SIMULATION AND CONTROL OF A PASSIVELY COOLED SMALL MODULAR REACTOR

Samet E. Arda and Keith E. Holbert
School of Electrical, Computer and Energy Engineering
Arizona State University
Tempe, AZ 85287-5706
S.E.Arda@asu.edu; Keith.Holbert@asu.edu

ABSTRACT

This work regulates a small modular reactor (SMR) with traditional control methodologies and analyzes its response to typical disturbances. An analytical model for the passively cooled NuScale SMR is developed to represent the essential dynamics. The MATLAB/Simulink based model consists of reactor core, steam generator, pressurizer, hot leg riser and downcomer, and turbine representations. The point kinetics equations with a single combined neutron precursor group and the lumped parameter representations with single-phase natural circulation account for the neutronics and thermohydraulics in the reactor core. A lumped parameter, moving-boundary approach forms the basis of the nonlinear model adopted for the once-through helical-coil heat exchangers in which boundaries between regions of different fluid states (i.e., subcooled, boiling, and superheated) vary over time. A proportional-integral-derivative controller employing a sliding-average temperature strategy commonly used for pressurized water reactors is implemented. The responses of the SMR to two different disturbances are analyzed and discussed in detail. For the first scenario, a 5% step increase in the load is applied to the system, which results in a change in the steam valve opening. For comparison, two different simulations under this same disturbance are run: one including and one excluding the control systems. The second scenario tests the effectiveness of the control system to increase (or decrease) the reactor thermal power to a certain level within a desired time period. The simulation results show that important system variables are kept at the desired values by the proposed control strategy.

Key Words: Small modular reactor, natural circulation, dynamic modeling, reactor control.

1 INTRODUCTION

Starting in the last decade, there has been a growing interest in the development and commercialization of small modular reactors (SMRs) throughout the world. Compared with the today's large pressurized water reactors (PWRs), SMRs have distinguishing features. Among many others, the most prominent differences can be summarized as: (1) many SMRs have an integral design which utilizes both steam generator and pressurizer inside the reactor pressure vessel [1], and (2) these new designs are intrinsically safer and more secure [2] by placing the SMR into a pool under ground level, eliminating primary coolant pumps and, therefore, associated failure modes.

In this work, it is aimed to regulate an SMR with traditional control methodologies for PWRs and analyze the response of the SMR to typical disturbances. Keeping the above statement in mind, an analytical dynamic model for a passively cooled small modular reactor (SMR), i.e., the NuScale SMR, is adopted to represent the essential dynamics. The performance of the system introduced in this work is evaluated within the MATLAB/Simulink dynamic environment.

2 NUSCALE SMR

2.1 Overview

The NuScale SMR, capable of producing 45 MWe, is based on the Multi-Application Small Light Water Reactor (MASLWR) concept which was developed by a consortium including Idaho National Laboratory and Oregon State University under a DOE-sponsored project [3]. Fig. 1 represents a schematic showing the key elements of the NuScale SMR. Each nuclear steam supply system (NSSS) is immersed in a reactor pool, which has dimensions of 6 m wide by 6 m long and a depth of 23 m. The reactor pressure vessel is housed in the containment vessel sitting inside the reactor pool. The integral design allows the NSSS to encompass all major components, which are the reactor core, two helical-coil once-through steam generators, and pressurizer [4].

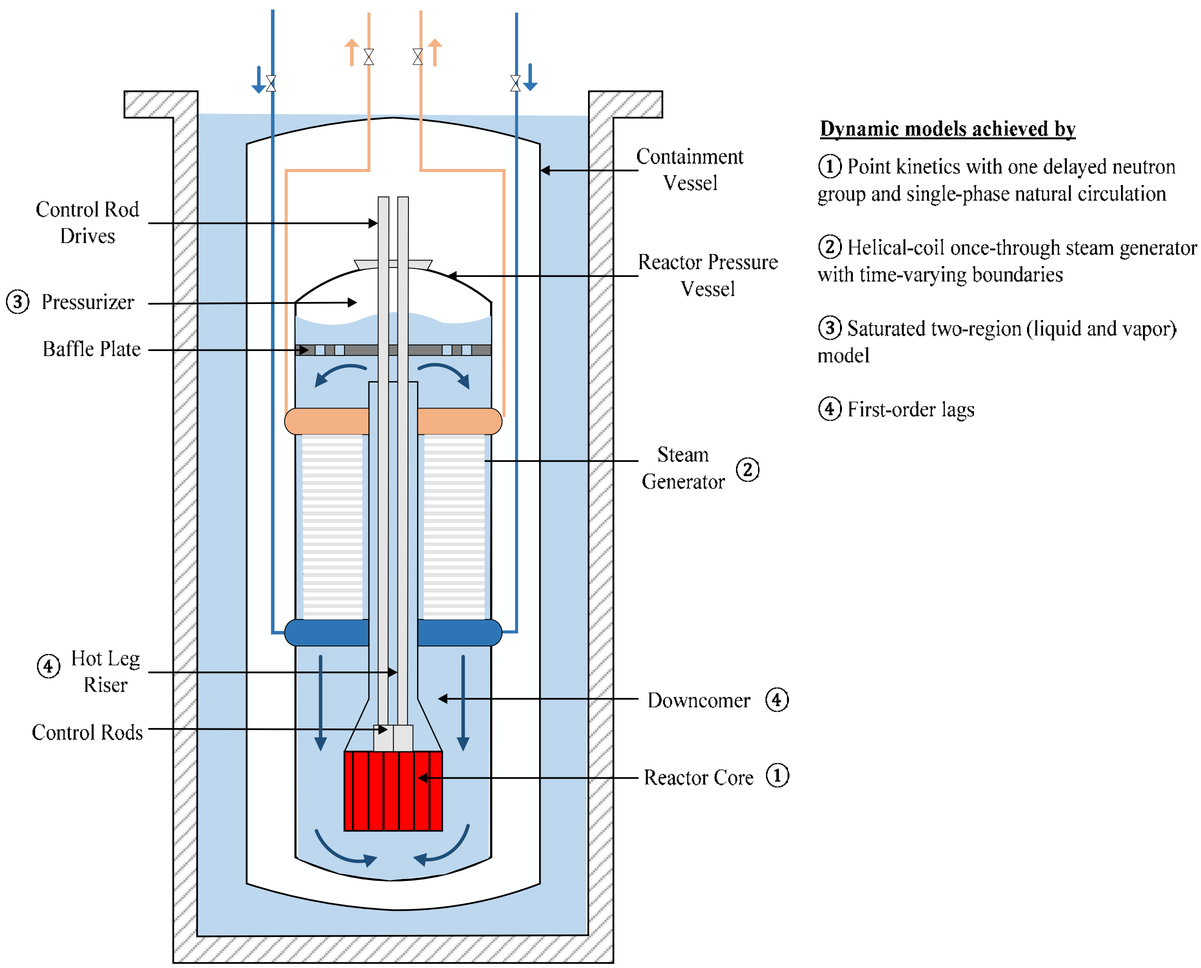


Figure 1. Schematic diagram of a single NuScale SMR unit depicting reactor core, steam generators, pressurizer, hot leg riser and downcomer.

The 160 MWt reactor core is comprised of 37 standard Westinghouse pressurized water reactor 17×17 square lattice array fuel assemblies with half of the nominal PWR height [5]. Each fuel assembly has 264 fuel pins, 24 guide tube locations for control rods, and a central instrument tube. The core also includes 16 control rod assemblies (CRAs). While four CRAs are used for power regulation during normal plant operation, the others, called the shutdown group, are used for reactor shutdown and scram events.

The NuScale SMR design employs natural circulation for the primary coolant system and therefore eliminates reactor coolant pumps. The primary coolant is heated as it passes over the fuel rods and enters the hot leg riser where convection and natural buoyancy provide enough force to drive the fluid upward. After leaving the riser, the primary coolant follows a downward path over the steam generator tubes and the heat is transferred to the feedwater. The denser primary coolant reaches the bottom of the core via the downcomer.

Each NSSS includes two vertical, once-through, helical-coil steam generators. The steam generators are located in the annular space between the hot leg riser and the reactor pressure vessel wall and connections to upper and lower plenums are provided via tubesheets. Each steam generator consists of 506 tubes which are thermally-treated Inconel 690. The tubes have an outside diameter of 16 mm with a 0.9 mm wall thickness and a total length of 22.25 m. The tubes are arranged on a square pitch, with transverse and longitudinal pitch ratios of 1.8 and 1.5, respectively [6]. Preheated feedwater enters the lower steam generator plenum through nozzles on top of the reactor pressure vessel. As feedwater rises through the interior of the steam generator tubes, heat is added from the reactor coolant and the feedwater boils and exits the steam generator as superheated steam.

The pressurizer is integrated into the top of the reactor pressure vessel and a baffle plate separates the pressurizer from the primary coolant system (see Fig. 1). The baffle plate, which serves as a thermal barrier between the saturated liquid inside the pressurizer and the primary coolant, has orifices to control the insurge (or outsurge) flow. The pressurizer regulates the primary coolant pressure with electric heaters, installed above the baffle plate, and spray through nozzles at the top of the reactor pressure vessel. An increase in the coolant pressure is accomplished by actuating the electric heaters while the coolant pressure is reduced by spraying cold water from the chemical and volume control system. Unlike traditional PWR pressurizers, a continuous spray flow is not anticipated.

2.2 Dynamic Modeling

The nuclear steam supply system (NSSS) model used herein is adopted from our previous work [7] and includes representations for reactor core, steam generator, pressurizer, hot leg riser and downcomer. The point kinetics equations with a single combined neutron precursor group and the lumped parameter models for an overall heat transfer resistance and single-phase natural circulation account for the neutronics and thermohydraulics in the reactor core region, respectively.

The single-phase natural circulation concept in SMRS is established mainly by the temperature differences between various locations inside the primary coolant system (principally the reactor core and steam generator). These differences induce a natural buoyancy force enough to carry the coolant through the reactor core and hot leg riser. An expression for the mass flow rate ($\dot{m}_C$) is derived after performing a momentum balance for the primary coolant system, which is, in fact, a single-phase closed loop, with the assumption of uniform heating and cooling at the core and steam generator regions of the loop [8].

$$\dot{m}_C = \sqrt{\frac{2\rho_{core}^2 A_{ft}^2 \beta_t \, g\left(T_{HL} - T_{DR}\right)\Delta L}{R_p}} \tag{1}$$

where ρ_{core} is the density of the primary coolant inside the reactor; A_{ft} is the total cross-sectional flow area inside the reactor core; β_t stands for the moderator (coolant) volumetric thermal expansion coefficient; g is gravitational acceleration; ΔL is the vertical distance from the center of the reactor core to the center of the steam generator; R_p is the overall flow resistance; and T_{HL} and T_{DR} are the temperatures of the hot leg riser and downcomer, respectively.

A lumped parameter, moving-boundary approach is adopted for the once-through helical-coil heat exchanger in which boundaries between regions of different fluid states (i.e., subcooled, boiling, and superheated) can vary over time. The helical-coil steam generator is described by nonlinear differential equations and the final form of the equations can be represented via a state-space formulation given by

$$\dot{\mathbf{x}} = \mathbf{D}^{-1}(\mathbf{x},\mathbf{u})\,\mathbf{f}(\mathbf{x},\mathbf{u}) \tag{2}$$

where $\dot{\mathbf{x}}$ is a 10x1 state vector, **u** is a 5x1 input vector, **D**(**x**,**u**) is a 10x10 coefficient matrix, and **f**(**x**,**u**) is the forcing function.

For the pressurizer model, an expression for the pressurizer pressure is derived from the fundamental mass, volume and energy balances. Hot leg riser and downcomer are treated as first-order lags. Finally, the NSSS model is incorporated with a turbine model which allows to observe the attainable power with given steam flow, pressure, and enthalpy as input. Attainable power, as defined here, is the deliverable power to the steam turbine and therefore does not include any dynamics related to a typical steam turbine.

3 CONTROL SYSTEMS

3.1 Reactor Control

The control of a reactor can be accomplished by three different modes in a PWR, any one of which alter reactor thermal power in accordance with changes in certain parameters, i.e., average primary coolant system temperature (T_{avg}), and steam pressure (p_S) [9].

1. Constant-average-temperature control mode,
2. Constant-steam-pressure control mode, and
3. Sliding-average-control mode.

Since a sliding-average-control mode is utilized in the work, only that control scheme is further discussed.

In this control mode, the cold leg temperature (or downcomer temperature) is kept constant which lets the average and hot leg temperatures increase as the power output increases. The advantage of this program over the constant-average-temperature program is that the change in the steam pressure according to the power level is diminished. This program is also termed as a compromise program or non-constant program since it is intended to provide a balance between the needs of the primary and secondary systems.

Most large PWRs utilizes a sliding-average-temperature program [10] and for this reason, the same approach is adopted in this study. The control action in this mode is achieved in MATLAB by a proportional-integral (PI) transfer function which takes the mismatch between the setpoint and actual value of the cold leg temperature as the input and produces a positive or negative external reactivity depending on the polarity and magnitude of the mismatch, see Equation (3).

$$\delta\rho_{ext} = \left[K_{P,T} + \frac{K_{I,T}}{s}\right]\left(T_{DR,ref} - T_{DR}\right) \tag{3}$$

where $\delta\rho_{ext}$ stands for the change in the external reactivity; T_{DR} and $T_{DR,ref}$ are the actual and reference values of the downcomer temperature, respectively; $K_{P,T}$ and $K_{I,T}$ are the proportional and integral gain, respectively.

3.2 Primary Coolant System Pressure Control

Control of the primary coolant system pressure is achieved by a bank of heaters which compensate steady-state heat losses from the pressurizer and also regulate the pressure under normal operating conditions. If the pressure is low, more power is applied to the heaters to increase the pressure, and in the case of high pressure, the power input to the heaters is decreased accordingly. When the pressure is below the control range, then, additional (auxiliary) heaters are turned on. For the reverse situation in which the pressure is too high and decreasing the heater power level is not sufficient, a spray flow from the chemical and volume control system provides cooling and reduces the pressure.

The controller model used in this study is a proportional-integral-derivative (PID) controller given by Equation (4) and only acts on the normally operated heaters to keep the reactor coolant pressure constant.

$$\delta Q_h = \left[K_{P,p} + \frac{K_{I,p}}{s} + K_{D,p} s \right] \left(p_{P,ref} - p_P \right) \quad (4)$$

where δQ_h is the change in the heat output by the electric heaters; p_P and $p_{P,ref}$ are the actual and reference values of the primary coolant system pressure, respectively; $K_{P,p}$, $K_{I,p}$, and $K_{D,p}$ are the proportional, integral and derivative gain, respectively.

4 DYNAMIC SIMULATIONS

The effect of the control systems on the dynamic response of the single SMR unit model is analyzed with two different scenarios:

1. Increase in steam valve opening, and
2. Increase in reactor thermal power.

4.1 Increase in Steam Valve Opening

For the first scenario, a 5% step increase in the load is applied to the system at $t = 20$ s, which results in a change in the steam valve opening. For comparison, two different simulations under the same disturbance are run with and without the control systems. Figs. 2-5 exhibit the changes in the important state variables of the system and the relevant discussion is provided afterwards.

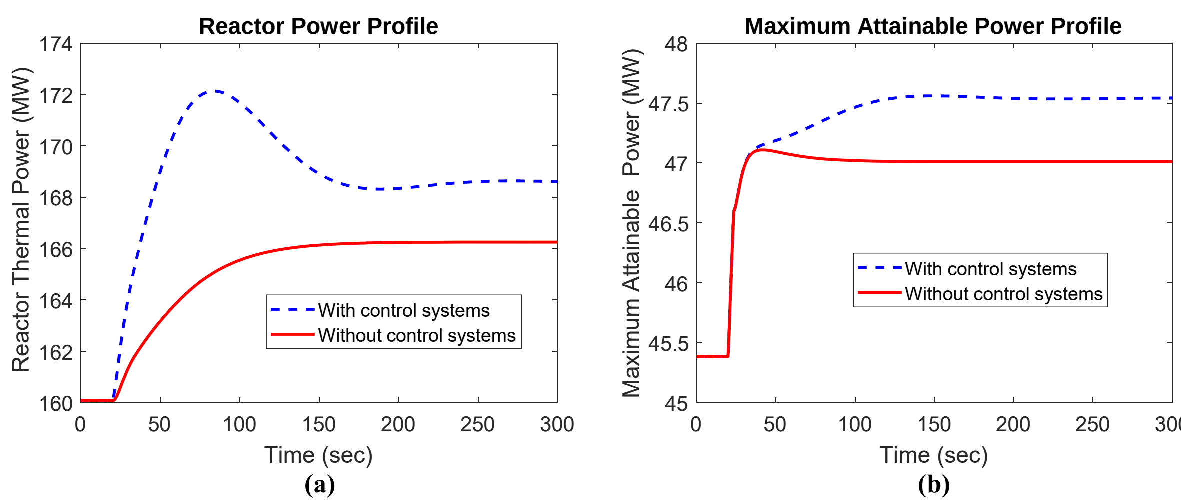
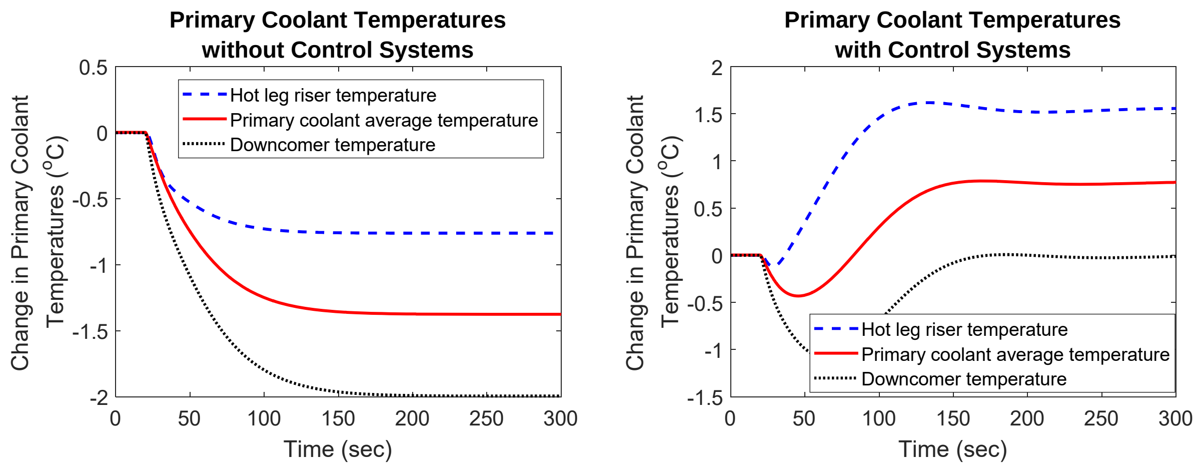
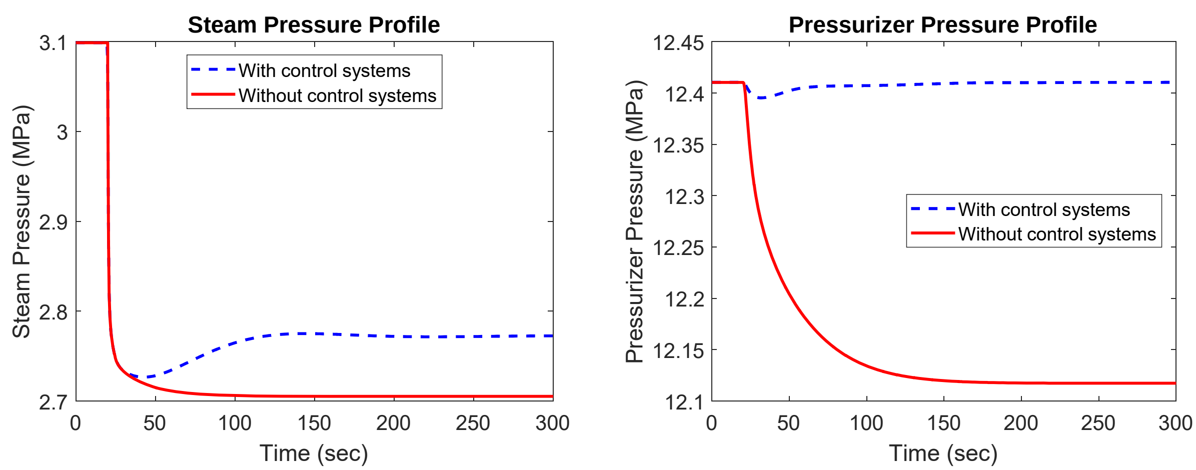


Figure 2. Reactor thermal power (a) and maximum attainable turbine power (b) responses for a step increase in the load for single SMR unit with and without control systems.



(a) **(b)**

Figure 3. Change in primary coolant temperatures for a step increase in the load for single SMR unit without (a) and with (b) control systems.



(a) **(b)**

Figure 4. Steam pressure (a) and pressurizer pressure (b) responses for a step increase in the load for single SMR unit with and without control systems.

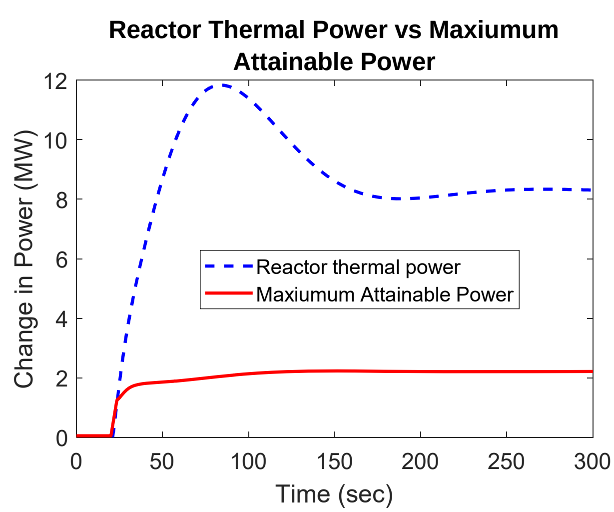


Figure 5. Change in reactor thermal and maximum attainable turbine powers for a step increase in the load for single SMR unit with control systems.

When the disturbance is introduced without control systems, the steam pressure decreases (see Fig. 4(a)) and flash steam is produced momentarily. The rise in the steam demand causes more heat transfer from the primary side to secondary. Thus, the primary coolant temperatures decrease as shown in Fig. 3(a) if no control action is taken. The reactivity feedback mechanisms induce a positive reactivity into the system due to the reduction in the temperatures, thereby leading to a gradual increase in the reactor thermal power (see Fig. 2(a)) even though no adjustment to the control rod positions is made. However, the increase does not satisfy the demand as the new steady-state reactor power is around 166 MW, which is 3.5% higher than the initial steady-state value but a reactor power increase of 8.2 MW is needed to meet the demand. The attainable turbine power also goes up by 1.7 MW and reaches a value of 47 MW accordingly, as depicted in Fig. 2(b), at the new equilibrium operating point.

The decrease in the primary coolant temperatures reduces the coolant volume in the primary loop and, therefore, an outsurge flow from the pressurizer via the baffle is observed. As the liquid-vapor balance inside the pressurizer is lost, the pressure diminishes with no active control of the heaters until a new equilibrium is established (see Fig. 4(b)).

If the same disturbance is applied while the control systems are active, the initial decrease in the downcomer temperature (see Fig. 3(b)) produces an error signal for the sliding-average-temperature controller. Following that the control rods are withdrawn accordingly, thereby introducing a positive external reactivity. The reactivity input results in a faster increase in the thermal power compared to the no-control case as shown in Fig. 2(a). After an overshoot, the power level settles down to a value of 168.3 MW which is congruent with the new setpoint established by the change in the load. Furthermore, the downcomer temperature starts increasing, after the initial dip, and reaches the pre-transient steady-state value (Fig. 3(b)), which is the desired behavior achieved by the sliding-average-temperature controller. Finally, a small recovery is noticed in the steam pressure with the reactor control as seen in Fig. 4(a).

In a similar manner, the pressurizer pressure controller senses the difference between the reference and actual values of the primary pressure after the transient is initiated, and then applies more power to the heaters to keep the pressure constant. Fig. 4(b) reveals that around 60 s after the disturbance, the primary pressure is returned to its initial steady-state value.

The attainable turbine power rises in accordance with the thermal power and reaches a value of 47.56 MW as desired in the control case (Fig. 2(b)). Fig. 5 shows the equilibrium deviation of the thermal (+8.2 MW) and attainable (+2.3 MW) power which yields the known thermal efficiency of 28%.

4.2 Increase in Reactor Thermal Power

The other scenario to test the effectiveness of the control system is to increase (or decrease) the reactor thermal power to a certain level within a desired time period when it is necessary.

For this simulation case, the reference value of the sliding-average-temperature controller is set to a new value of 253.3 °C, which was 245 °C initially, by a ramp function between t =20 s and t = 320 s. And the setpoint is kept at this new value for the rest of the simulation (t > 320 s) as seen in Fig. 6. A ramp is used instead of applying a step function to avoid large power overshoot. This is congruent with the industry practice for PWRs [11]. This control action is intended to reach a new thermal power level of 5% higher than the initial power level. Figs. 7-10 depict how some of the important system variables changes over time for this simulation case.

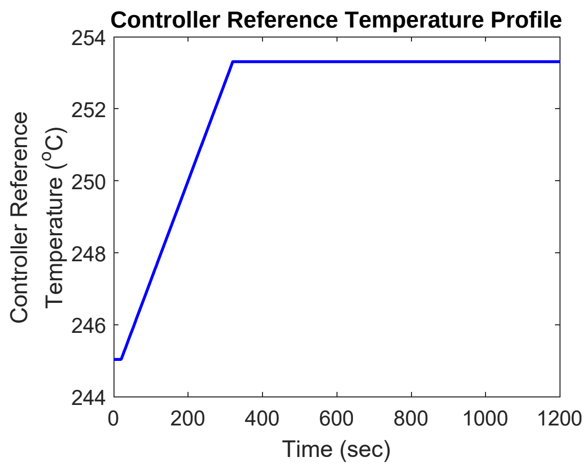
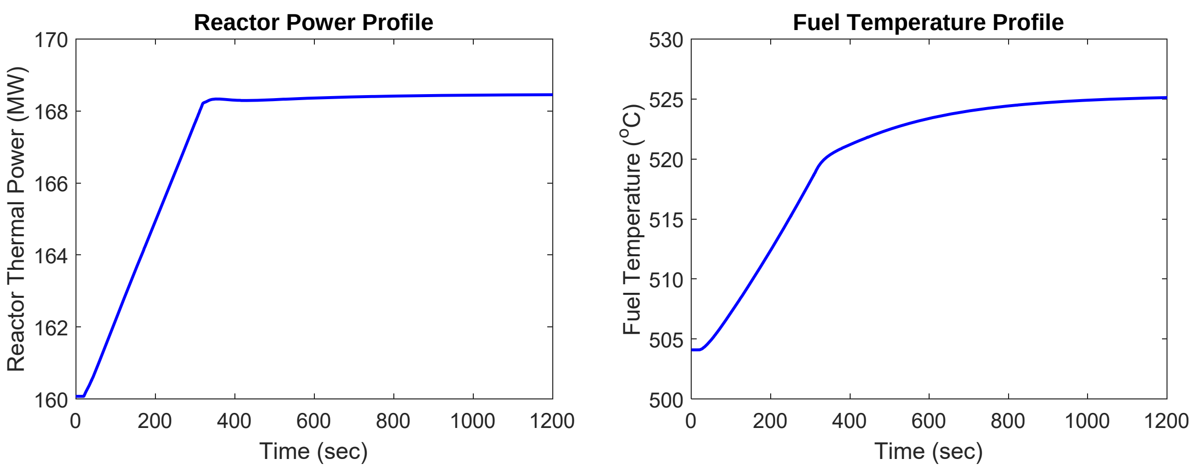
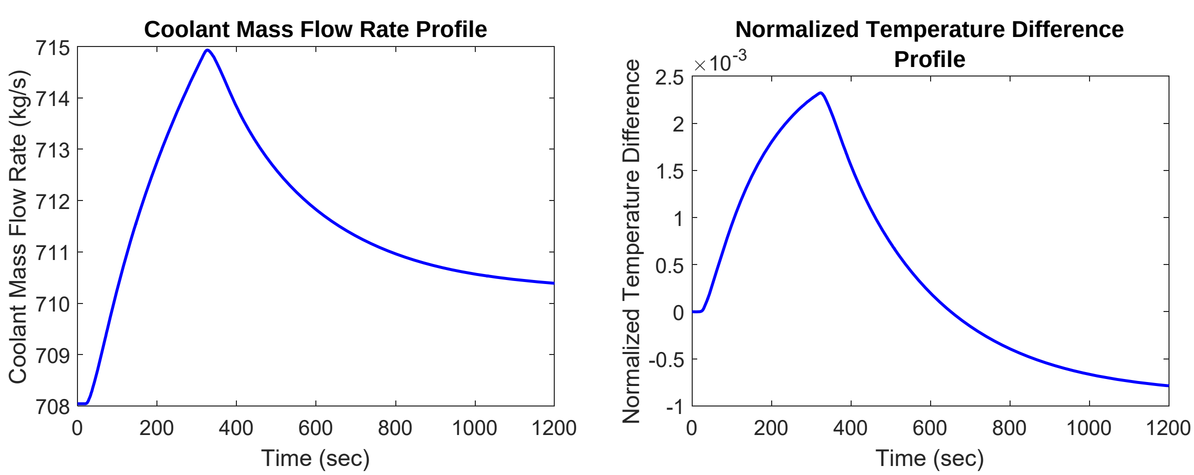


Figure 6. Controller reference temperature for a ramp increase in reactor power controller setpoint.



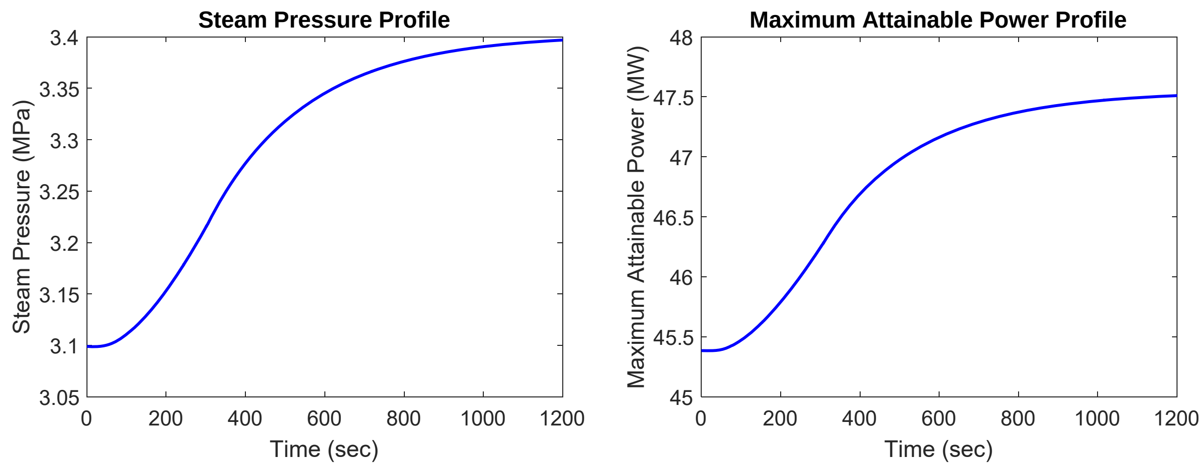
(a) **(b)**

Figure 7. Reactor thermal power (a) and fuel temperature (b) responses for a ramp increase in reactor power controller reference value for single SMR unit.



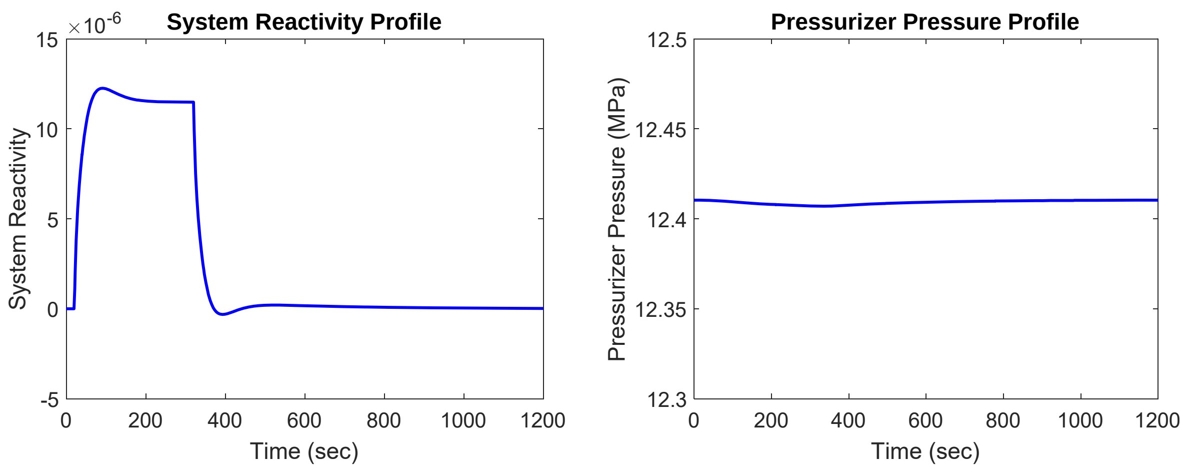
(a) **(b)**

Figure 8. Primary coolant mass flow rate response (a) and normalized temperature difference (b) ($T_{HL}/T_{HL,0} - T_{DR}/T_{DR,0}$) for a ramp increase in reactor power controller power reference value for single SMR unit.



(a) (b)

Figure 9. Steam pressure (a) and maximum attainable turbine power (b) responses for a ramp increase in reactor power controller reference value for single SMR unit.



(a) (b)

Figure 10. System reactivity (a) and pressurizer pressure (b) responses for a ramp increase in reactor power controller reference value for single SMR unit.

As the controller reference value starts increasing, the difference between the actual and reference downcomer temperatures introduces an error signal to the controller which then causes the movement of the control rods to induce a positive reactivity insertion (see Fig. 10(a)). Accordingly, the reactor thermal power and fuel temperatures show a rise as seen in Figs. 7(a) and 7(b). Furthermore, the coolant mass flow rate exhibits an upward trend over the course of the ramp increase in the controller setpoint and then a downward trend for the constant controller setpoint as seen in Fig. 8(a). This latter behavior is a result of the temperature difference in the primary system (see Fig. 8(b)) which is the main driving mechanism for the coolant mass flow rate as discussed in Section 2.2 by Equation (1).

With the increased temperature of the primary coolant, the temperature difference between the primary and secondary sides of the steam generator expands, thereby resulting in more heat transfer to the secondary side. The latter changes cause a growth in the steam generation. Thus, steam pressure increases as shown in Fig. 9(a). The attainable power rises gradually and settles to a new steady-state value of 47.56 MW as depicted in Fig. 9(b) which is congruent with the new, desired operation conditions discussed earlier.

The system reactivity exhibits a response similar to a square pulse shape (see Fig. 10(a)). This is the result of external reactivity (control rods) and internal reactivity (reactivity feedback mechanisms) acting together on the system. In other words, when the disturbance is initiated, the external reactivity is dominant and the system reactivity increases. However, feedback mechanisms level the reactivity off at a positive value after a while. When the disturbance stops, since there is no external reactivity due to the control rod movement, reactivity feedback mechanisms bring the system reactivity back to its initial, pre-transient value. Finally, Fig. 10(b) shows that this perturbation has minimal impact on the regulated pressurizer pressure.

5 SUMMARY

A detailed mathematical model for a passively cooled SMR and conventional control strategies for PWRs are adopted in this work to analyze the response of the SMR under common disturbances, i.e., increase in power demand (steam valve opening) and reactor thermal power.

The simulation results show that important system variables are kept at the desired values by the proposed control strategies despite the fact that SMRs are noticeably different from PWRs in design.

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