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Transient Modelling of HTGR Thermal Load Follow in Modelica

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INTRODUCTION

Label	Component	Con
1	Turbine Control Valve (TCV)	Elec
2	Feedwater Heating Valve (FHV)	Feed
3	Feedwater Control Pump (FWCP)	Stea
4	Helium Circulator	Stea
5	Control Rod Reactivity	Stea
6	Pressure Control Valve (Primary)	Pres
7	Pressure Relief Valve (Secondary)	Pres

The ability of nuclear power plants to load follow electrical power demand is particularly important as we move to higher variable renewable (VRE) energy production on low carbon energy grids. High temperature gas reactors (HTGRs) are capable of load following by adjusting thermal output, but their high temperatures and thermal inertia significantly impact the power transients they are able to follow. To aid investigation into new integrated energy systems with advanced reactors, it is necessary to have an open-source transient model of a full HTGR primary and secondary. This paper introduces two new open-source models for a HTGR and corresponding balance of plant (BOP) written for the HYBRID library developed at Idaho National Laboratory [1]. A transient thermal load follow test case was taken by the work from Brits et al. to benchmark our open-source model against transient operation results from other proprietary codes that exist [2]. The control scheme for the two new models in combination is discussed and a comparison of the response in transient load follow between the two codes performed.

THEORY

The Choice of Testcase

We decided to follow a 100-25-100% test case for the HTGR taken from the paper by Brits et al., as this gave sufficient transient data in operation to allow a useful comparison of the open source Modelica HTGR model with another transient analysis code. The model from Brits et al. is a Flownex model of the XE100 reactor and balance of plant detailed by van Antwerpen et al. [3]. In the test case, the turbine control valve (TCV) is throttled from its position in steady operation (100%) to 25% of this nominal value and is subsequently returned to its 100% position. This throttling takes place over 5% a minute with the plant maintained at 25% nominal power for 20min.

Transient Model Control Design

To perform a comparable transient simulation to the one performed in Brits et al., a simple configuration of the BOP model in the HYBRID library was used. This consists of a two-stage turbine with open feedwater heating utilizing steam bled from the intermediate stage between the high and low pressure turbine models (HPT and LPT respectively). A

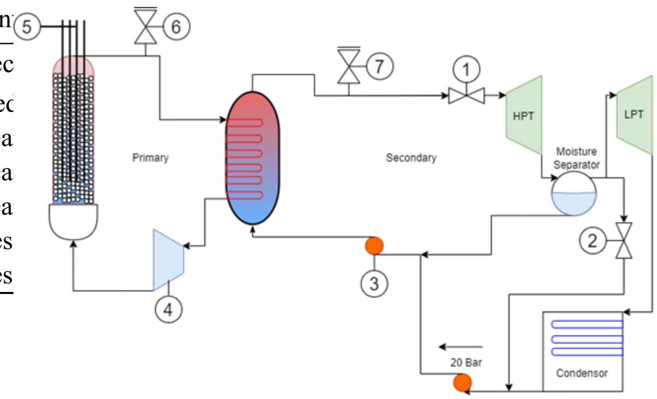


Figure 1. The control system for the model was designed

Fig. 1. Transient Analysis System Configuration and Control

based on the control method described in Brits et al. (Table 1). The control scheme we implemented is reproduced in Figure 1 and Table 1 for clarification.

Whilst this control system mostly follows the one implemented in Brits et al., there are some notable differences. No Deaerator is used; instead, an ideal condenser is assumed with a moisture separator implemented between the HPT and LPT turbine stages. Extra pressure relief valves were added to aid the system in initialization in Modelica with the primary pressure relief valve aiding to maintain the correct pressure in the primary circuit.

The model of the helium circulator is controlled by its pressure ratio rather than speed. These two control methods have very similar effects in the transient test but do significantly impact the helium circulator modelling parameters in the comparison between the codes results.

The control system was primarily implemented in Modelica by using proportional-integral controllers (PI), with the helium circulator controller adding a derivative term (PID) to improve damping of any pressure oscillations in the core. The PI controllers work well to control the HTGR during initialization to a normal operation steady state. However, using them alone to achieve a 100-25-100% thermal load follow at an aggressive ramp rate proved difficult. This was primarily due to the steam generator's large size creating significant lag in the thermal and fluid momentum feedback in the primary and secondary circuits. It should be noted that the implementation of the controllers in the Brits et al. control scheme was not discussed and so the control system used in Modelica was the one found to give sufficient agreement with the transient test case whilst maintaining stable operation of the system.

TABLE I: Transient Analysis control methods summary.

To improve the control in the transient maneuver, feedforward signals based off the applied TCV transient were added to the controllers for the feedwater control pump and the helium circulator. These feedforward signals counteract the long timescales of the feedback when changing the feedwater coolant pump (FWCP) speed in influencing the temperature at steam generator exit. They also negate the effect of the long timescale of the feedback when changing the helium circulator pressure ratio in causing a pressure variation at HPT inlet. The influence of feedforward control is demonstrated in Figure 2, with the feedforward controller helping follow the ramp rate desired in the simulation.

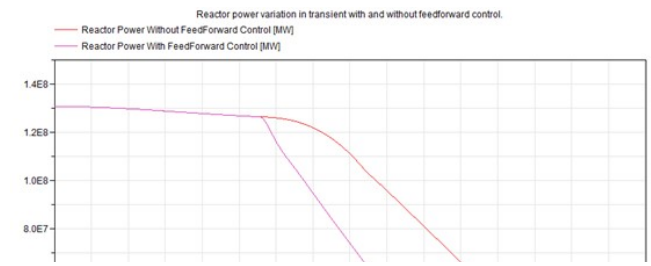
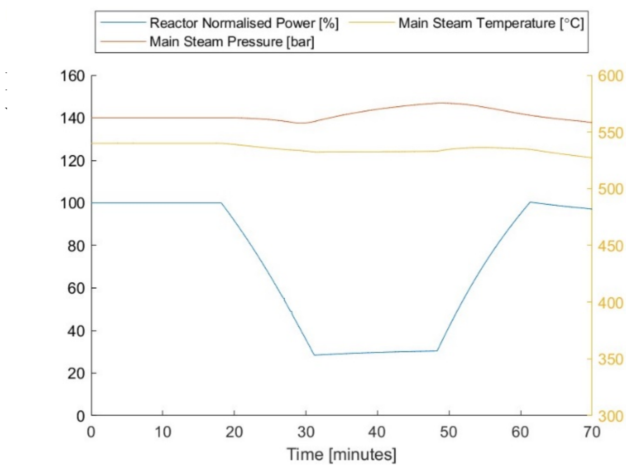


Fig. 3: Manipulated variable response to load following.

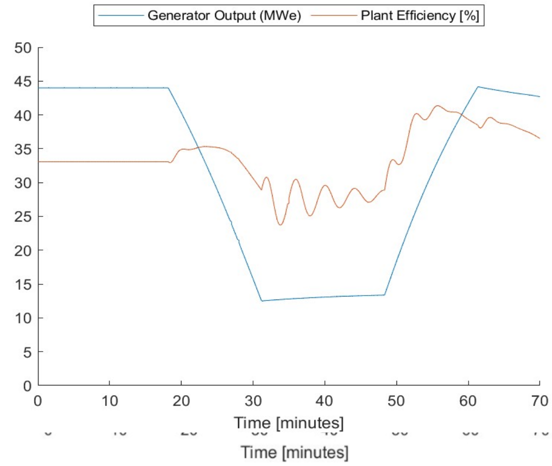


Alongside implementing feedforward signals, the control systems for the FWCP and the helium circulator were also designed to be flexible between initialization of the Modelica simulation and transient operation. The result of this variation meant that slower controlled transients were employed for the model to find steady state operation without entering any unstable operating conditions. During the transient maneuver more aggressive transients could be handled by the PI controllers without affecting stability.

RESULTS AND ANALYSIS

TABLE II: Comparison of maximum and minimum deviation of key variables during transient from brits et al. Note the averaged deviation of the variables over the transient will be significantly smaller than those at the extremities given here.

Figures 3-10 show key parameters in the transient test of the transient load follow test case. These graphs are designed to closely follow the Figures 8-15 from Brits et al. and it can be seen that there is strong agreement between the two transient analyses. Table 2 looks at the maximum deviation of key parameters during the transient from the results of Brits et al. These values reflect the maximum deviations during the transient and not the averaged values of the error. Consequently, significant percentage deviation can be attributed to curves that closely match over much of the



transient but differ at a few points.

The relative TCV position is shown in Figure 3 and, as is described above, was manipulated to control the desired power transient. Throttling the TCV causes the desired ramp rate on the plant electrical output as can be seen in Figure 5. The reactor total power is shown in Figure 9 and changes similarly to the generator output giving the efficiency shown in Figure 6.

The main controlled variables, as detailed in Table 1 are: feedwater temperature, steam temperature and pressure and reactor outlet temperature. These are seen in Figure 9. Whilst some fluctuation is seen due to the design of the feedback control these variables all maintain roughly constant profiles during the transient maneuver.

As can be seen in the comparison Table (Table 2), the feedwater parameters show the most deviation. These parameters were heavily influenced by the use of the feedforward signals in the controllers and additional refinement in this implementation may aid agreement between the two profiles. It is also clear that the control of the feedwater heating valve in the Modelica implementation is too slow to respond to the transients upstream of the valve. As a result, we see large swings in the feedwater temperature which are not observed in the Flownex model. It is therefore suggested that the valve controller may also benefit from a feed-forward during the transient.

Fig. 4: Controlled Variable Response to Load Following.

The key variables that differ significantly in shape from the variables observed in Figures 8-15 from Brits et al. are the fuel temperature profile and the control rod reactivity (or depth in Brits Fig. 8). The fuel temperature profile is closely correlated with the control rod reactivity in the core. The control rods can be seen to be significantly under-damped a condition which was necessary to follow the power transient but one that gives rise to significant oscillation being observed in core total reactivity (demonstrated in Figure 6). Whilst the oscillation of the reactivity and temperature profiles vary the overarching shapes are closely related. It is hoped that future work undertaken by the authors in optimizing control schemes such as the controller for the control rods in this model could help stabilize and prevent this oscillation.

The Helium circulator is modelled differently to the Flownex helium blower. This basic modelling leads to a very different set of parameters for the helium circulator shown in Figure 8. The circulator inlet and outlet temperatures do not follow well the general trapezoidal shapes followed by the other variables due to the significant lag in the steam generator.

CONCLUSIONS

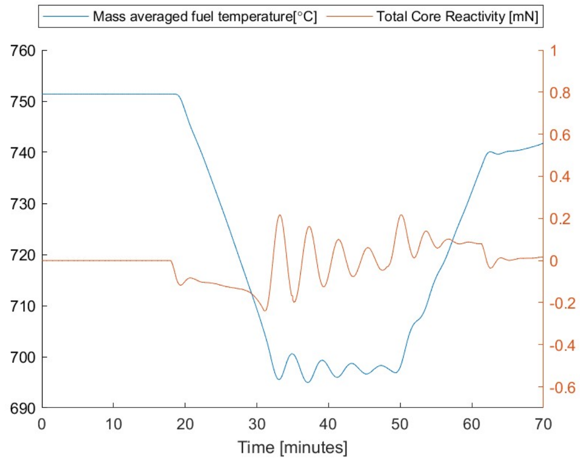
Overall, the open-source model for the pebble bed reactor in Modelica is able to closely follow the results observed by the significantly more complex Flownex model. Whilst the

Fig. 5: Plant electric output and overall efficiency

	Maximum Value During Transient		Minimum Value During Transient	
Key Variable	Value	Percentage Deviation	Value	Percentage Deviation
Reactor Power [MW]	132.1	0.8%	40.8	13.3%
Turbine Inlet Pressure [bar]	146.9	3.5%	136.9	0.8%
Turbine Inlet Temperature [°C]	540.0	2.0%	525.3	0.1%
Electrical Power [MWe]	44.2	0.3%	12.5	8.7%
Plant Efficiency [%]	41.4	15.0%	23.7	18.3%
Fuel Temperature [°C]	751.4	2.0%	695.0	0.8%
Reactor Inlet Temperature [°C]	281.0	8.1%	270.0	12.5%
Circulator Mass Flow [kg/s]	54.0	5.9%	19.0	18.8%
Turbine Inlet Mass Flow Rate [kg/s]	49.0	2.00%	15.4	2.7%
	198.4	10.0%	146.0	30.5%

Feedwater Temperature [°C]		
Feedwater Mass Flow [kg/s]	52.7	3.3%

agreement in the control rod reactivity and feedwater



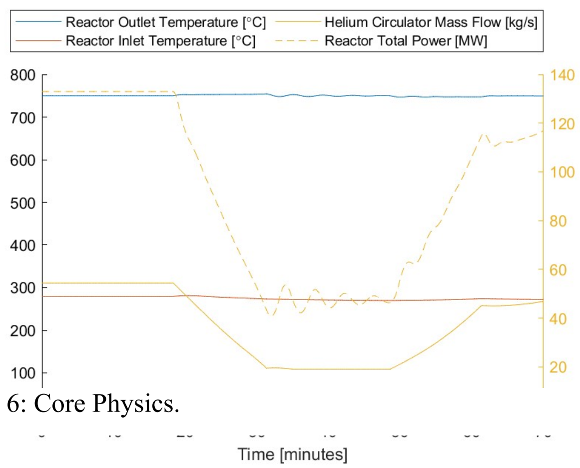
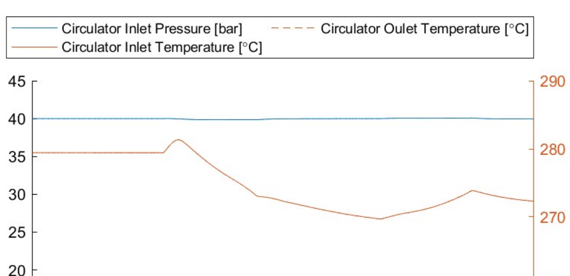
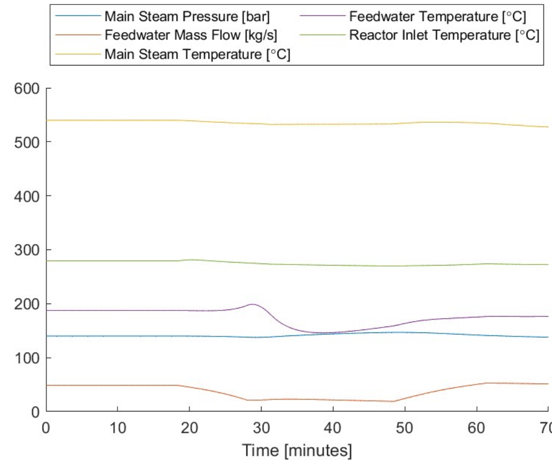


Fig. 6: Core Physics.

Fig. 7: Core Thermal Hydraulics.





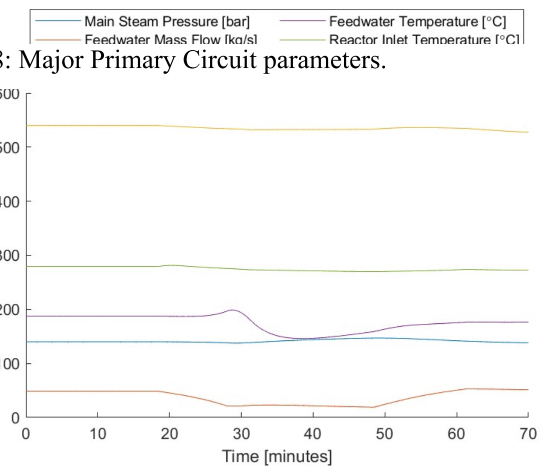


Fig. 8: Major Primary Circuit parameters.

Fig. 9:

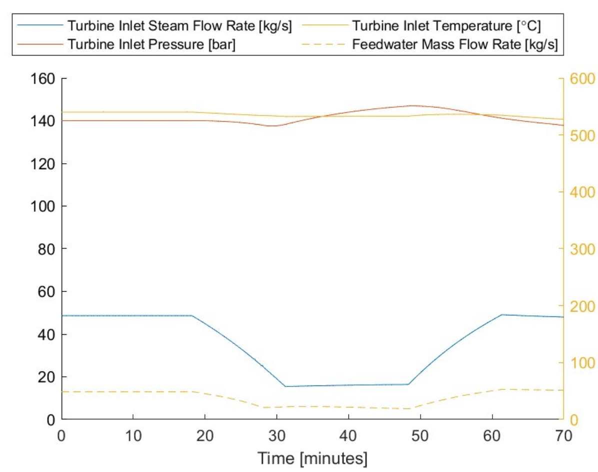


Fig. 10:

ACKNOWLEDGEMENTS

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