DYNAMIC SIMULATION OF A CANDU® 6 REACTOR

M. Borairi (borairim@aecl.ca)

J. Tseng, M. Fonooni, P. Zahedi*

Abstract

This paper describes a CANDU® 6 Simulation (C6SIM) engineering software, currently under development at the Information and Control Design Centre at Atomic Energy of Canada Limited (AECL) Mississauga Office. C6SIM is being developed using the mathematical and simulation software package, MATLAB/Simulink, and will simulate the dynamics of the major CANDU® 6 plant and control systems. C6SIM is a design assist tool and can be used for analyses in time and frequency domains. Interfaces to other software simulations are also under development, which will allow C6SIM to work in conjunction with other codes such as CATHENA.

1. Introduction

AECL uses CATHENA (Canadian Algorithm for THErmalhydraulic Network Analysis) for detailed modelling of thermalhydraulics and heat transfer systems. CATHENA is a one-dimensional, two-fluid thermalhydraulic simulation code that is designed to analyze two-phase flow and heat transfer in piping networks. Its primary use has been the analysis and simulation of the consequences of postulated upset scenarios in AECL designed CANDU® and research reactors.

CATHENA offers control system modelling capabilities by using one of the following methodologies:

- Calculate the control system response using the CATHENA input file.
- Link CATHENA to an external executable code that supplies the major portion of the control logic. This separate control code then interacts with the CATHENA simulation by taking values of CATHENA "accessible" variables (temperature, pressure, etc) and produces changes in the simulation by altering CATHENA "controllable" parameters (e.g., valve positions). This is achieved by using Parallel Virtual Machine (PVM) as an integration environment and is a proven method.

The primary challenge with embedding reactor control system models in the CATHENA input file, as opposed to coding in a separate executable program, is that the specific control functions may be distributed through-out various parts of the input deck, and models and documentation become more difficult to maintain. Changes in control strategy have to be made in CATHENA (synchronized). Although the system control within CATHENA is flexible, it is sometimes difficult to code the system control routine.

SOPHT (Simulation of Primary Heat Transport System) was developed to study the transient performance of the nuclear Heat Transport System (HTS). SOPHT was designed to differ from the simulation programs customarily used by the control system designers by emphasizing the transient properties of the thermalhydraulic system as well as the response of the associated control system. The primary interest of the program is to predict the system transient during a

* Polad Zahedi is currently completing his final year study at University of Western Ontario. He worked on CATHENA-Simulink integration during his internship work at AECL

relatively large, low frequency disturbance (upset conditions) as well as during normal controlled manoeuvring operation.

C6SIM is an analytical simulation tool and under development on the MATLAB/Simulink platform. The hardware and software requirements are therefore identical to the requirements for running MATLAB and Simulink (see References [1] and [2]). The C6SIM model includes detailed plant and control models that simulate the dynamic behavior of the CANDU® 6 reactor and its major control systems, using the same control logic and algorithms as configured in the Digital Computer Control (DCC). C6SIM is designed to be flexible so that it may be quickly modified to suit various design or test scenarios. As an analytical simulation tool that can be run faster than real time, C6SIM is being designed to permit testing or verification of any proposed control design changes to the DCCs to be performed quickly.

The main objectives of developing C6SIM are:

- to permit sufficiently accurate prediction of transient behaviour of the CANDU® 6 reactor by solving a set of differential equations that model the behaviour of the reactor physics, thermalhydraulics, instrument dynamics, and control systems;
- to permit the analysis of the performance of specific components such as the steam generator (SG) and pressurizer;
- to provide a tool for analysis and diagnosis of difficult problems related to plant dynamics or control that are reported to AECL by CANDU® stations that will help provide optimal solutions in a timely manner with higher confidence; and
- to have an integrated tool to analyze and determine the effects of proposals to improve reactor performance.

C6SIM could be used as an effective tool to respond in a timely manner to the requests for analysis by nuclear stations. Utilities traditionally use the full scope simulators for training operators and sometimes for non-training purposes such as supporting design analysis, optimization, and process diagnostics. C6SIM usually runs faster than real-time and could be used when analysis and diagnosis is required which cannot be provided by training simulators. In addition, the control logics in C6SIM can be linked, with minor modifications, with CATHENA for use in future safety analysis (see Section 4 for more details).

2. CANDU® 6 Reactor Overview

C6SIM is composed of thermalhydraulic models and control models. The thermalhydraulic circuits and their associated equipment models are developed based on the following assumptions:

- A CANDU® 6 plant has two symmetrical HTS circuits. C6SIM utilizes one quarter circuit of the HTS, that is, the two loops of the HTS circuit are combined into one and the two lobes of the composite loops are further integrated into one lobe. The pressurizer and the HTS feed and bleed systems are also modelled.
- In the secondary circuit, the four Steam Generators (SG), which are connected to the four outlet headers are combined into a single representative SG located at the integrated outlet header. Steam from the SG goes through two turbine stages on the way to the condenser. The SG model includes the steam generating section, riser, downcomer, and the steam drum.

- Steam from the SG goes through two turbine stages on the way to the condenser. A simple turbine model is used to capture the dynamics of the mechanical energy translating into electrical energy in the generator.
- The feedwater train is modelled downstream from the deaerator and the feedwater temperature is obtained as a function of steam flow to the turbine and the feedwater flow through the control valves.

The control model is designed for the complete circuit and includes:

a) SG Pressure Control (SGPC)
b) SG Level Control (SGLC)
c) Pressure and Inventory Control System (P&IC)
d) Bleed Condenser Pressure and Level Control
e) Reactor Regulating System (RRS)
f) Circuit Overpressure Protection.

Figure 1 illustrates a schematic of the C6SIM model.

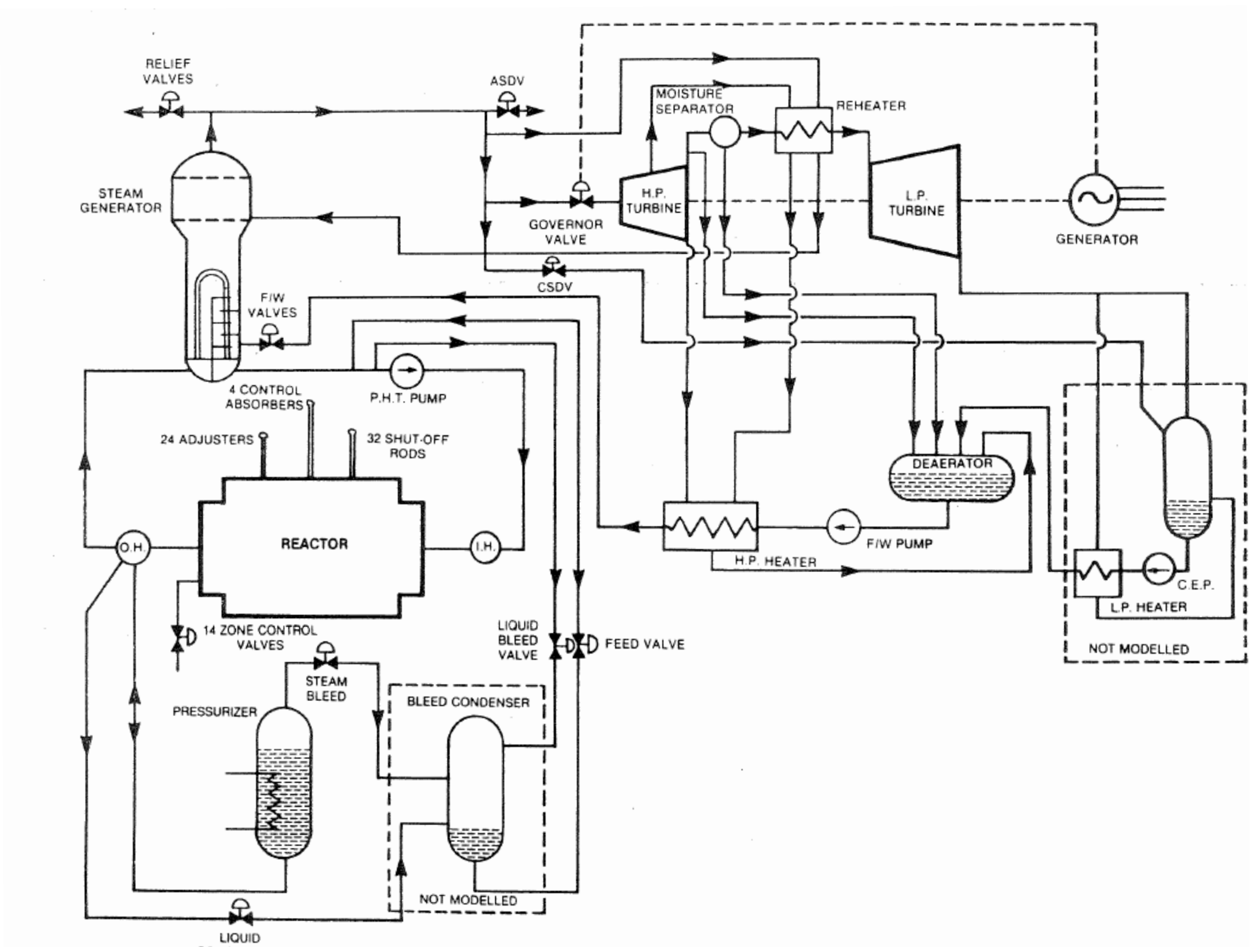

Figure 1: CANDU® 6 Process Diagram

3. C6SIM PROCESS MODEL

The C6SIM development process (i.e., life-cycle) involves the use of modularity and encapsulation. Each module will be developed and tested independently. Modules will be integrated to form the overall model of the CANDU® reactor. This approach provides flexibility, process discipline, consistency, and reusability of the developed codes.

The thermalhydraulic model is obtained by breaking the system into a series of nodes and links. A node can be thought of as a volume that has both mass and energy, which represents equivalent mass, energy, and volume associated with a particular segment of the represented circuit. Each node is then connected to its neighbours through a network of links. The link does not have any mass or energy associated with it, but it does have both momentum and resistance.

The reactor model is based on a nodal model. The modelling process starts from a two-group diffusion description of the reactor dynamics. The interaction between neighbouring zones is characterized in terms of coupling coefficients, which basically describes the possibility of a neutron born in one zone to cause a nuclear reaction in another zone [3].

The control logics are based on various CANDU® 6 Program Specifications (PS).

At the current stage, the reactor physics and RRS control modules have been implemented.

Figure 2 shows the zonal power and the liquid zone level responses for a change in the reactor power setpoint from 0.5 to 1 FPU at 50 seconds and an increase in reactivity in zone 1 at 220 seconds, representing a refuelling change.

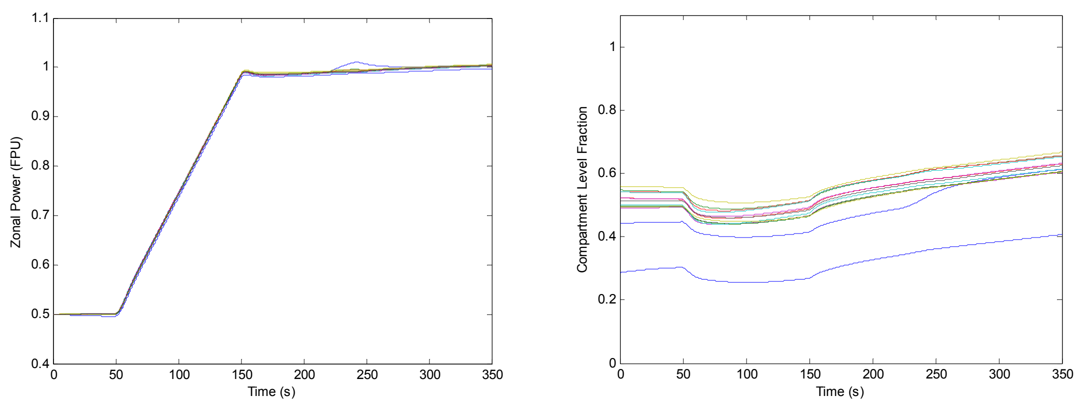

Figure 2: Zonal Power and the Liquid Zone Level Responses Due to a Power Setpoint Change for C6SIM

The figures show that the C6SIM reactor physics and RRS control models create a stable response with very little overshoot, and with power reaching its setpoint at approximately150 seconds.

4. Integration of C6SIM Control Modules with CATHENA

The detailed control models that have been created during the development of C6SIM can have further uses. A communication link has been developed so that a Simulink model can run in conjunction with a model from an external code, such as CATHENA. This communication interface essentially provides a new, detailed simulation model, but by using models that have already been separately developed and verified, only a relatively small amount of development time is required for this new model. This integrated model can then take advantage of the high fidelity components of the separate codes and provide additional cross-validation.

As an example of this approach, a simulation software has been developed at AECL named "SIMCAT" that consists of the detailed C6SIM RRS control modules and a high fidelity CATHENA thermalhydraulic plant model specifically developed for the liquid zone control system. CATHENA calculates the dynamic behaviour of the 14 liquid zone compartment levels. Simulink reads these levels and calculates the reactor power response and the RRS logic response to these levels and calculates the 14 liquid zone control valve positions for CATHENA.

The communication link between CATHENA and Simulink includes several components such as:

- *Parallel Virtual Machine (PVM):* This provides a unified framework within which parallel programs can be developed in an efficient and straightforward manner using existing hardware. PVM enables a collection of heterogeneous computer systems to be viewed as a single parallel virtual machine. PVM transparently handles all message routing, data conversion and task scheduling across a network of otherwise incompatible computer architectures. PVM is used to interface CATHENA with external models and utilizes the following API and software language:
    - *Open Database Connectivity:* This is a procedural application programming interface (API), which allows the Structured Query Language (SQL) commands communicating with PVM variables to access the database in which the integrated simulation's common database resides. Microsoft Excel is used as the Common Database (CDB).
    - *Structured Query Language:* This is used to communicate between the CATHENA PVM variables and the Common Database.
- *Dynamic Data Exchange (DDE):* This is a standard for inter-process communication that uses shared memory to exchange data between applications. DDE is used to establish a dynamic communication between C6SIM and the CDB.

When the CATHENA information is transferred to CDB, C6SIM indirectly acquires these values for its calculations. For this purpose, a MATLAB specific code (an M-file) was written to communicate with the Common Database. Figure 3 illustrates the communication cycle.

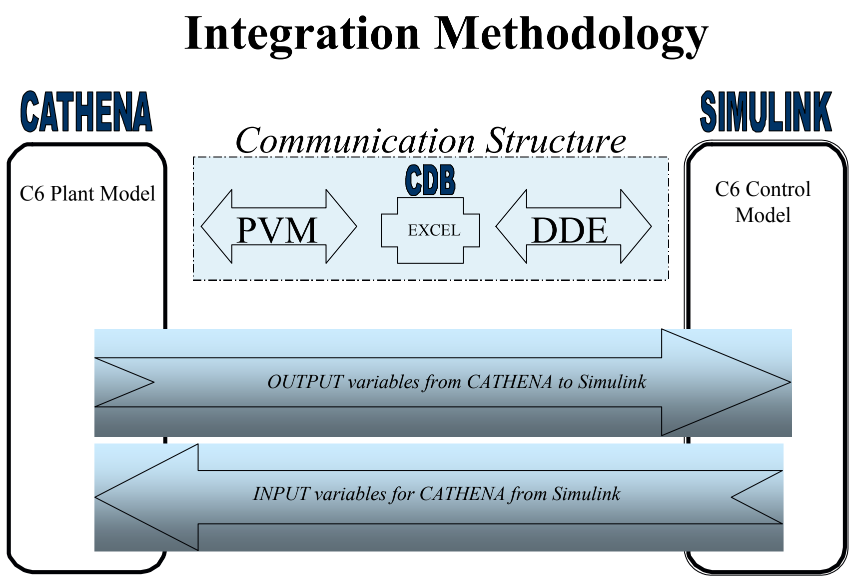

Figure 3: SimC6-CATHENA Communication Cycle

Figure 4 shows a zonal power and liquid zone responses calculated by SIMCAT for the same power manoeuvre shown in Figure 2. There is a good match between the results obtained from SIMCAT and C6SIM. The overall reactor power performance is stable with little overshoot; again, power reaches its setpoint at approximately 150 seconds. It should be noted that the simulation time for CATHENA's calculations are approximately 19 minutes to calculate 1 second of simulation time. C6SIM currently has a much more simplified liquid zone control plant model resulting in a much faster simulation: approximately 20 seconds to calculate 1000 seconds of simulation time.

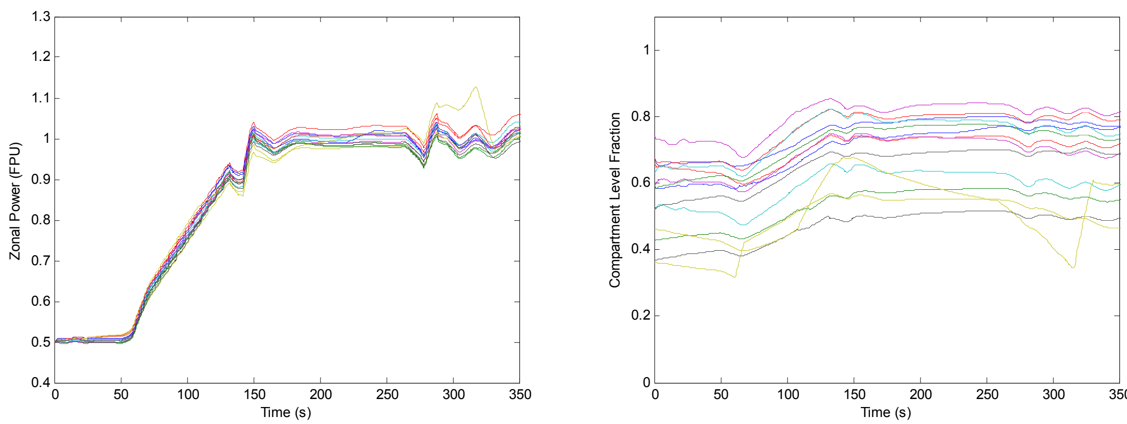

Figure 4: Zonal Power and Liquid ZoneLevel Response Due to a Power Setpoint Change for SIMCAT

5. Discussion and Conclusions

C6SIM is being developed to be an effective tool for analysis and design. It will provide a basis for prediction, verification, and optimization of plant design. In comparison the some preliminary results obtained by SIMCAT, the C6SIM results are very encouraging. For future work, the fidelity of systems such as liquid zone control will be improved to produce even closer results to SIMCAT.

Moreover, a link has been established between C6SIM control modules and CATHENA, allowing both codes to run together. This integrated model contains the detailed thermalhydraulic model of the liquid zone control system in CATHENA, and the detailed RRS control logic model in Simulink.

When the C6SIM development is completed, it will be validated against real plant data and will also be cross-validated against SIMCAT. Then the validated C6SIM will be able to be used as a powerful and accurate simulation tool to support improved analysis and response to existing and future design and operation questions in a timely manner.

6. References

[1] R. Pratap, "Getting Started with MATLAB 7: A Quick Introduction for Scientists and Engineers", The MathWorks Inc., September 2006.

[2] "Simulink 6.5 User's Guide", The MathWorks Inc., Release 2006b, online only.

[3] H. Javidnia, J. Jiang, and M. Borairi, "Modeling and Simulation of a CANDU Reactor for Control System Design and Analysis", to be appeared in Journal of American Nuclear Society, February 2009.

7. Acronyms

AECL	Atomic Energy of Canada Limited
API	Application Programming Interface
C6SIM	CANDU 6 Simulation
CATHENA	Canadian Algorithm for THErmalhydraulic Network Analysis
CDB	Common Database
DCC	Digital Computer Control
DDE	Dynamic Data Exchange
HTS	Heat Transport System
P&IC	Pressure and Inventory Control System
PS	Program Specifications
PVM	Parallel Virtual Machine
RRS	Reactor Regulating System
SG	Steam Generator
SGLC	SG Level Control
SGPC	SG Pressure Control
SIMCAT	Simulink and CATHENA integrated model
SOPHT	Simulation of Primary Heat Transport System
SQL	Structured Query Language