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Dynamic Response of LFR in Cogeneration Mode

Riccardo Chebac
Politecnico di Milano, Department of Energy, Nuclear Engineering Division
Via La Masa 34 20156, Milan, Italy.
Riccardo.chebac@polimi.it

[a]Antonio Cammi, [a]Marco E. Ricotti, [b]Khashayar Sadeghi, [b]Seyed Hadi Ghazaie, [b]Ekaterina Sokolova, [b]Evgeniy Fedorovich
[a]Politecnico di Milano, Department of Energy, Nuclear Engineering Division
[a]Via La Masa 34 20156, Milan, Italy.
[a]20156, Milan, Italy
[b]Peter the Great St. Petersburg Polytechnic University
[b]195251 Russian Federation

ABSTRACT

In this paper a novel object-oriented simulator capable of transient analysis of the Advanced Lead-cooled Fast Reactor European Design, based on the model envisioned by Ponciroli et al.[1], was developed within the Dymola software based on the Modelica language. The nuclear power plant (NPP) model was conceived as part of a more complete simulator capable of studying the technical feasibility of hybrid systems scenarios. The plant was built in such a way to enable steam extraction from the turbine unit therefore enabling the user to study different cogeneration options. The reactor core behaviour was implemented via point reactor kinetics coherently with ALFRED specifications. For the Steam Generator (SG) a single block modelling the combined effect of eight bayonet-type SGs was developed. Temperature of the extracted steam from the low-pressure turbine (LPT) can be determined by the sink pressure, which makes the model more flexible in studying the various cogeneration systems. Three scenarios were studied, namely: control rods step insertion and extraction, water mass flowrate linear increase and extraction valve regulation. Results highlight the time constants of the various components and show the potential of steam extraction which will indeed require further investigation and development of a suitable controller in order to efficiently use this system.

1 INTRODUCTION

Throughout mostly the past two decades, the penetration of renewable energy power plants into the electrical grid has steadily increased. Considering both the public acceptability of this technology and the goals of the Paris Agreement [2] of keeping the Earth′s average temperature below the 2°C increase from the pre-industrial level, it is foreseeable that in the near future the share of renewable energies in the global energy market will surely increase. It is expected that by 2040 their share will pass from nowadays 26.6% to approximately 45%. Nowadays renewable energy sources are leading the transition from a centralized power production unit to several small distributed plants. Unfortunately, the intrinsic physical limitations of these technologies such as variability due to meteorological and temporal availability of the source and the uncertainty given by unexpected changes in boundary conditions will bring to grid instability and problems with energy demand satisfaction. Given these technical difficulties, a transition to high shares of renewables require a drastic change in grid design and a rethinking on how power plants are envisioned. Having a high share or intermittent energy brings the need for all the programmable power plants such as fossil fuel and nuclear to contribute heavily in the load following strategy. In such a context, supply and demand will be matched in a much more flexible and diverse manner. Therefore, the construction of a modular simulator capable of analysing the technical feasibility of various hybrid systems scenarios was carried out. The Nuclear Power Plant (NPP) was developed within the Dymola software which, by taking advantage of the Modelica language enables a high degree of (i) modularity, to enhance the reusability of pre-existing components; (ii) openness, which enables easy reading of the equations used; and (iii) efficiency, since the simulation should be fast running. With this in mind, a novel simulator based on Ponciroli et al.[1] works has been developed considering the Lead-cooled Fast Reactor (LFR) technology. Heavy Liquid Metal (HLM) coolants enable important design simplifications and higher operating efficiencies. Given the increased temperatures reached by this technology, the cogeneration option also becomes an attractive solution. The LFR technology was chosen since a control strategy was developed by Ponciroli et al.[3] that enables prompt mechanical power variation by only working on the secondary loop effectively keeping the reactor core untouched and enabling load following with time constants similar to that of renewable energy systems. As such, in this paper the development of a simulation tool for studying the dynamics of a modified ALFRED NPP was carried out.

2 REFERENCE REACTOR DESCRIPTION

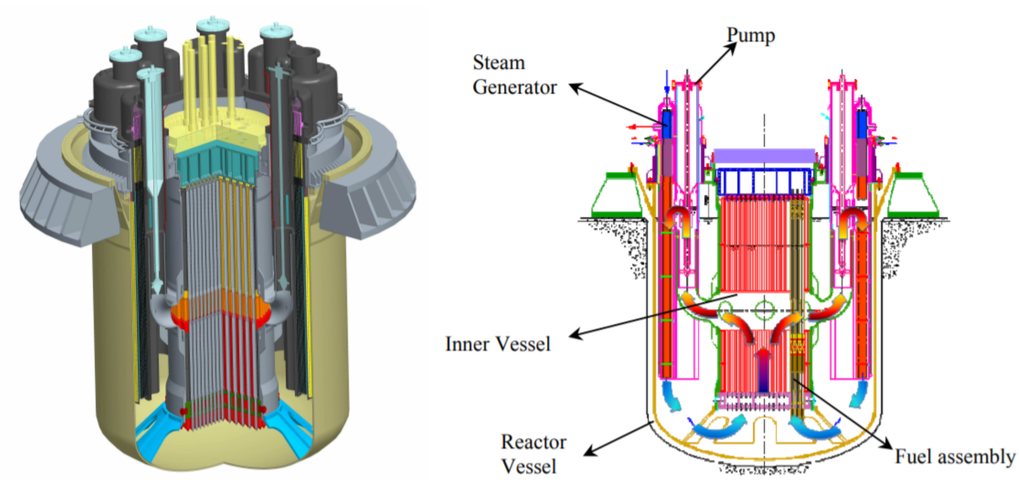


Figure 1: ALFRED 3-D sketch and reactor block vertical sections

Identified by the GIF as one of the six most promising GEN IV systems [4] [5], the LFR technology is based on a fast neutron energy spectrum and a closed fuel cycle capable of efficiently managing minor actinides and convert fertile $^{238}_{92}$U into fissionable $^{239}_{94}$Pu. Lead as a coolant has interesting performances such as being inert, thus permitting important design simplifications, high boiling point which will lead to lower operational pressures and higher temperature therefore increasing the plant efficiency. Moreover it can use technologies already developed for the light-water counterparts such as passive heat removal systems, thereby enhancing the overall safety of the system. As an added bonus the use of MOX fuel make this technology an extremely unattractive route for theft of weapon-grade materials. ALFRED is an SMR [6] designed to have a nominal power of 125MWe. It will contain all the primary coolant in the reactor vessel in what is defined as a pool-type configuration as shown in figure 1. The position of the core with respect to the riser, the SG and the downcomer enables natural circulation to occur. An innovative solution has been used for the SG where a bayonet-type configuration ensures the production of super-heated steam at pressures of 18 MPa and temperatures of 450°C. Thus enabling an estimated plant net efficiency of about 41%. From a safety standpoint ALFRED uses two passive, independent Decay Heat Removal (DHR) system each having four ICs designed on a single failure criteria (i.e. if one IC fails the DHR still works). As previously mentioned the core uses MOX fuel. The nuclear fuel is inside wrapped hexagonal FA and produces a nominal thermal power of 300 MWth.

3 SIMULATOR DEVELOPMENT

A realistic plant representation was achieved in fig.2 thanks to the component-based description and acausal approach of the Modelica language [7]. For the reactor core an updated version of Ponciroli et al.[1] model was carried out. It is based on the implementation of point reactor kinetics with an eight group delayed neutron precursor concentration model, represented in eq.1.

$$\begin{cases} \dfrac{dn}{dt} = \dfrac{\rho - \beta}{\Lambda} n + \displaystyle\sum_{i=1}^{8} \lambda_i c_i + S \\ \dfrac{dc}{dt} = \dfrac{\beta_i}{\Lambda} n - \lambda_i c_i \qquad\qquad i = 1 \div 8 \end{cases} \tag{1}$$

To the latter, a one-dimensional heat transfer model from fuel the coolant and an effective fuel temperature model to correctly describe reactivity feedback phenomena have been added. The steam is produced by a bayonet type steam generator modelled within the simulator in a counter-current configuration.

For the power conversion unit the simplified model of the Steam Turbine Unit found in the ThermoPower library in Dymola was used to simulate a high and low pressure stage. The mechanical and isoentropic efficiencies of both stages were calculated to deliver a maximum power of 130 MWe in nominal conditions (i.e with Bleed1 valve opened and Bleed valve closed). The model is extremely flexible on choosing the desired pressure of the extracted steam. This enables the study of different co-generation scenarios. In our case, the pressure was set to 0.5 bar thereby letting us use saturated steam at approximately 80°C useful for a MED desalination plant. The Bypass is nominally closed and is opened only in low power conditions such as start-up thus avoiding jeopardizing the turbine integrity. It is also used to change the turbine mass flow rate in the case that no cogeneration is required and also suitable for pressure control. The bypass is nominally closed and is opened only in low power conditions such as start-up thus avoiding jeopardizing the turbine integrity. It is also used to change the turbine mass flow rate in the case that no cogeneration is required and also suitable for pressure control. Finally the admission valve shown as kv valve in fig.2 can be used to control the mass flow rate entering the turbine. At the inlet the steam is superheated hence the relationship between the mass flow rate at the inlet is approximately proportional to the admission valve coefficient and the inlet pressure as expressed in eq.2:

$$\Gamma \approx k_v p \tag{2}$$

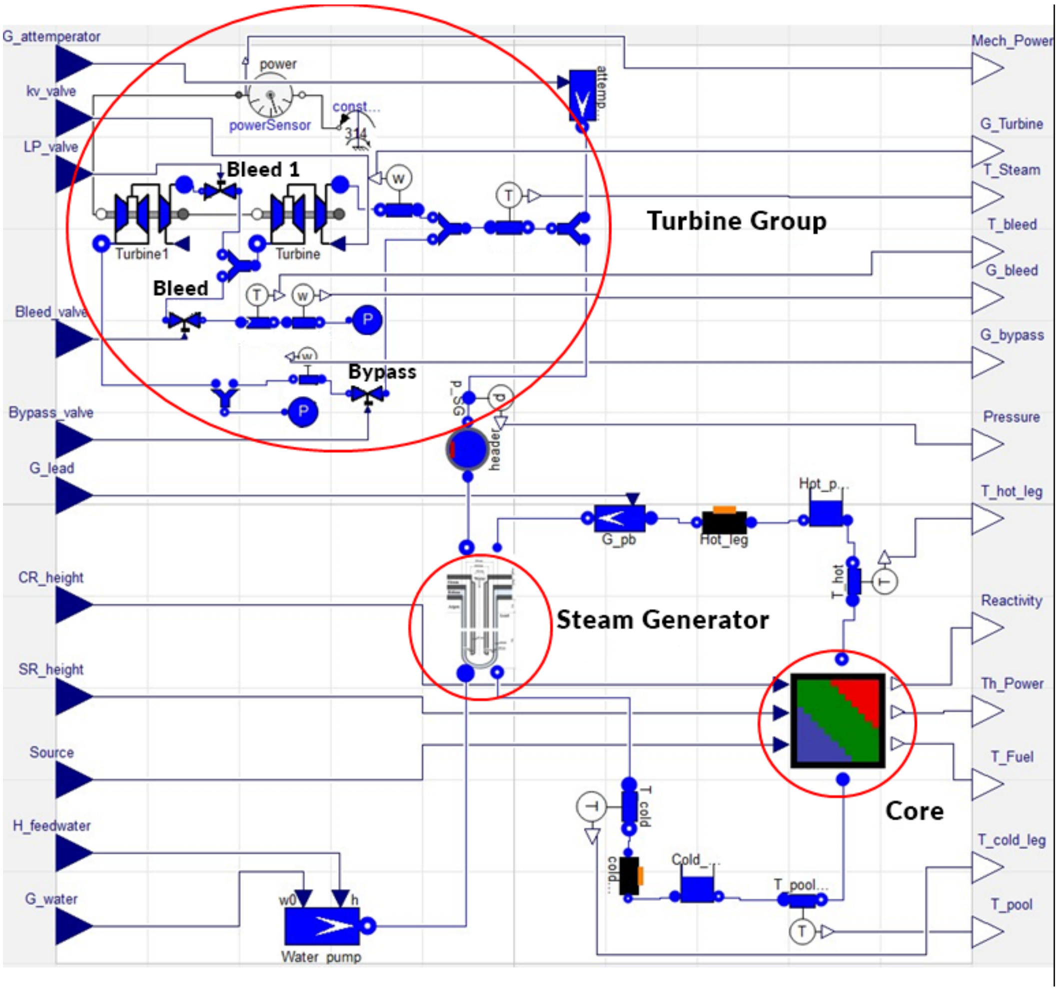


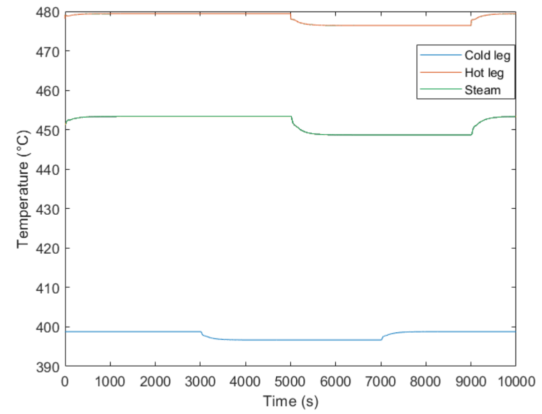
Figure 2: ALFRED power plant simulator

4 SIMULATIONS AND RESULTS

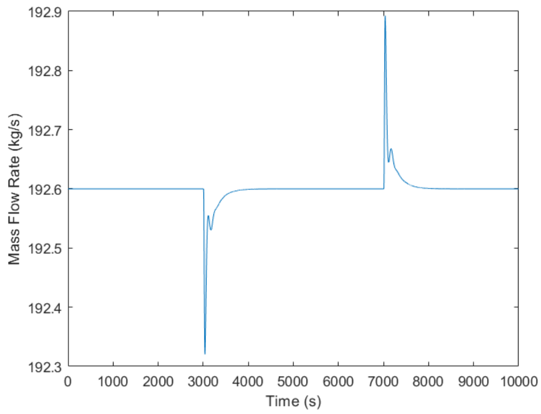
Starting from nominal full power steady state operation, the reactor dynamics were investigated via transient initiators. A step insertion and extraction of the control rods transient was studied as well as a careful evaluation of the possible mass flow rate extracted from the turbine low pressure stage by varying both Bleed Valve and Bleed Valve1.

4.1 Control rod step insertion and withdrawal

The dynamic response of the system to a variation of the control rod height of ±5 cm was undertaken. This is of primary importance to evaluate the correct transient behavior and time constants of the system. At 3000 seconds the control rods are inserted while at 7000 second they're brought at their initial position. With no further external input the core automatically balances out the excess and defect of reactivity thanks to its intrinsic negative feedback phenomena between neutronics and thermo-hydraulics as shown in figure 3.d. The thermal power closely follows the reactivity by suitably adjusting itself. Indeed the control rods insertion will lead to a decrease of the power level and a withdraw will give the opposite effect as it can be seen in fig.3.e. This in turn will lead to a drop of the temperature level of both water and lead with a consequent reduction in mechanical power production (fig.3..a and fig.3.c). It is important to keep an eye on the steam temperature since an excessive increase or decrease could bring to damaging the turbine permanently. As an example a harsh reduction in steam temperature could bring, if not taken into account, to a water droplet production in the low pressure stages of the turbine thus leading to serious damages to the system. In nominal power production the model is in good agreement with ALFRED's design parameter with a relative error lower than 4%.



(a)



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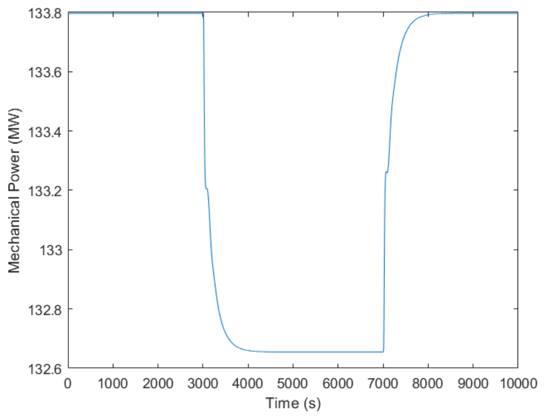

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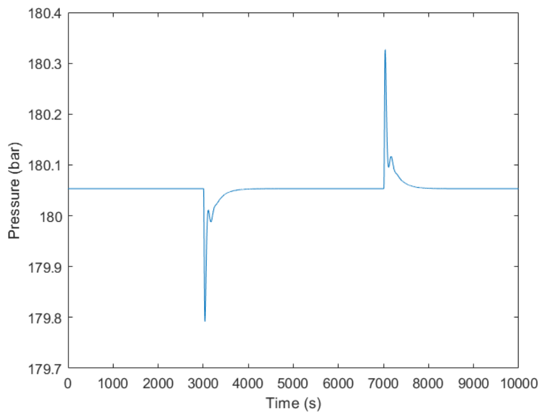
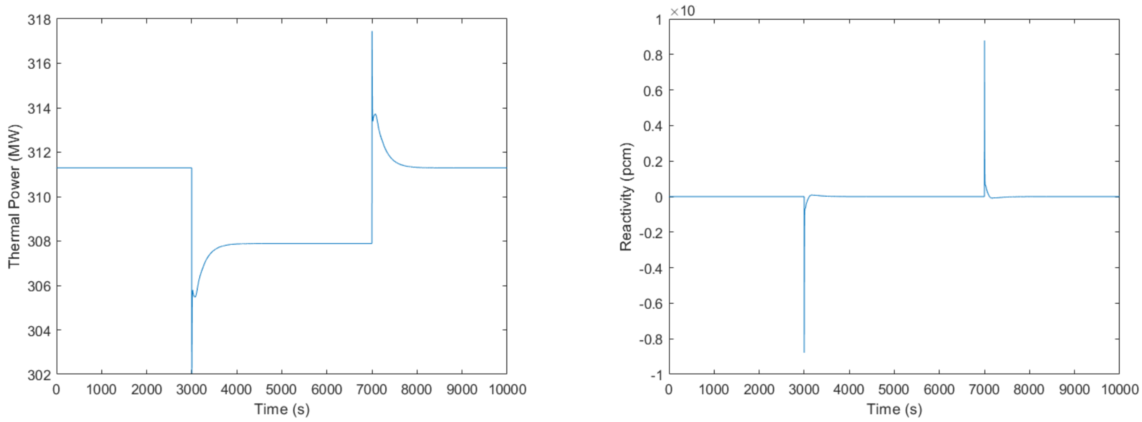


(d)

4.2 Cogeneration

Given the high temperatures and pressures reached by the steam, ALFRED power plant could be suitably modified to enable various cogeneration options. By using the turbine modifications shown in fig.2, the steam extraction was carried out (at the end of the high pressure block) at a pressure of 0.5 bar thus giving a temperature of the extracted steam of roughly 80°C .



(e) (f)

Figure 3: Variables evolution after control rod step insertion and withdraw:(a) SG, cold leg and hot leg temperatures; (b) mass flowrate entering the turbine; (c) mechanical power; (d) pressure in the secondary side; (e) reactor thermal power ; (f) reactivity.

These values have been chosen for both the possibility of district heating and for thermal desalination in particular for MED systems. The simulation was carried out by completely opening the extraction valve denominated Bleed Valve in fig.3.4 at 1000 seconds and subsequently at 1500 seconds by closing the low pressure stage valve called LP Valve leaving it only at a 2% opening giving us an extracted mass flow rate of roughly 14 kg/s. Indeed temperature, thermal power level and turbine mass flow rate remain untouched since the extraction only changes the mechanical power output and it is confirmed in fig.4.b, fig.4.c, fig.4.d and fig.4.e. Finally some interesting considerations have to be made on the influence of both valves. As previously mentioned, the Bleed Valve was completely opened at 1000 seconds but, taking as an example fig.4.a and fig.4.c, and 4.d, just a negligible effect on both efficiency, mass flow rate and mechanical power can be noticed. Contrarily to the above stated valve, the LP Valve is the major contributor to the steam extraction. It is of extreme importance to understand that the former valve is necessary to have a proper steam extraction but only the latter influences the final output. The efficiency of the plant was also taken into account to see the overall reduction generated by steam extraction. As seen in fig.4.d we obtain a roughly 1.5% decrease that was calculated as:

$$\eta = \frac{P_{mech}}{Q_{in}} \tag{3}$$

With Q_{in} the thermal power produced by the reactor and P_{mech} the mechanical power produced.

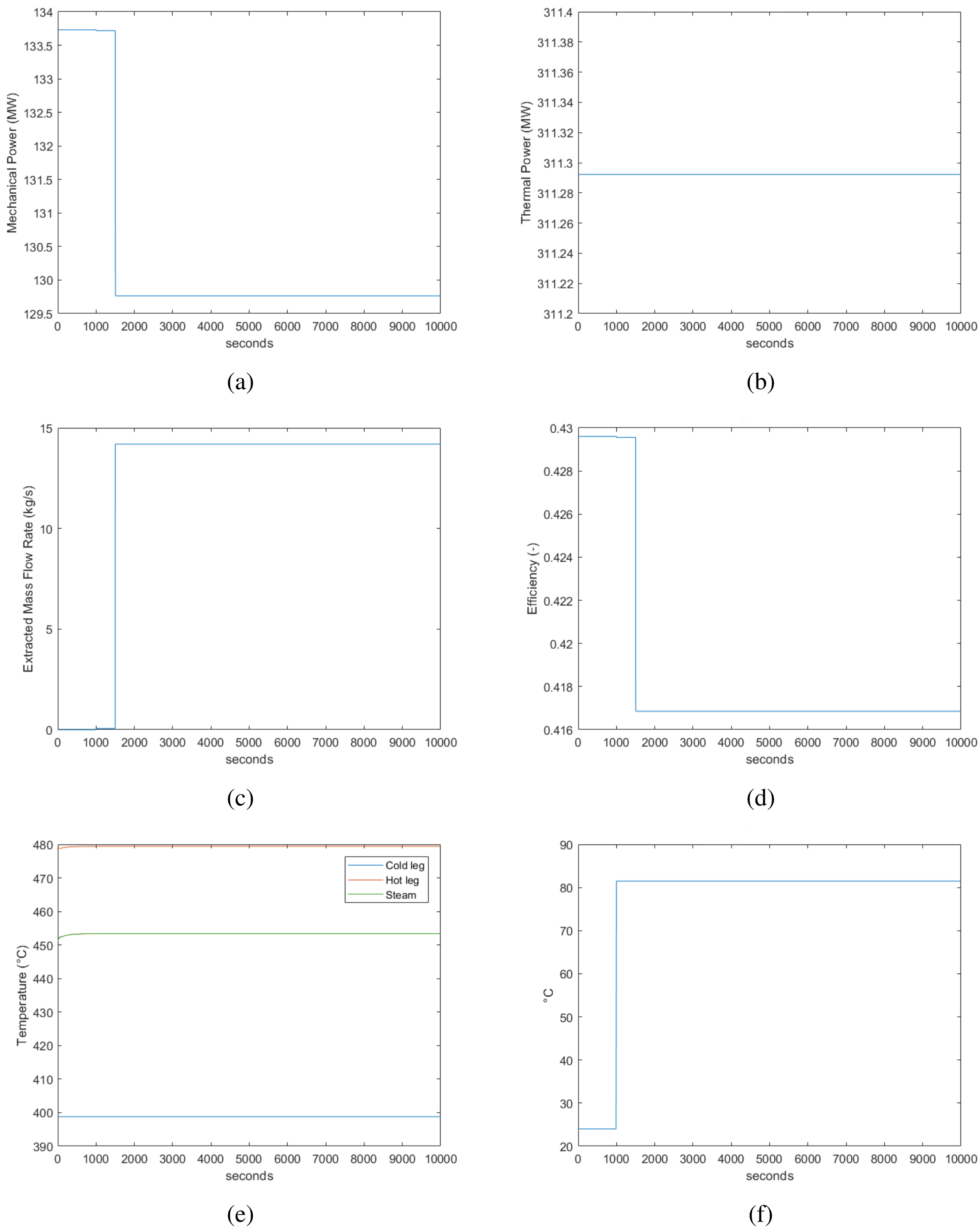


Figure 4: Variables evolution after steam extraction:(a) extracted mass flowrate; (b) mass flowrate entering the turbine; (c) mechanical power; (d) reactor thermal power; (e) SG, cold leg and hot leg temperatures; (f) extracted steam temperature.

5 CONCLUSIONS

A complete simulator of ALFRED nuclear power plant was carried out on the Dymola software given the advantages it has compared to other programs. Both updates and modifications on the work of Ponciroli et al.[1] where performed to bring the model to the newest version of the program and to enable the turbine group to have steam extraction for cogeneration scenarios. The complete simulator has been conceived as part of a more general model capable of studying the technical feasibility of various hybrid system scenarios. The turbine block has been developed in order to extract steam at temperatures which are optimal for multi-effect distillation (MED) desalination plants. Tests involving control rod insertion and withdraw show good agreement with both the design parameter and the characteristic times of the plant envisioned. The steam extraction test have highlighted some of the potential advantage of using LFR technology for cogeneration. Higher temperatures of the power plant enable the steam extraction at low pressure to only mildly influence the overall thermodynamic efficiency of the system. This would not be the case with a light water type reactor. Overall, the lead cooled fast reactor technology is promising not only from the power production standpoint but also for applications where high operating temperatures are required. Currently, this simulator is being developed in a more complex model capable of studying complex hybrid systems scenarios to effectively show how this reactor technology may be able to tackle hurdles deriving from renewables energy sources such as grid frequency instability.

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