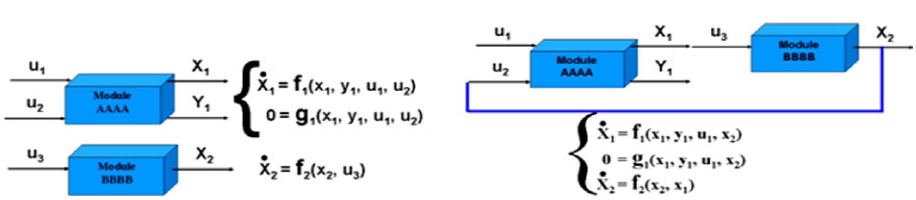

Fig. 2. LegoPC module link translation into a differential algebraic non-linear equation system.

conditions. Within each steam generator, the water–steam mixture flows inside helicoidal coil tubes bundles, and liquid lead is in counter-current flow.

To perform a preliminary test of the LegoPC capabilities in LFR modelling, taking as reference the available data of the BREST 300 [10–12] (Tables 1 and 2) the simplified model of a plant section was built (Fig. 5). Each plant section includes: one steam generator, the main steam pipe, the main steam stop valve, the steam turbine bypass valve and a simple steam pressure control chain which manages the bypass valve.

The assumed scenario to evaluate dynamic behavior of the model is quite comparable to a plant load rejection. In that case, the resulting steam turbine trip sets the main steam stop valve rapid closure (Fig. 6), consequently the main steam pressure increases (Fig. 7) over the prefixed set-point an the bypass valve opens to control the pressure itself (Fig. 8).

Table 1
BREST 300 steam generator data

Evaporator and superheater tubes		Shell	
Material	9Cr–1Mo	External casing inner diameter	2.25 m
Outer diameter	17 mm	Internal casing outer diameter	1 m
Thickness	3 mm	Height	6 m
Average length	28 m		
Number	580		
Heat transfer area	852 m^2		
Number of helical rows	20		

Table 2
BREST 300 steam generator design conditions

	Water–steam	Liquid lead
Mass flow rate [kg s^{-1}]	115	10400
Inlet temperature [K]	608	813
Outlet temperature [K]	798	693
Outlet pressure [Pa]	26×10^6	

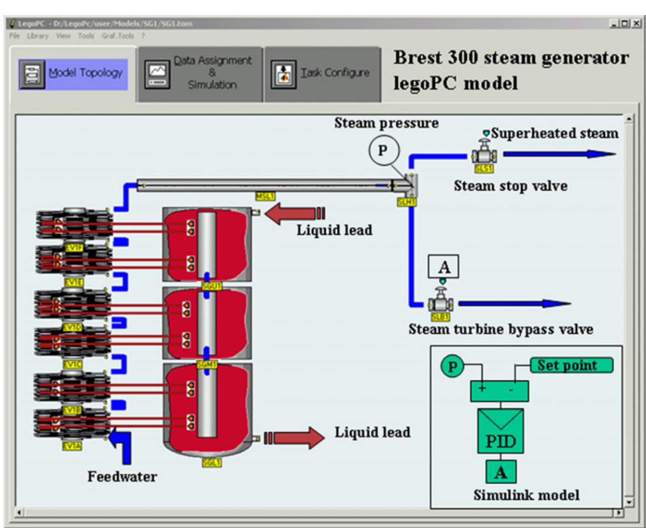

Fig. 5. BREST 300 steam generator LegoPC model.

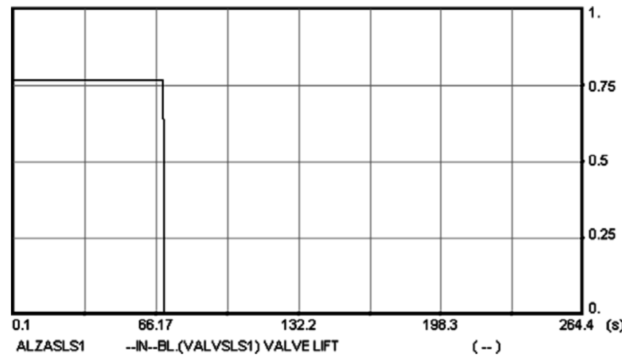

Fig. 6. Stop valve actuator position [p.u.].

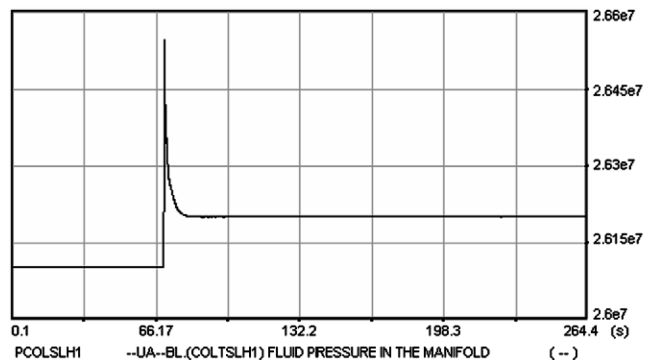

Fig. 7. Steam pressure [Pa].

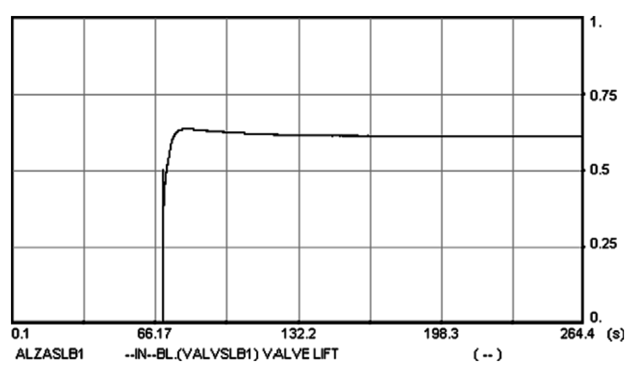

Fig. 8. Bypass valve actuator position [p.u.].

Table 3 resumes steady state results compared to the reference data [10]. The results agree with the reference both for water and lead. In particular, the lead outlet temperature deviation from the expected value is less than the 2% of the temperature difference between the steam generator inlet–outlet.

Figs. 9 and 10 report the time evolution of the steam and lead outlet conditions. Even if reference data related to this operation transient are not yet available, a reasonable dynamic behavior of the system is obtained.

Table 3
BREST 300 steam generator – LegoPC model steady state results

	Water–steam			Liquid lead		
	Calculated	Expected	$\|\Delta\varepsilon\|/\|\Delta T\|$ [%]	Calculated	Expected	$\|\Delta\varepsilon\|/\|\Delta T\|$ [%]
Outlet temperature [K]	789	798	4.7	695	693	1.7

$|\Delta\varepsilon|/|\Delta T|$ = |Calculated temperature − expected temperature|/|outlet temperature − inlet temperature|

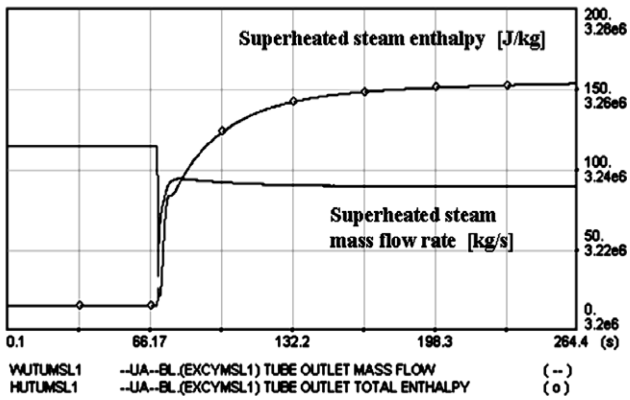

Fig. 9. Steam outlet enthalpy [J kg^{-1}] and mass flow rate [kg s^{-1}].

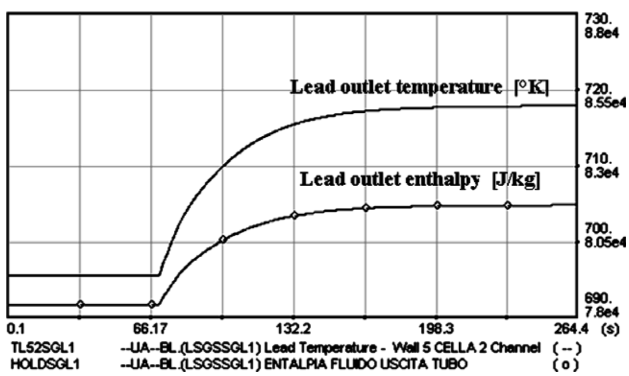

Fig. 10. Liquid lead outlet temperature [K] and enthalpy [J kg^{-1}].

4. Conclusion

The satisfactory results of the preliminary test confirm the effectiveness of the LegoPST modular approach in lead fast reactor modelling to analyse plant operational transients in real time. This first step permits to plan the development of new component models (as valves, pumps or drums), whose validation will require comparisons with experimental measurements or with the responses given by other computational tools.

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