RICERCA DI SISTEMA ELETTRICO

Relazione programmatica sul simulatore

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RELAZIONE PROGRAMMATICA SUL SIMULATORE

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Settembre 2010

Titolo

Relazione Programmatica sul Simulatore

Ente emittente   CIRTEN

PAGINA DI GUARDIA

Descrittori

Tipologia del documento: Rapporto Tecnico

Collocazione contrattuale: Accordo di programma ENEA-MSE: tema di ricerca "Nuovo nucleare da fissione"

Argomenti trattati: Reattori nucleari evolutivi
Reattori nucleari ad acqua
Controllo dei reattori nucleari

Sommario

Il documento descrive il software sviluppato dal Politecnico di Milano per un simulatore di impianto che sia in grado di affrontare problematiche di controllo e gestione di reattori nucleari. La caratteristiche chiave di tale simulatore sono:

- modularità, l'intero sistema reattore è costruito connettendo i modelli dei singoli componenti, che sono indipendenti dale diverse condizioni al contorno;
- accessibilità, ogni componente è facilmente identificabile e modificabile da utenti esperti;
- efficienza, la velocità di calcolo è elevata;
- affidabilità, il software è testato ed è disponibile ampia documentazione.

Per raggiungere questi obiettivi, come base per lo sviluppo del simulatore è stato utilizzato il linguaggio Modelica. Questo linguaggio è il risultato dei recenti sviluppi nel campo della modellistica "object-oriented" per multi-fisica e dinamica del sistema. Esso ha il vantaggio di essere open-source ed è già stato utilizzato in diversi campi industriali.

Il caso test per l'applicazione di questo approccio "objected-oriented" è stato il reattore nucleare di tipo integrale IRIS
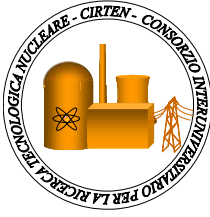
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REPORT PAR 2007 LP5.B - CERSE-POLIMI RL 1145/2010

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Copia n.   **In carico a:**

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2			NOME				
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			FIRMA				
0	EMISSIONE	27.9.2010	NOME		NA	S. Monti	NA
			FIRMA				

CIRTEN

CONSORZIO INTERUNIVERSITARIO

PER LA RICERCA TECNOLOGICA NUCLEARE

POLITECNICO DI MILANO

DIPARTIMENTO DI ENERGIA, Sezione INGEGNERIA NUCLEARE-CeSNEF

Relazione programmatica sul simulatore

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CERSE-POLIMI RL-1145/2010

Milano, Settembre 2010

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EXECUTIVE SUMMARY

This document presents the development of an adequate modeling and simulation tool for Dynamics and Control. The key features of the developed simulator are: "Modularity" - the system model is built by connecting the models of its components, which are written independently of their boundary conditions; "Openness" - the code of each component model is clearly readable and close to the original equations and easily customized by the experienced user; "Efficiency" - the simulation code is fast; "Tool support" - the simulation tool is based on reliable, tested and well-documented software.

To achieve these objectives, the Modelica language was used as a basis for the development of the simulator. The Modelica language is the result of recent advances in the field of object-oriented, multi-physics, dynamic system modelling. The language definition is open-source and it has already been successfully adopted in several industrial fields.

The test bed for the application of the object-oriented approach has been the new generation, integral type, IRIS nuclear reactor. To provide the required capabilities for the analysis, specific models for the nuclear reactor components have been developed, to be applied for the dynamic simulation of the IRIS integral reactor, albeit keeping general validity for PWR plants. The following Modelica models have been written to satisfy the IRIS modelling requirements and are presented in this work: point reactor kinetic, fuel heat transfer, control rods model, and a once-through type steam generator, thus obtaining a specific library of nuclear models and components. As far as other classical power generation plant components are concerned, the ThermoPower open library, developed at Politecnico di Milano as well, has been adopted and is briefly presented in the report. Originally conceived for conventional, fossil-fired plants, the highly modular approach allowed to effectively re-use the models of the balance of plant systems, which have been connected to the models of the nuclear power generation process, to obtain a system simulator for the IRIS reactor.

1   INTRODUCTION

Academic education and operational training of engineers and power plant operators is essential for their acquiring the necessary knowledge, skills and qualification for designing and operating a nuclear power plants, and for effective feedback of real life experience including human based operating errors. To develop, assess, monitor and improve functional competence of nuclear engineers and nuclear power plant staff, it is essential to use adequate simulation tools, assessment methods and training support and management tools working in close relation and warranting quality and traceability.

As a statement of general validity, the key features for an optimal reactor system simulator appear to be: "Modularity" - the system model should be built by connecting the models of its components, which have to be written independently of their boundary conditions; "Openness" - the code of each component model should be clearly readable, close to the original equations and easily customised by the experienced user; "Efficiency" - the simulation code should be fast running; "Tool support" - the simulation tool should be based on reliable, accurate, tested and well-documented software.

Few simulation environments and tools fulfilling all the above mentioned characteristics seem to be currently available for nuclear applications. Recent advances in the field of object-oriented, multi-physics, dynamic system modelling led to the definition of the Modelica language, representing a viable path to achieve the above-mentioned goals. The language definition is open-source and it has already been successfully adopted in different fields, such as automotive, robotics, thermo-hydraulic and mechatronic systems.

In this frame, specific models for nuclear reactor components have been developed, to be applied for the dynamic simulation of the IRIS integral reactor albeit keeping general validity for PWR plants. The reactor pressure vessel houses not only the nuclear fuel, control rods and control rods drive mechanisms, and support structures, but also all the major reactor coolant system components including the coolant pumps, the steam generators and the pressurizer, as depicted in Fig. 1.
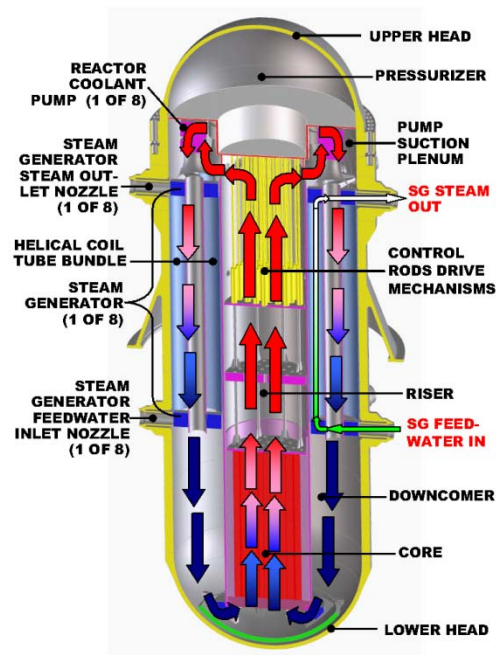
Fig. 1. IRIS reactor view and main components (arrows show primary fluid path).

Steam generator (Cioncolini et al., 2003) and pressurizer (Popov and Yoder, 2008) components, together with the internal control rod drive mechanism (Conway et al., 2004), represent innovative features with respect to current PWRs, thus requiring a further effort in terms of modelling. In particular: i) the steam generators are of once-through type, framed into modules and made up by helical coil tube bundles 30 m long, with the secondary two phase mixture generated inside the tubes and flowing upward, while the primary flow rate is in downward crossflow on the external side; ii) the pressurizer is placed into the reactor pressure vessel, therefore it represents a large volume of saturated steam and saturated or subcooled liquid, with a non regular geometry and without sprays as one of the pressure control systems; iii) the internal control rod drive mechanism (ICRDM) considered for this study has been the hydraulically driven type (Ricotti et al., 2003), with an external pump system supplying the required flow rate and pressure to sustain the hydraulic piston, to which the control rods are linked, and with a set of valves needed to temporarily modify the equilibrium pressure, thus allowing the withdrawal and insertion steps. Notwithstanding the IRIS design has recently moved towards a different technological solution, i.e. an ICRDM based on electro-magnetic motors and devices, the models library includes also this type of component, the adoption of which is foreseen in other integral type reactor designs (Xiaotian and Shuyan, 2006; Fukami and Santecchia, 2000).

Besides the inherent distinctive design characteristics of the main components, other features affect the dynamic response of the reactor and significantly differ from current plants: the large water inventory of the integral reactor is three times that of an equivalent PWR of the same power, resulting in an increased thermal inertia of the primary fluid; the large volumes of the primary side, mainly the riser and the downcomer, lead to a wide characteristic period for the primary circuit transit time, one order of magnitude bigger than current plants; on the other hand, the once-through type steam generators allow a quick response of the component on the secondary side, because of the reduced secondary fluid inventory and thermal inertia.

As a consequence of the above mentioned considerations, a dynamic simulator of an innovative, integral reactor has been set up, in order to study the dynamic response of IRIS, by adopting the Modelica object-oriented language. The primary and secondary systems of the reactor have been simulated, by assembling component models already available in a specific thermal-hydraulic library and suitable nuclear component models developed for this specific purpose. Both the language and the models are described in the following sections, with preliminary results of test transients reported as well.

2   MODELICA - OBJECT-ORIENTED LANGUAGE FOR SYSTEM AND PLANT SIMULATION

The Modelica language (Mattsson et al., 1998; Modelica Association web site, 2007; Fritzson, 2004) was first introduced in 1997, as the product of an international cooperative effort toward the definition of an object-oriented language for the modelling of general physical models, described by algebraic and differential equations. The key features of the language are briefly summarised.

A-causal modelling. The equations of each model are written independently of the actual boundary conditions, without deciding a-priori which are the inputs and which are the outputs. The causality of the model is determined automatically by the Modelica model interpreter or compiler at the aggregate level, when a system model is assembled out of elementary ones. In this way, models are much easier to write, document, and reuse, while the burden of determining the actual sequence of computations required for the simulation is entirely left to the compiler.

Code transparency. Equations written in Modelica models tightly match the way they are written on report, so that it is very easy to understand what's inside a given model, as well as to modify or enhance it.

Encapsulation. The models of a system components are connected through rigorously defined interfaces or "connectors" corresponding to the physical interaction with the outside whole. For example: electrical connectors carry a voltage and a current, thermal connectors carry a temperature and a heat flow, and so on. As long as two different components have compatible connectors, they can be bound together, regardless of their inner details. This feature is essential for the development of libraries of re-usable models; moreover, it allows to easily replace a part of a system model with a more detailed or a more simplified one, without affecting the rest of the model.

Inheritance. Model libraries can be given a hierarchical structure, in which more complex models are obtained from basic models by adding specific variables, equations or even models. For example, it is possible to write the equations describing the flow of a generic gas in a tube; the model of the flow of a particular, e.g. a multi-component ideal gas mixture, can be obtained by inheriting from the general one and by adding the specific model of the ideal gas.

Multi-physics modelling. The Modelica language is general in scope, as it provides modelling primitives such as generic algebraic, differential and difference equations, and is not tied to any specific engineering domain, such as mechanics, electrical engineering, or thermodynamics. It is then quite straightforward to model systems having a multi-disciplinary nature, such as mechatronic systems, resulting from the interaction of mechanical, electrical and control sub-systems, or nuclear plants, resulting from the interaction of thermo-hydraulic, nuclear and control sub-systems.

Reusability. A-causal modelling and encapsulation are a strong incentive towards the development of libraries of general-purpose reusable models for different engineering domains. Some basic standard libraries are already included

in the definition of the Modelica language, while others are being developed for more specific domains, either as open-source or as proprietary codes.

The Modelica language has already been applied to a wide range of system modelling problems in different engineering domains, as demonstrated by the topics in the annual international conference specifically devoted to it (Otter, 2002; Fritzson, 2003; Schmitz, 2005; Kral, 2006).

When developing a new application using Modelica, it is often the case that some, or most, of the needed models are already available in some previously developed library, so that it is possible to concentrate the effort on the writing of the fewer models which are not already available. In the case of the project illustrated in this work, it has been possible to develop the model of a complete nuclear power plant by only writing the models of the nuclear power generation processes, and then connecting them to taken from the ThermoPower library (Casella and Leva, 2003, 2006), which was not originally conceived to deal with nuclear power plants.

As to the efficiency of the actual simulation code obtained from a complex Modelica model, one may wonder whether the possibility of describing the process with a high-level modelling language has to be paid in terms of increased computational burden. It turns out that this is usually not the case: Modelica compilers incorporate sophisticated symbolic manipulation algorithms, which allow, among other things, to obtain index-1 systems of differential-algebraic equations from higher-index ones, to symbolically solve both linear and non-linear model equations, and to find efficient calculation sequences through sorting and automatic tearing of system equations; the resulting code is then linked to state-of-the-art numerical integration codes such as DASSL (Brenan et al., 1989). All of this process is completely transparent to the user, and the resulting efficiency is often comparable, or even higher, than that of laboriously hand-crafted Fortran, C or Matlab code, which is error-prone and hard to document and reuse.

Finally, it is worth noting that the definition of the Modelica language, owned by the non-profit Modelica Organisation, is in the public domain, so it is not tied to any specific simulation tool vendor. As of today, there are two commercial tools supporting this language: Dymola (2008), which was used in this project, and MathModelica (2008). An open-source tool, OpenModelica (2008), has been under development for several years, and is expected to be usable for industrial-strength projects in a few years. Other simulation tool vendors, such as LMS-Imagine and ITI, are currently developing Modelica-compatible front-ends for their tools. It is therefore expected that good support for this language will be available and improved in the long term.

3 LIBRARY STRATEGY: "THERMOPOWER" COMPONENTS AND MODELS

The complete model of the IRIS reactor has been built using models from two different libraries: ThermoPower and NUKOMP.

The ThermoPower library has been developed as an open-source library for the modelling of thermal power plants at the system level, to support the design and validation of control systems. The library has been developed according to the following guidelines:

a) models are derived from first principle equations whenever possible, e.g. mass, momentum, and energy dynamic balance equations, or from acknowledged empirical correlations;

b) the level of detail of the models is flexible, up to the maximum fidelity which is compatible with a system-level simulation, e.g. ruling out complex models with 3-dimensional CFD;

c) the structure of the model interfaces is as simple as possible and is independent of the modelling assumptions inside each model (lumped-parameter vs. distributed-parameter model, one-phase vs. two-phase flow, homogeneous vs. non-homogeneous flow, inertial effects accounted for or neglected, etc.), so that models of specific parts of the process can be effortlessly replaced with more accurate or more simplified counterparts;

d) the library is structured with a limited use of the inheritance mechanism, so that the code of a particular physical component is not scattered through many different classes; in this way, it is straightforward to understand the equations of a specific model by just looking in a single place in the code;

e) the library is an open-source software and available on the Web (ThermoPower Home Page, 2008).

As for the simulator of the IRIS integral reactor, several ThermoPower models have been used without modification. Their modelling principles are summarised here; for further details, the reader is referred to (Casella and Leva, 2003, 2006), as well as to the online documentation in (ThermoPower Home Page 2008). As an example, the detailed equations and the corresponding Modelica code given in the solving system Eq.(1) and Fig. 2 refer to the header, a thermalhydraulic basic component corresponding to a control volume in the best estimate system codes. This gives a flavour of the way models are formulated in an object-oriented context.

The model of the fluid flow in a cylindrical conduit is based on the dynamic mass, energy, and momentum conservation equations, which are originally given as one-dimensional, partial differential equations. Since Modelica can only describe systems of ordinary differential-algebraic equations, the original distributed-parameter model is first discretised by using either the finite-volume method (Casella, 2006), or a Petrov-Galerkin finite-element method (Schiavo and Casella, 2007). The model is formulated in order to correctly handle possible flow reversal conditions. A homogeneous model, i.e. same velocity for the liquid and vapour phases, is adopted for two-phase flow conditions. The heat transfer coefficients are computed using Dittus-Boelter's and Chen's correlations.

The fluid flow model is used both for the primary side, i.e. the core coolant loop, and for the secondary side, i.e. the once-through steam generators.

The heat transfer model computes the actual heat flow between two 1-dimensional interacting objects, usually a fluid and a metal wall. The heat transfer coefficient can be assumed either as constant, or supplied by the fluid flow model.

A cylindrical metal wall is modelled by a simplified 1-dimensional version of Fourier's equations: the thermal resistance is computed according to the formulation of Fourier's equation in cylindrical coordinates, while the heat capacity terms are lumped in the middle of the tube thickness. This model is used to represent the steam generator pipe walls.

A turbulent, lumped pressure drop model is assumed, proportional to the kinetic pressure.

Other specific models refer to typical power plant components. As an example, the coolant pump model is based on the characteristic curves of the centrifugal pumps, the first relating head, flow rate and shaft speed, the second to compute the mechanical power consumption; the thermal effects of the pump on the fluid are thus correctly represented.

The header is modelled as a rigid plenum filled with water exchanging heat, with a metal wall having a finite thermal capacitance. If the pressure P and the specific enthalpy h of the fluid and the wall temperature T_m are chosen as the state variables, it is possible to write the mass, energy and momentum balances for the fluid and the energy balance for the metal wall as:

$$\begin{cases} V\left(\dfrac{\partial \rho}{\partial P}\dfrac{dP}{dt} + \dfrac{\partial \rho}{\partial h}\dfrac{dh}{dt}\right) = w_i + w_o \\[3mm] V\left[\left(h\dfrac{\partial \rho}{\partial P} - 1\right)\dfrac{dP}{dt} + \left(\rho + h\dfrac{\partial \rho}{\partial h}\right)\dfrac{dh}{dt}\right] = w_i h_i + w_o h_o - \gamma\, S\,(T - T_m) \\[3mm] C_m \dfrac{dT_m}{dt} = \gamma\, S\,(T - T_m) \\[3mm] P = P_o \\[3mm] P_o - P_i = \rho g H \end{cases} \qquad (1)$$

where ρ is the fluid density, P is the fluid pressure, w_i and w_o are the inlet and outlet flow rates (assumed positive when entering), P_i and P_o the corresponding pressures, h_i and h_o the corresponding specific enthalpies, T is the fluid temperature, C_m is the metal wall thermal capacity, γ is the fluid-metal heat transfer coefficient, S is the fluid-metal interface area, H the height of the inlet over the outlet.

The model is connected to the outside world through two connectors of type referred as "FlangeA" and "FlangeB", having the Modelica code definition as reported in Fig. 2.

When an A-type connector is bound to a B-type connector, connection equations are generated automatically: the sum of the flow variables is zero while the remaining variables having the same name are equalled to each other.

The Modelica corresponding to Eq. (1) can be written as shown in Fig. 2.

The actual code is slightly more complex, in order to provide features such as a replaceable fluid model, whose description is however beyond the scope of this work.

As mentioned above, two important features are worth stressing again: the model code tightly resembles the way equations are written on report, and the model equations are written using the boundary conditions provided by the two connectors, without introducing artificial causality, and without bothering how the specific model equations, coupled with the outside world equations, will be actually solved by the final simulation code.

```
connector FlangeA "A-type flange connector for water/steam flows"
  Pressure p "Pressure";
  flow MassFlowRate w "Mass flowrate";
  output SpecificEnthalpy hAB "Specific enthalpy of fluid going out";
  input SpecificEnthalpy hBA "Specific enthalpy of entering fluid";
end FlangeA;

connector FlangeB "B-type flange connector for water/steam flows"
  Pressure p "Pressure";
  flow MassFlowRate w "Mass flowrate";
  input SpecificEnthalpy hAB "Specific enthalpy of entering fluid";
  output SpecificEnthalpy hBA "Specific enthalpy of fluid going out";
end FlangeB;
```

```
model Header "Header with metal walls for water/steam flows"
  parameter Volume V "Inner volume";
  parameter Area S "Inner surface";
  parameter CoefficientOfHeatTransfer gamma=0 "Heat Transfer Coefficient";
  parameter HeatCapacity Cm "Metal Heat Capacity";
  parameter Length H "Height of inlet over the outlet";
  parameter Pressure pstart "Pressure start value";
  parameter SpecificEnthalpy hstart "Enthalpy start value";
  parameter Temperature Tmstart "Metal wall start temperature";
  constant  Acceleration g = 9.80665;
  FlangeA inlet;
  FlangeB outlet;
  Pressure p(start=pstart);
  SpecificEnthalpy h(start=hstart), hi, ho;
  Density rho;
  DerDensityByPressure drdp;
  DerDensityByEnthalpy drdh;
  Temperature T, Tm(start=Tmstart);
equation
  (T,rho,drdp,drdh) = water_prop_ph(p, h);
  V*(drdp*der(p) + drdh*der(h)) = inlet.w + outlet.w;
  V*((h*drdp-1)*der(p) + (rho+h*drdh)*der(h))=
           inlet.w*hi + outlet.w*ho - gamma*S*(T-Tm);
  if Cm > 0 then Cm*der(Tm) = gamma*S*(T - Tm);
           else Tm = T;
  end if;
  outlet.p = p;
  outlet.p - inlet.p = rho*g*H;
  hi = if inlet.w  >= 0 then inlet.hBA  else h;
  ho = if outlet.w >= 0 then outlet.hAB else h;
  inlet.hAB = h;
  outlet.hBA = h;
end Header;
```

Fig. 2. Modelica language: connection type definition and component modelling examples.

4 "NUKOMP" LIBRARY: COMPONENTS AND MODELS

The models available in the ThermoPower library allowed a fast assembling of the largest part of the reactor primary and secondary systems. The remaining components, i.e. the pressurizer, the reactor core and the hydraulically driven ICRDM, have been ad-hoc simulated by writing suitable models, derived from elaborating open literature (Todreas and Kazimi, 2001) or previous works (Brega et al., 1996; Vitulo, 2003), thus leading to a first release of the NUKOMP library of Nuclear Components and Models, specific for nuclear reactor components.

The pressurizer model has been written by considering a separate phases approach. The core has been simulated by assembling a neutron kinetics model and a thermal model for the fuel. The nuclear component models are briefly described in the following paragraphs.

4.1 Pressurizer Model

The physical model is based on a non-equilibrium, two regions formulation of the fluid balance equations with a control volume approach, as shown in Fig.3. The two regions are supposed to be isobaric and singularly isothermal, and will be referred to as liquid zone and vapour zone, respectively. The mathematical model is a system of coupled, nonlinear equations in five primary unknowns, namely the liquid zone mass (M_l) and the vapour zone mass (M_v), the corresponding enthalpies (h_l and h_v) and the system pressure (p_v). The solving system refers to the mass and energy balance equations for the liquid zone (Eq.2 and 3, respectively) and the vapour zone (Eqs.4 and 5), plus a congruence equation on the control volume, as in Eq.6.

$$\frac{dM_l}{dt} = \Gamma_{sl} + \Gamma_{cnd} + \Gamma_{spr} - \Gamma_{eva} - \Gamma_{l,rel} - \Gamma_{l,saf} \tag{2}$$

$$\frac{d}{dt}(M_l h_l) = \Gamma_{sl} h_{sl} + \Gamma_{cnd} h_{l,sat} + \Gamma_{spr} h_{l,sat} - \Gamma_{eva} h_{v,sat} - \Gamma_{l,rel} h_l - \Gamma_{l,saf} h_l + W_{prh} + W_{bh} - W_{l,wall} + V_l \frac{dp_v}{dt} \tag{3}$$

$$\frac{dM_v}{dt} = \Gamma_{eva} - \Gamma_{cnd} - \Gamma_{v,rel} - \Gamma_{v,saf} \tag{4}$$

$$\frac{d}{dt}(M_v h_v) = \Gamma_{eva} h_{v,sat} - \Gamma_{cnd} h_{l,sat} - \Gamma_{v,rel} h_v - \Gamma_{v,saf} h_v - \Gamma_{spr}(h_{l,sat} - h_{spr}) - W_{v,wall} + V_v \frac{dp_v}{dt} \tag{5}$$

$$V = \frac{M_l}{\rho_l} + \frac{M_v}{\rho_v} \tag{6}$$

where the variables are: *M* for mass, *h* for specific enthalpy, *p* for pressure, Γ for mass flow rate, *W* for thermal power, *V* for volume, ρ for density, *t* for time, while the following subscripts hold: *l* for liquid, *v* for vapour, *sat* for saturation condition, *sl* for surge line, *cnd* for condensation, *eva* for evaporation, *spr* for sprays (note that albeit spray and relief valves are not included in the simulation presented in this work, the pressurizer model was developed to be generically applicable to PWRs), *rel* for relief valves, *saf* for safety valves, *prh* for proportional heaters, *bh* for backup heaters, *wall* for pressurizer wall heat losses. The closure equations needed are the evaporation and condensation flow rates, as reads

in Eq.7 where τ_{eva} and τ_{cnd} are the bubble rising time and the droplet falling time, and the state equations (Eq.8), as obtained from the IAPWS IF97 water properties correlations (Wagner, W., et al. 2000):

$$\Gamma_{eva} = \frac{M_l(h_l - h_{l,sat})}{\tau_{eva}(h_{v,sat} - h_{l,sat})}; \; \Gamma_{cnd} = \frac{M_v(h_{v,sat} - h_v)}{\tau_{cnd}(h_{v,sat} - h_{l,sat})} \tag{7}$$

$$h_{l,v}\big|_{sat} = f(p_v); \; \rho_{l,v} = g(h_{l,v}, p_v) \tag{8}$$
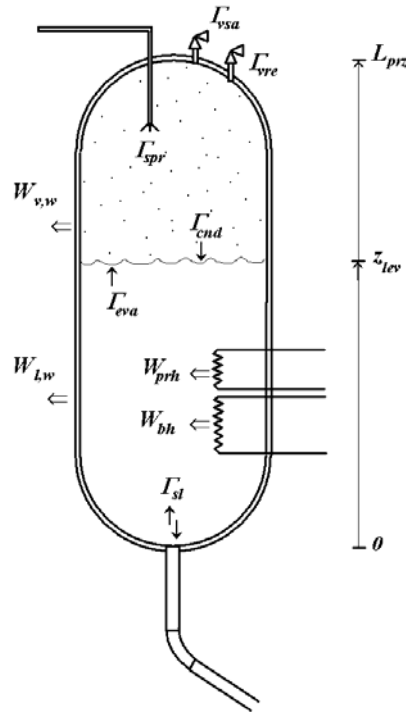

Fig. 3. Conceptual scheme for a typical pressurizer component.

4.2 Point Kinetics Neutronic Model

The neutronic power generated into the fuel is proportional to the neutronic population n, which responds to the point reactor kinetics balance equations (Eq.9 and 10):

$$\frac{dn}{dt} = \left(\frac{\rho - \beta}{\Lambda}\right)n + \sum_{i=1}^{6}\lambda_i c_i \tag{9}$$

$$\frac{dc_i}{dt} = \left(\frac{\beta_i}{\Lambda}\right)n - \lambda_i c_i \qquad i = 1,...,6 \tag{10}$$

where c is the precursor concentration leading to a delayed neutron source, ρ is the total reactivity of the core, β is the fraction of delayed neutrons, λ is the decay constant of the precursors and Λ is the mean neutron generation time. The model set up for the *NUKOMP* library is able to treat enriched uranium, plutonium or thorium-based fuels.

Reactivity feedbacks are taken into account as well, by considering linear or non linear feedback coefficients, for the coolant density effect (α_c), the fuel Doppler effect (α_f), the effect of the boron concentration (α_B) into the primary fluid as a neutronic poison and the level of insertion of the control rod banks into the core (ρ_{CR}).

These relations are reported in Eq.11:

$$\begin{cases} \rho = \rho_{CR} + \rho_f + \rho_c + \rho_B \\ \rho_f = \alpha_f \left(T_{eff} - T_{eff_0} \right) \\ \rho_c = \alpha_c \left(\frac{1}{v_c} - \frac{1}{v_{c_0}} \right) \\ \rho_B = \alpha_B \left(C - C_0 \right) \end{cases} \tag{11}$$

where T_{eff} and T_{eff_0} are the instantaneous and reference effective fuel temperature, respectively, obtained from the fuel model described in the next paragraph, v_c and v_{c_0} are the instantaneous and reference specific volumes of the coolant, C and C_0 are the instantaneous and reference boric acid concentration in the coolant. The reference values are those corresponding to the nominal, full power operation of the reactor.

4.3 Fuel Model

The time dependent Fourier equation in one dimensional cylindrical geometry is applied to the three fuel rod zones: pellet, gap and cladding. The main assumption of the model is to consider only the radial heat transfer, thus disregarding both the axial and the circumferential diffusions.

For the pellet, gap and cladding the corresponding balance equations read:

$$\rho_p c_{p,p} \frac{\partial T_p}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \, k_p \frac{\partial T_p}{\partial r} \right) + q''' \tag{12}$$

$$\frac{\partial}{\partial r} \left(r \, k_g \frac{\partial T_g}{\partial r} \right) = 0 \tag{13}$$

$$\rho_c c_{p,c} \frac{\partial T_c}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \, k_c \frac{\partial T_c}{\partial r} \right) \tag{14}$$

where ρ is the density, c_p is the specific heat, T is the temperature, k is the thermal conductivity, q''' is the volumetric source term, r is the radial dimension and t the time, while the subscripts stand for: p, the pellet, g, the gap, c, the cladding. Note that the heat capacity of the gap region has been neglected in this model.

The heat transfer model is represented in Fig.4, with the pellet discretized into three zones of equal volume. Eqs.12 to 14, together with the conditions of heat flux vanishing at the pellet centre and the continuity of the temperatures and heat fluxes at the three boundaries pellet-gap-cladding-coolant allow the determination of $T_p(r,t)$, $T_c(r,t)$ and $T_g(r,t)$.

In particular, the condition at the cladding-coolant interface reads:

$$-k \frac{\partial T_c}{\partial r} \bigg|_{r=Rc,o} = H \left(T_{Rc,o} - \overline{T}_m \right) \tag{15}$$

in which the rhs of Eq.15 refers to the coolant mean values into the core, i.e. H is the convective heat transfer coefficient and $\overline{T}_m$ is the mean water temperature over the entire core height L:

$$\overline{T}_m = \frac{\int_0^L T_m(z)\,dz}{L} \tag{16}$$

The coolant temperature profile $T_m(z)$ is obtained from the solution of the thermal-hydraulic model. In addition to the above equations, five correlations synthesising the dependences of $c_{p,p}, c_{p,c}, k_p, k_c$ as a function of the temperature and k_g as a function of both the reactor power and the burn-up have been adopted.

The effective fuel temperature, used to evaluate the Doppler feedback contribution on neutronics, is defined as follows:

$$T_{eff} = \frac{4}{9} T_{r=0} + \frac{5}{9} T_{r=R} \tag{17}$$
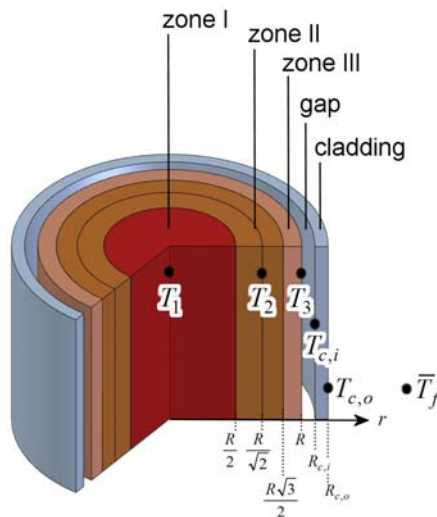

Fig. 4. Fuel pellet radial scheme for heat transfer modelling.

5   IRIS SIMULATOR: COMPARISON WITH RELAP CODE RESULTS

A Modelica-based simulator has been obtained by assembling the required components from ThermoPower and NUKOMP libraries, as shown in Fig.5. Both the primary and the secondary systems of the IRIS integral reactor have been simulated, the boundary conditions for the reactor being the steam generator feed water flow rate, temperature and pressure and the condenser pressure on the secondary side, and the control rod banks level of insertion into the core on the primary side.
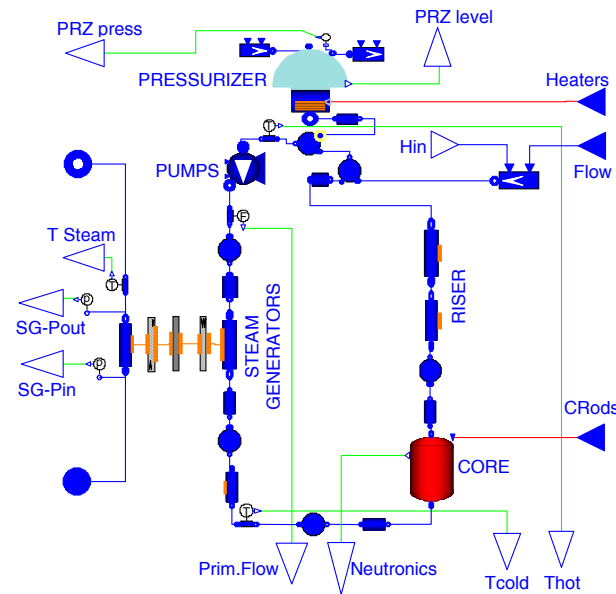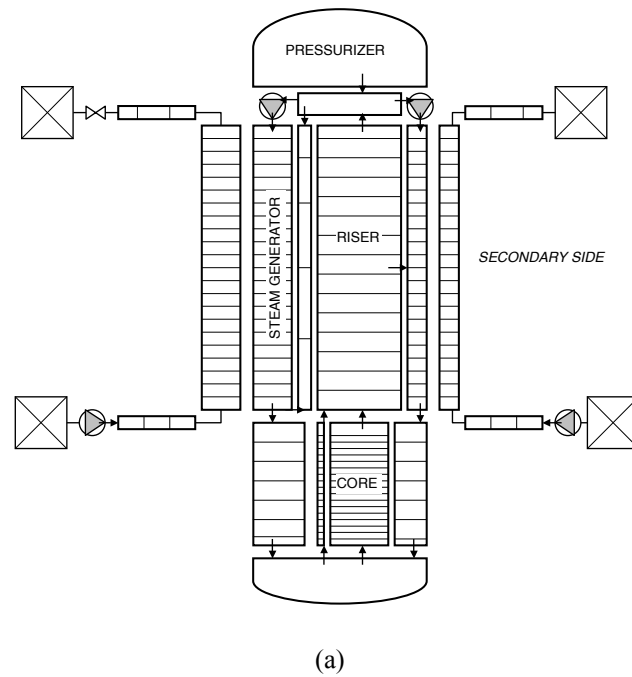
(a)

Fig. 5. RELAP nodalization scheme (a) and Modelica simulator (b) for the IRIS reactor.

The simulator has been validated against the well established, best estimate code RELAP, based on more complex and detailed thermal-hydraulic models. Moreover, a comparison with a simulator SIMULINK-based, which represents one of the most popular and widely adopted tool for dynamic simulation and control, has been carried out as well. The results are encouraging: the computational time required for the transient computation of 2000 seconds transient is

reduced by a factor about 300 (from about seven hours to less than one minute) with the Modelica model; the effort required to implement the same component models and the whole plant simulator is roughly one order of magnitude lower for the Modelica model than the SIMULINK model, roughly equivalent to some man-months in the latter case. As far as the accuracy of the results is concerned, the same degree of accuracy has been obtained by both simulators, with better results for the Modelica model when transients with stiff parameters or boundary conditions are to be simulated.

As part of this validation process, a set of open-loop transients has been analysed for the IRIS plant, namely the responses of the reactor to instantaneous step variation of i) the Feed Water flow rate, ii) the Control Rods position and iii) the Turbine Admission Valve opening. Note that at this stage of the investigation, the interest was more on the simulator performance and benchmark with different models than on the accurate and realistic analysis of various operating sequences.

During the transients, no plant controls are in operation and the pressure in the primary side is kept to constant. At the beginning of the transient, all the neutronic and thermal-hydraulic parameters are at values corresponding to the plant nominal, full power, steady-state operating conditions. A first comparison between the Modelica simulator and the RELAP code has been performed on the steady state, nominal conditions for the reactor. Table 1 summarizes the main data, showing a good agreement both between the codes and with respect to the design data for the IRIS reactor. The mismatch in the primary flow rate is due to the different correlations for water/steam properties used in Modelica and RELAP.

Parameter		IRIS design data	RELAP model data	MODELICA model data
Thermal Power	*MW*	1000	999.998	1000.000
Primary Flow Rate	*kg/s*	4500	4512.120	4588.752
Core Inlet Temp.	*K*	565.15	565.181	565.402
Core Outlet Fluid Temp.	*K*	603.15	603.082	602.716
Secondary Flow Rate	*kg/s*	502.8	502.801	502.800
Steam Temperature	*K*	590.15	590.893	590.993
Secondary Pressure	*bar*	58	58.004	58.007

Table 1

Main IRIS reactor design data at full power, nominal operating conditions, and corresponding values obtained by the RELAP code and the Modelica simulator.

5.1 Plant Dynamics – Steam Generator Feed Water Flow Rate Step reduction (20%)

The first event considered to benchmark the Modelica simulator to the RELAP5 mod3.2 plant model (Grgic et al., 2003) has been a step reduction in the steam generator feedwater flow rate by 20%. During the transient the control rod system was assumed not available, thus the core neutronics response depends only on the neutronic feedbacks. The expected plant response in these conditions is that following the reduction in feedwater flow, the heat removal rate from

the steam generators will decrease and the reactor coolant system temperature will increase as more heat is generated in the system than is removed by the steam generators. Due to the core negative feedback, the power of the reactor will decrease until a new equilibrium condition is reached at a lower power level.

The results reported in Fig. 6 and 7 show an excellent agreement between the Modelica simulator and the detailed RELAP plant model.
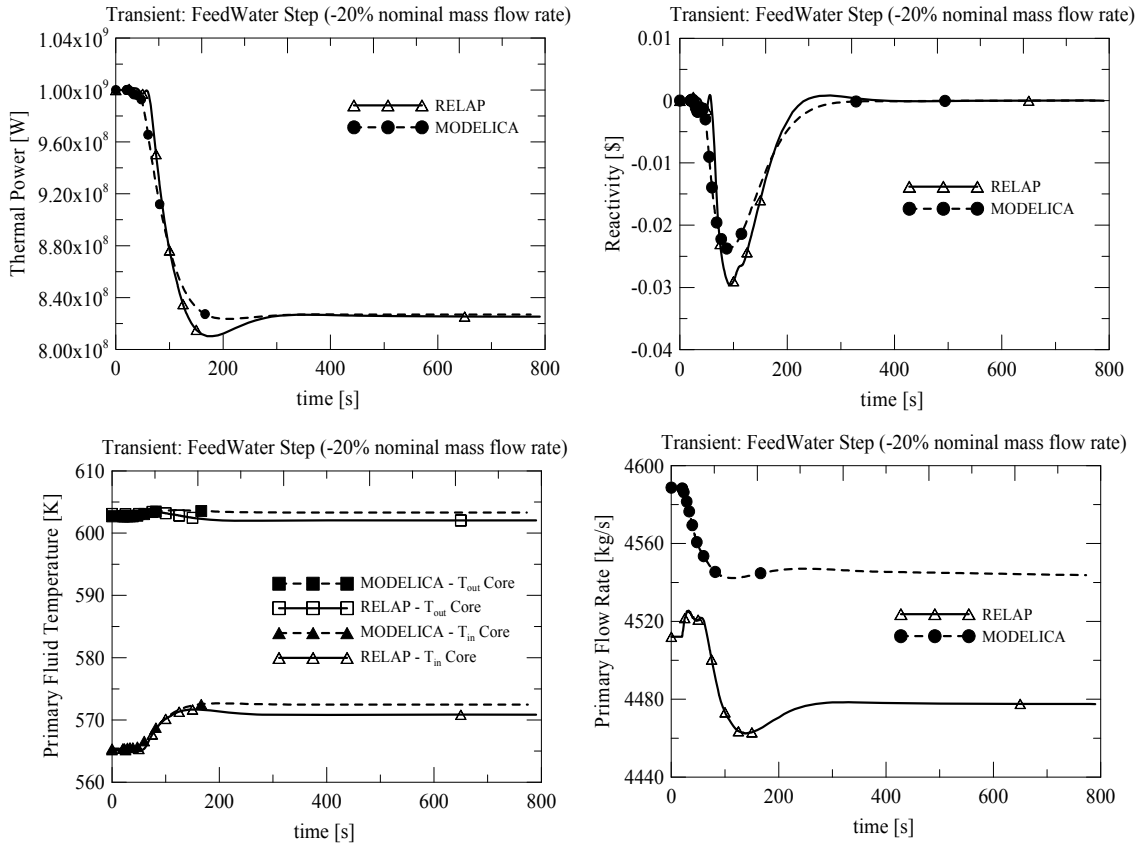

Fig. 6. Modelica vs. RELAP comparison – Core Thermal Power, Core Reactivity, Primary Temperature and Primary Flow Rate for the Feed Water flow rate step reduction (20%) transient.
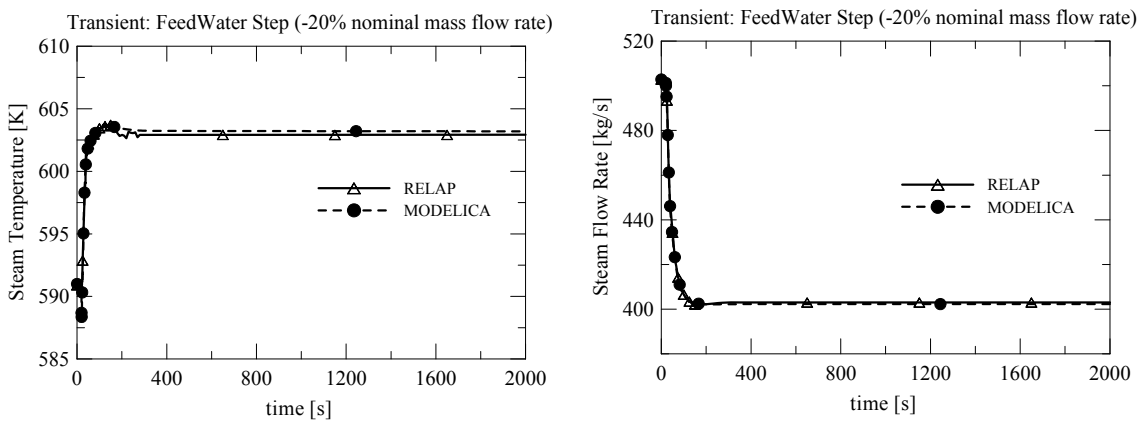

Fig. 7. Modelica vs. RELAP comparison – Steam Generator Steam Temperature and Feed Water Flow Rate for the FW flow rate step reduction (20%) transient.

During the transient the core inlet temperature increases by ∼ 6 K and the core outlet temperature decreases from 603.1 K to 602.6 K. The final equilibrium power at the end of the simulation is a function of the feedback coefficients: the more negative the doppler and moderator density coefficients, the power will be more reduced. In the presented simulation the neutronic feedback coefficients have been assumed equal to 8.86 pcm/kg m^{-3} for the mean coolant density and to –3 pcm/°C for the effective fuel temperature. Note that to allow a meaningful comparison the RELAP model was modified to adopt the same core feedback model of the Modelica simulator, since the RELAP model is devoted to safety analysis, not to operational-like transient analysis.

In this simulation, at the end of the transient after about 800 s when the overall reactivity is again at zero, the thermal power decreased from the nominal value of about 1 GW down to 0.827 GW, with a 17.3% reduction.

On the secondary side, the decrease of the feed flow rate leads to a decrease of the steam pressure, from the nominal value of 58 bar to 48 bar. The superheated steam temperature is instead increased from 591 K to 603 K.

5.2   Plant Dynamics – Control Rod Step Insertion and Withdrawal (20%, +5%)

The second event considered for the benchmark has been a control rod step insertion by 20% of the nominal worth. During the transient the core neutronics response depends only on the neutronic feedbacks. The expected plant response in these conditions is that following the insertion of the control rod, the thermal power will decrease as well as the reactor temperatures (coolant and fuel); because of the core negative feedback, the power of the reactor will increase until a new equilibrium condition is reached at a lower power level. The results are reported in Fig. 8.

The results of control rod step withdrawal simulation (insertion of 5% of nominal control rod worth) are shown in Fig. 9.

The results reported in Fig. 8 and 9 show an excellent agreement between the Modelica simulator and the detailed RELAP plant model.
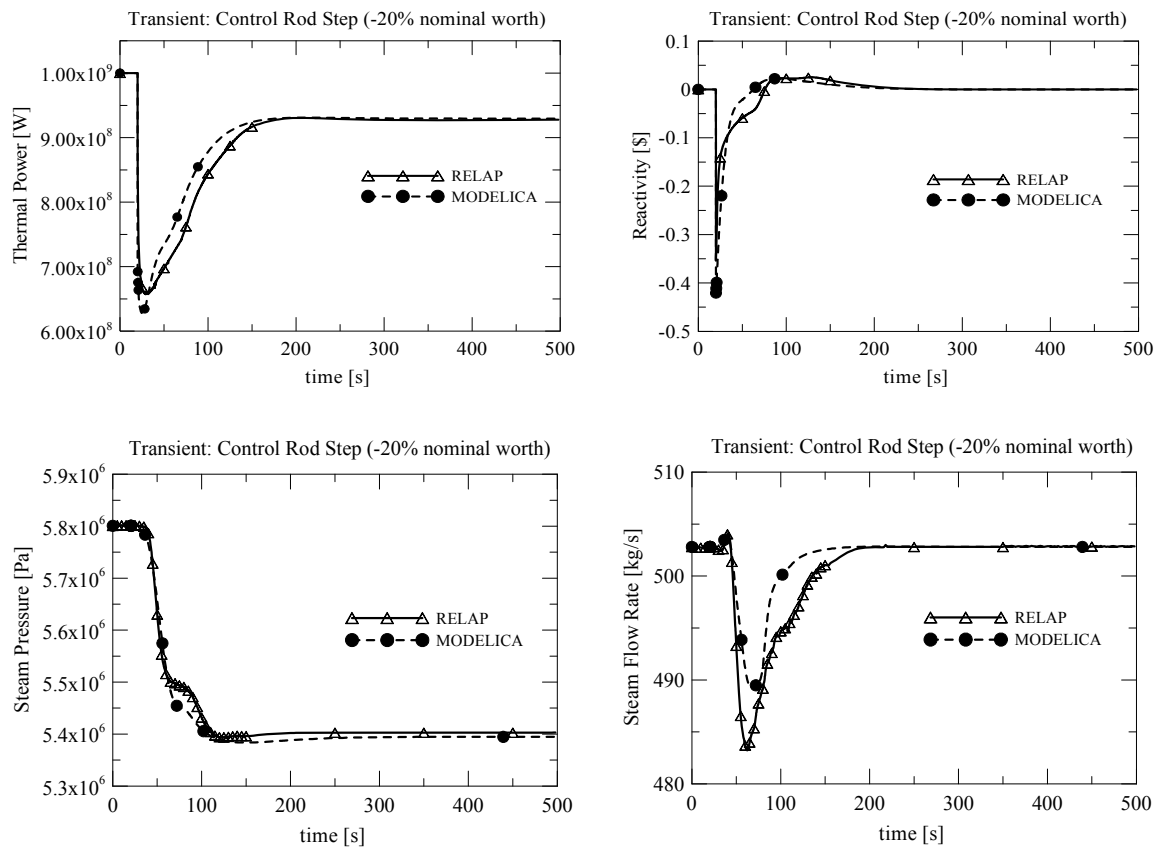
Fig. 8. Modelica vs. RELAP comparison – Core Thermal Power, Core Reactivity, Steam Generator Steam Pressure and Steam Flow Rate for the Control Rod step insertion (−20%) transient.
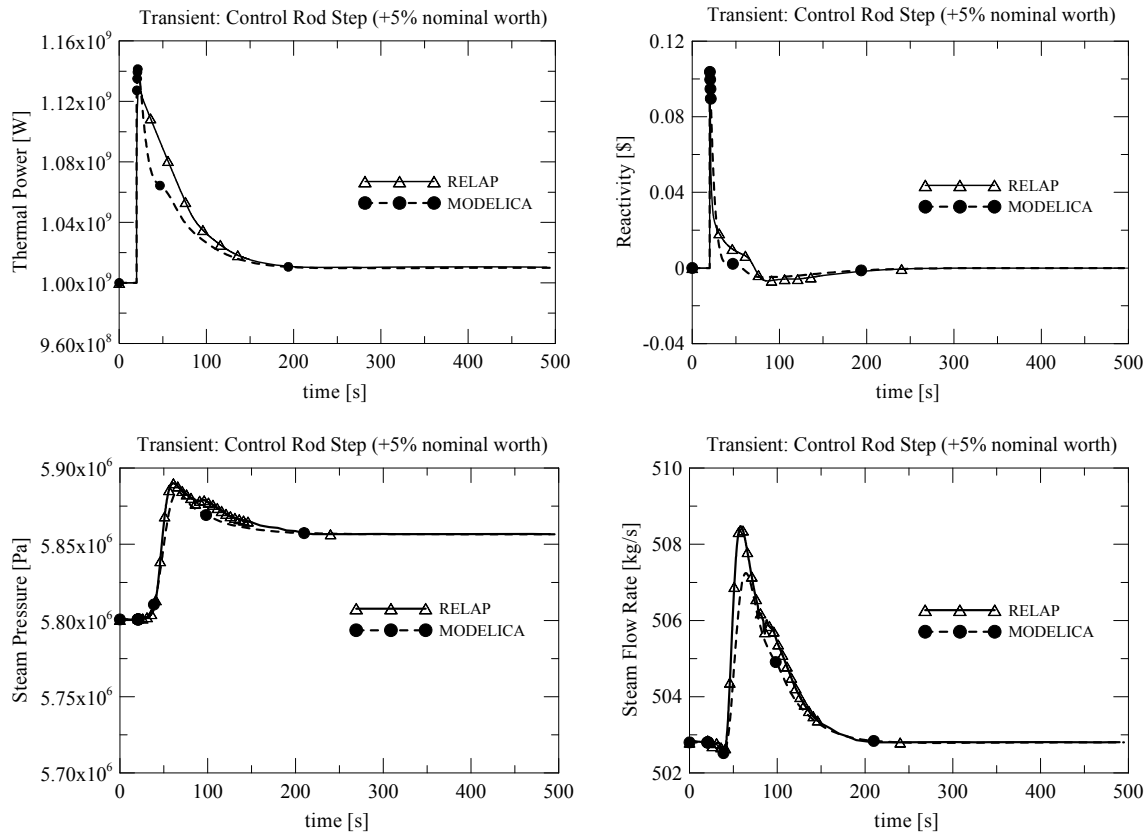
Fig. 9. Modelica vs. RELAP comparison – Core Thermal Power, Core Reactivity, Steam Generator Steam Pressure and Steam Flow Rate for the Control Rod step withdrawal (+5%) transient.

5.3 Plant Dynamics – Turbine Admission Valve Step opening (20%, +10%)

As a further example of transient analysis and comparison, useful to gain knowledge about the dynamic response of the reactor, a step opening (10% with respect to nominal value) and a step closing (-20% with respect to nominal value) of the Turbine Admission Valve has been simulated (Figs. 10, 11). The transient does not represent a real operational transient for the plant, since also in this case also the controls are supposed not to be in operation, but is a preliminary, valuable insight in order to identify the optimum strategy and configuration of the control system.

The step opening of the turbine valve allows the steam flow rate to follow with a sudden increase, due to the depressurization and corresponding flashing of the secondary fluid. The effect on the primary side is a slight overcooling, with a decrease of the coolant temperatures at core inlet (from 565.4 K to 564.6 K) while the core outlet temperature does not change (~ 601 K). The neutronic feedbacks push the core power to about 1.02 GW with an overall increase of 2 % with respect to the nominal value. The very mild response of the integral reactor is due to the limited inventory in the steam generators, that limits the amount of steam generated to the available feedwater flow into the steam generators (that is kept constant during the simulation), except for the very short spike shown in Fig. 11, where the results for the Turbine Admission Valve step closing (-20%) are reported.
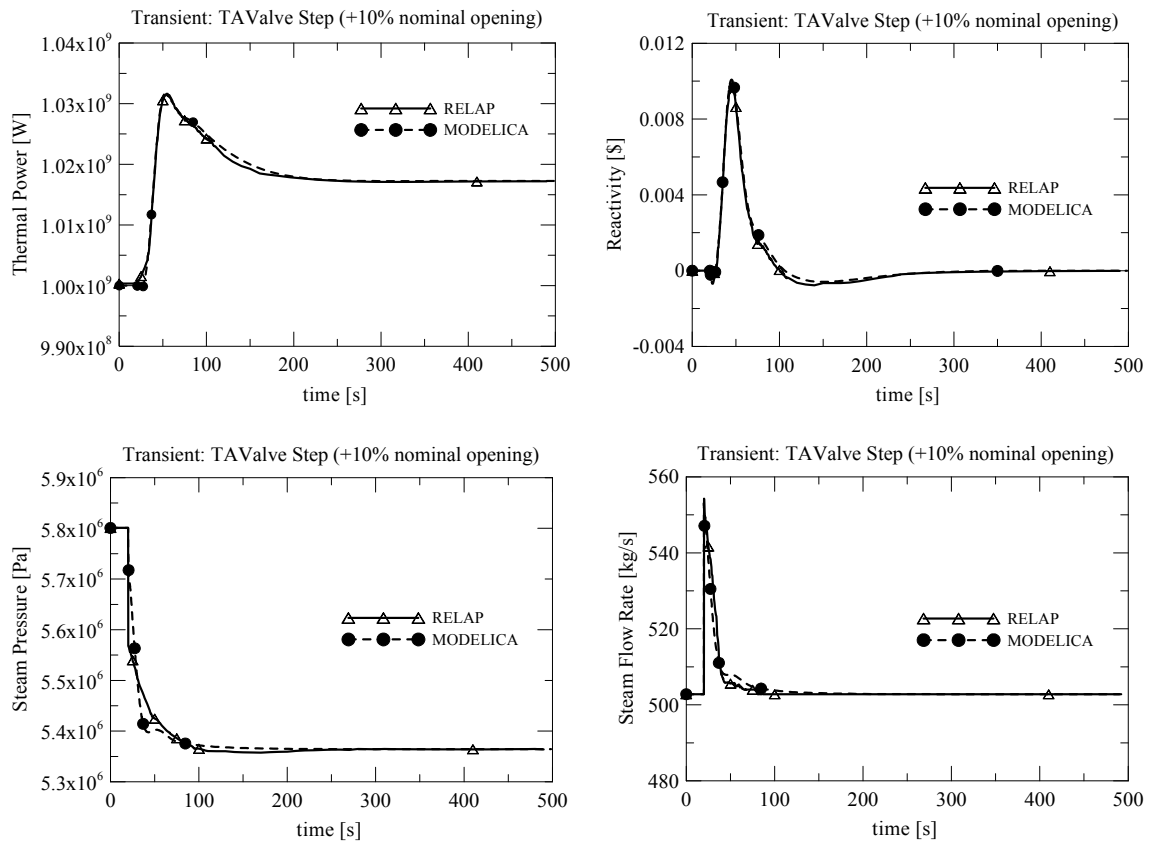
Fig. 10. Modelica vs. RELAP comparison – Core Thermal Power, Core Reactivity, Steam Generator Steam Pressure and Steam Flow Rate for the Turbine Admission Valve step opening (+10%) transient.
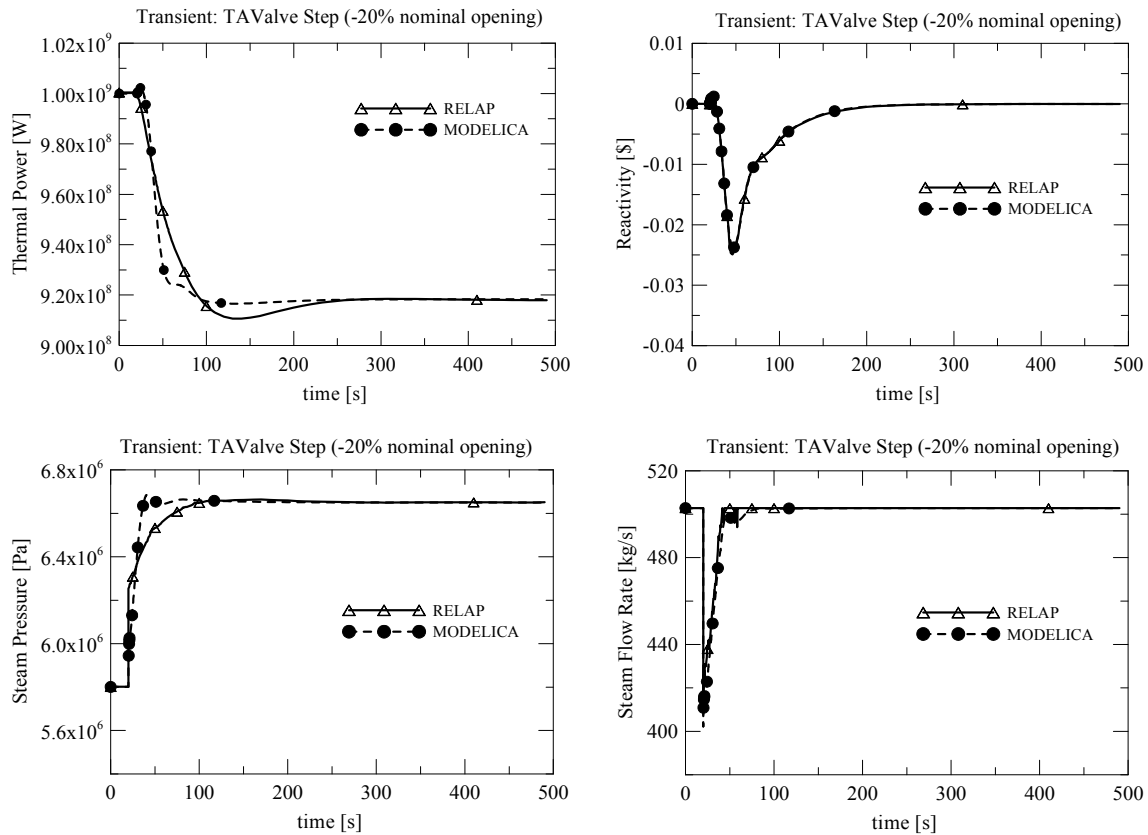
Fig. 11. Modelica vs. RELAP comparison – Core Thermal Power, Core Reactivity, Steam Generator Steam Pressure and Steam Flow Rate for the Turbine Admission Valve step closure (20%) transient.

6 CONCLUSIONS

The development of a plant simulator with Modelica for control studies on integral reactors and for the IRIS reactor in particular has been presented in this report.

The development cycle of the simulator has been shortened dramatically compared to alternative approaches, due to the re-use of existing models and to the object-oriented approach to write the model code. Moreover, the system model can be easily modified to improve the modelling of the nuclear generation process, without affecting the remaining parts of the code.

The simulation time for one transient is reduced by almost three orders of magnitude, while keeping the fundamental dynamic behaviour of the plant. This makes the model usable for control system studies.

Finally, it is planned to further validate this model against experimental results obtained from scaled laboratory models of parts of the plant.

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