**Dynamically Coupled Extended Balance of Plant for an SMR**

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**INTRODUCTION**

The nuclear power industry has a long history in using modeling and simulation to design nuclear systems. Both experience and existing simulation software can be leveraged to bring modeling capabilities to extended BoPs. Here we adopt a divide-and-conquer approach for modeling and simulation wherein significant sub-systems are modeled individually and coupled via an external framework. A power plant has many systems that appear repeatedly, either physically or logically, say a feed water system composed of many individual water heaters, or a Rankine turbine with many regenerative heating steps. In both cases, a network can be built for all the components, and a dynamic model assembled to represent an extended BoP. A key capability requirement of the framework is to allow for scalability and reusability of computational modules. Given the status of modern computing power, extended BoP’s can now be created to various levels of detail; for instance, valves and pipes can be included explicitly in the network. An extended network can be mapped on large scale parallel computing platforms to allow for increasingly modeling fidelity. This forward picture calls for a broader understanding of the elements of a power plant and the coupling of the corresponding flow of energy. This is the primary motivation of this work.

**THEORY**

The model created is enabled through the use of a computational framework which allows for dynamic coupling of power plant systems. This parallel framework, called Cortix [1], facilitates the time-coupling of a total of five different major power plant operations. There is a Reactor (SMPWR), a Steam Generator (Steamer), a Turbine, a Condenser, and a Water Heater model. The time-coupling of these modules is shown in Fig. 1.

Diagram

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Fig. 1. Diagram describing the time-coupled flow of information between each of the models in the simulation.

Here the Small Modular Power Water Reactor (SMPWR) heats up the primary loop and sends the heated stream to the steamer where it exchanges heat with the secondary loop causing the secondary loop to boil. The resulting primary loop is then fed back into the reactor to be reheated.

The SMPWR has a first order temperature profile function as well as a negative temperature feedback loop function to approximate the reactors function.

The Steamer takes in two streams called the primary and secondary inlet and uses a three-state heat transfer function to indicate the phase leaving in the secondary outlet side. (1) Check if the heat transfer is enough to heat the secondary side to boiling, if not, then the phase leaving is just liquid. (2) Check if the heat transfer is enough to boil all of the water coming in on the secondary side, if so, the phase leaving is a vapor. (3) If the heat transferred is somewhere in the middle, the heat to boil is removed from the secondary side and then a vapor fraction is calculated.

Next this secondary outflow goes into a turbine function where electricity is calculated from the change in steam pressure. The calculated electricity is removed in the form of power generated and heating for the Water Heater module that will be discussed later.

After the steam goes through the Turbine, it gets condensed to a standard water state that is assumed to be maintained by a water tower controller.

Using electricity from the turbine, the Water Heater heats up the water coming from the condenser to reduce load on the Steamer. This cycle repeats until the upper time limit is reached or until an accident scenario is added.

**Core**

The core module takes in a flow steam from the steam generator and then sends a flow steam back to the flow steam. Core neutron and heat phenomenon is accounted for using a single point kinetic model which couples six ordinary differential equations (ODEs).

These ODEs model the heat transfer using a two-temperature model where pressure is always assumed to be constant and the water is assumed to only be in the liquid phase.

**Steam Generator**

The steam generator has two different flow streams. On the primary side, the steam generator takes in a flow from the reactor and sends the same flow stream back to the reactor after the heat transfer. On the secondary side, the steam generator takes in a stream from the water heater and then sends the stream to the turbine for power generation. The steam generator is modeled with two coupled time-dependent differential equations, one for the primary side and the other for the secondary side.

This design uses two once-through counter-current helical steam generators which are approximated with one bundle of cylindrical shaped tubes.

The primary flow is assumed to be forced convection due to the high mass flowrate and relatively small flow rate. The secondary side flow is also modeled using forced convection. The two-phase flow region is modeled as nucleate boiling using the Jens-Lottes correlation. Heat transfer between the primary and secondary sides are solved for using an overall heat transfer coefficient where the convective heat transfer coefficients are solved for as functions of the Nusselt, Reynolds, Prandtl, and Stanton numbers.

**Turbine**

The turbine takes in a stream from the steam generator and then sends the low energy waste stream to the condenser. The turbine also sends an energy stream to power the water heater. The turbine is modeled as an adiabatic, isentropic, completely reversible process with an efficiency determined from steady state operating conditions. The turbine shaft work is calculated from thermodynamic properties using the PyPI IAPWS package [2].

**ANALYSIS AND RESULTS**

This model was made to show start-up, steady-state, and shutdown conditions with and without an accident scenario. To test the model a break in the pipe between the water heater and the steamer was chosen as the accident scenario. What this accident scenario specifically does is reduce the flowrate of water entering the steamer from 67 kg/s at normal steady state, down to 47 kg/s for 15 minutes.

The dynamic nature of the model can be shown by first looking at the normal start-up, steady-state, and shutdown conditions of each of the models.

Chart, line chart

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Fig. 2. Reactor core outflow temperature without any accident scenario.

The above figure (2) shows the temperature of the flow leaving the core. Two interesting points (points A and B) should be noted. Point A occurs at about 5 minutes into the simulation and is the result the switch from the Dittus-Boelter correlation to the nucleate boiling correlation of Jens-Lottes in the secondary side of the steamer. This change in correlation is also the cause of point B on the graph which is also where a phase change from boiling to single phase flow occurs.

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Fig. 3. Steam quality leaving the steam generator.

This correlation can also be shown to affect the steam quality. On figure 3, there is a small discontinuity at about the four-minute mark. This is a result of going from nucleate boiling, into full flow boiling.

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Fig. 4. Steamer primary outflow temperature with flow loss accident scenario at minute 30.

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Fig. 5. Steamer secondary flow quality plot with flow loss accident scenario at minute 30.

Figures 4 and 5 show the effect of our accident scenario compared to normal steady state conditions. The most notable change is in figure 5 where the secondary side instantaneously boils. This is caused by a lack of secondary-side water being fed to the steamer reducing the required heat needed to fully boil the secondary side.

Figure 4 shows that reduced flow has a significant effect on the amount of heat that can be transferred. After the accident is triggered, the temperature of the secondary side starts to rise indicating a loss of the heat transfer capabilities in the steamer.

**CONCLUSION**

This work has demonstrated a paradigm for building extended BoP networks including a diversity of operating components. The approach uses a divide-and-conquer method where similar units can be modeled by the same computational module and instantiated into the network. For example, a system with additional feed water heaters would not require any extra modeling work. We have applied this approach to a modified SMR industrial module and created an extended BoP.

**ACKNOWLEDGMENTS**

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**REFERENCES**

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