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PBMR: Transient Analysis of the PBMR

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Abstract

In this paper a brief description of the thermo-hydraulic simulation techniques used for analysis of the Pebble Bed Modular Reactor (PBMR) and applications thereof are presented.

Simulations of the PBMR power conversion unit coupled to the reactor can be used to analyse the effects that the transient response has on various components during different modes of operation. The design of the plant (as well as the reactor) can subsequently be improved to reduce transient effects during normal and upset conditions.

Using the transient response results a loading catalogue for components can be generated for normal and abnormal transients expected during the lifetime of operation. Simulation techniques currently used to analyse the PBMR are discussed and results detailing the most severe transients are presented.

1. INTRODUCTION

Controllability and transient performance of the PBMR are ultimately determined by the dynamic characteristics of the Reactor Unit and the Power Conversion Unit. The following dominant system characteristics should be well understood in understanding the dynamic response of the PBMR:

The thermal response of the Reactor is slow. This is because of the large thermal capacity of the graphite-moderated core relative to its heat generation and removal rates. The output and speed response of the turbo machinery is very fast when compared to the reactor dynamics. This is because of their relatively low inertia compared to the available power. The difference in speed of response of the Reactor Unit and Power Conversion Unit (PCU) has a certain advantage but at the same time also creates a demanding co-ordination requirement.

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[*] Formerly the International Working Group on Gas Cooled Reactors, name changed in 2001

The advantage is that the large thermal capacity of the core allows relatively fast load changes of the system without requiring fast response from the core. In principle, the energy stored in the core can be tapped or additional energy can be stored, with minimal core temperature changes. The reactor also has a negative temperature coefficient, which results in the reactivity, and consequently the neutronic power, counteracting the temperature changes. The reactor is largely self-regulating and the minimum of control interaction is required to maintain the reactor outlet temperature at a given value.

A demanding requirement is that, because of the low turbo-machine inertia, a sudden loss or partial loss of outside electric load will result in an almost immediate acceleration of the turbo-machines to potentially unacceptable rotational speeds. This is most noticeable in the case of the power turbine generator that requires active speed control when the generator is not connected to a stable grid. The high and low-pressure turbo units have the added stability of a compressor and turbine on a single shaft. The compressor improves the stability of a turbo unit by counteracting any speed variations. Nonetheless, the turbo unit speeds vary across a wide range due to changes in the PCU conditions.

Thus, in principle the PBMR consist of an inherently very stable and slow acting heat source coupled to very fast acting power conversion machines, which will require active control to remain stable under all anticipated operating scenarios.

2. TRANSIENT SIMULATION TECHNIQUES

The Module Dynamics & Control Group (MDCG) at PBMR is responsible for the thermo-hydraulic analysis and the design of control algorithms. This includes the analysis of the integrated plant performance, management of plant performance base lines, optimisations and techno-economic studies, safety analyses and model development of PBMR systems.

The simulation tools used includes thermo-hydraulic analyses, computational fluid dynamics (CFD), design and development of plant controllers, finite element analyses (FEA) and the analysis and simulation of the fuel handling and storage system.

2.1. Flownet

The reactor coolant system as well as integrated subsystems are analysed with the thermoflow network analysis code Flownet. The approach followed in this code is to model the coolant system as a network of interconnected components such as pipes, diffusers, heat exchangers, compressors, turbines, orifices, valves as well as the reactor. Components are connected to nodes at their upstream and downstream ends. Any number of components can be connected at one node. This makes it possible to model any arbitrary network. The code is also capable of evaluating gas mixtures, takes gravitational effects into account and solve for compressible and incompressible fluids.

The overall network solution algorithm is based on an implicit finite difference technique. This enables time step variations, which allows the simulation of slow and fast transients. With this technique, the nodal pressures and temperatures are iteratively adjusted at each time step to simultaneously satisfy the continuity and energy equations at each node, as well as the pressure drop/flow rate relationship for each element (component). It is important to note that the continuity equation is in the conservative form, thereby ensuring overall conservation of mass in closed systems.

Flownet can deal with both steady state and transient flows. In the case of transient flows, the inertia of the fluid as well as the thermal inertia of the heat exchanger walls and of the fuel spheres in the reactor core is taken into consideration.

Flownet Nuclear is PBMR intellectual property. Flownet was derived from first principles, which enables it to be used for safety analyses. The Flownet user interface enables system changes to be rapidly incorporated and is extensively used at PBMR for design purposes. Flownet is used as an accurate plant model for control design and development and is also used in conjunction with the controllers as an analysis tool for the generation of loading catalogues. Flownet will also be used as the plant simulation tool in the operator-training simulator.

2.2. Control Design

An interactive control system design between the control development software, SIMULINK (MATLAB) and the Flownet nuclear simulator is used to develop the PBMR controllers. Thermo-hydraulic simulations have been used to accurately study the system response and to identify the actuators and measurement devices needed for accurate control of the PBMR plant.

The use of a simulator in control development enables the testing of control strategies on a simulator before implementation on the plant hardware. The interaction of different controllers can be studied and the performance of the controllers and the plant capabilities can be analysed. The use of accurate control models for the transient analysis of the PBMR plant is essential since the plant response depends to a great extent on the controllers that are used.

The controllers are made up of interconnected function blocks. A variety of function blocks are available: Simple arithmetic functions, transfer functions, advanced state space control functions and user-defined functions and algorithms are available. The control implementation consists of a hierarchy of function blocks. This enables the use of supervisory control and advanced process control techniques. Accurate sensor and actuator dynamical models are also incorporated.

3. SIMULATION RESULTS

Some of component results for a start-up and synchronisation transition and a loss of load transient are presented in this section. These are typically the results given to component manufactures for detailed design of systems and components.

3.1. PCU Start-up and Synchronisation Transition

The initial condition for the start-up and synchronisation transition is a conditioned PCU with the power turbine generator (PTG) speed at 30 Hz. The continuous resistor bank (CRB) is used to dissipate the produced electrical power.

The start-up and synchronisation transition can be outlined as follows:

A. Reduce the power dissipated by Resistor Bank to zero, which allows the PTG to speed-up. The Power Turbine fluidic power is controlled with compressor bypass valves. During the PTG spin up process the Brayton cycle becomes self-sustaining.

B. The CRB is activated when Power Turbine reaches 50 Hz and the speed controller is switched on to maintain the PTG speed at 50 Hz and the generator is synchronised to the grid.

Some of the results from a start-up transition are shown in Figures 1 to 4.

3.2. Loss of Load Transient (Load Rejection)

A loss of load transient results from the loss of electrical load during power operation resulting in a sudden Power turbine generator (PTG) speed increase. During a loss of load transient the fluidic power of the power turbine must be reduced rapidly in order to avoid a PTG over-speed condition. Furthermore the Brayton cycle must be kept functioning and the PTG speed controlled to 50 Hz in order to provide the plant house load.

Some of the results from a loss of load transient are shown in Figures 5 to 7.

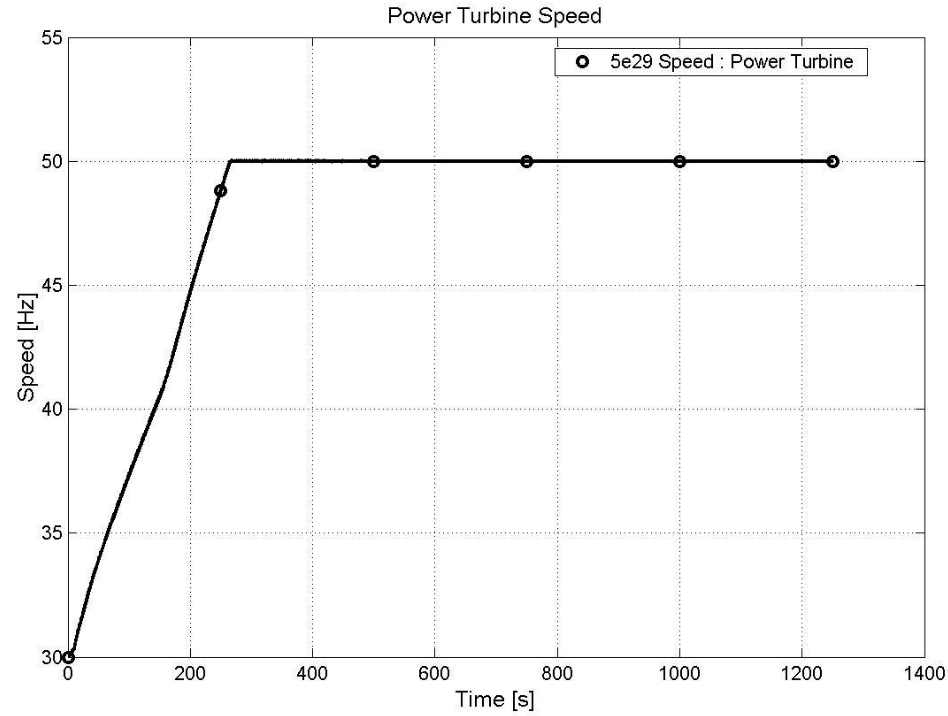

Figure 1: Start-up transition - Power Turbine Speed

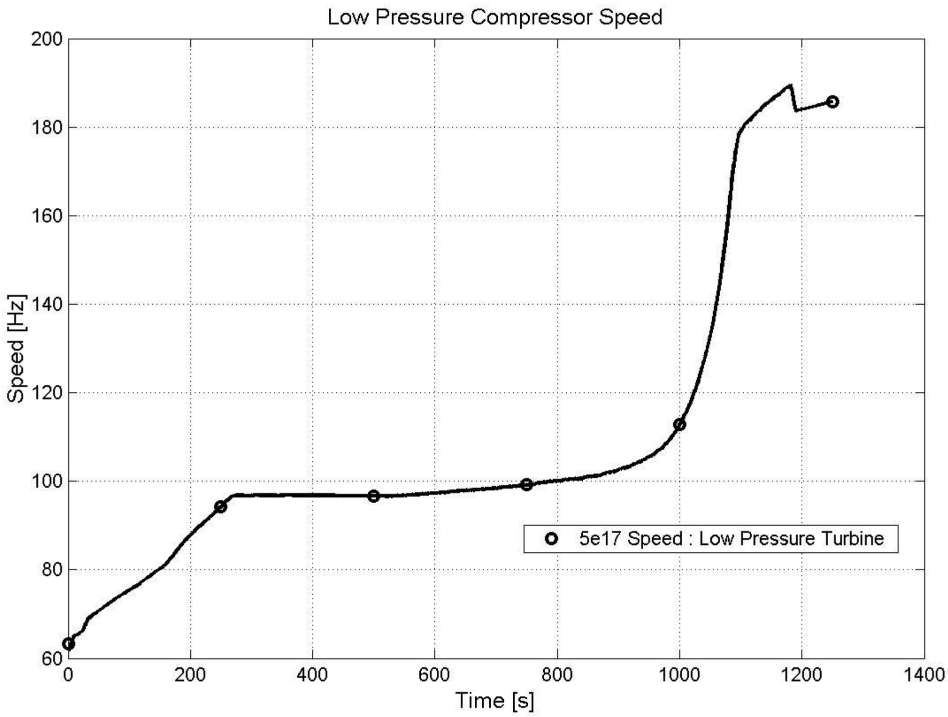

Figure 2: Start-up transition - LP Turbo Unit Speed

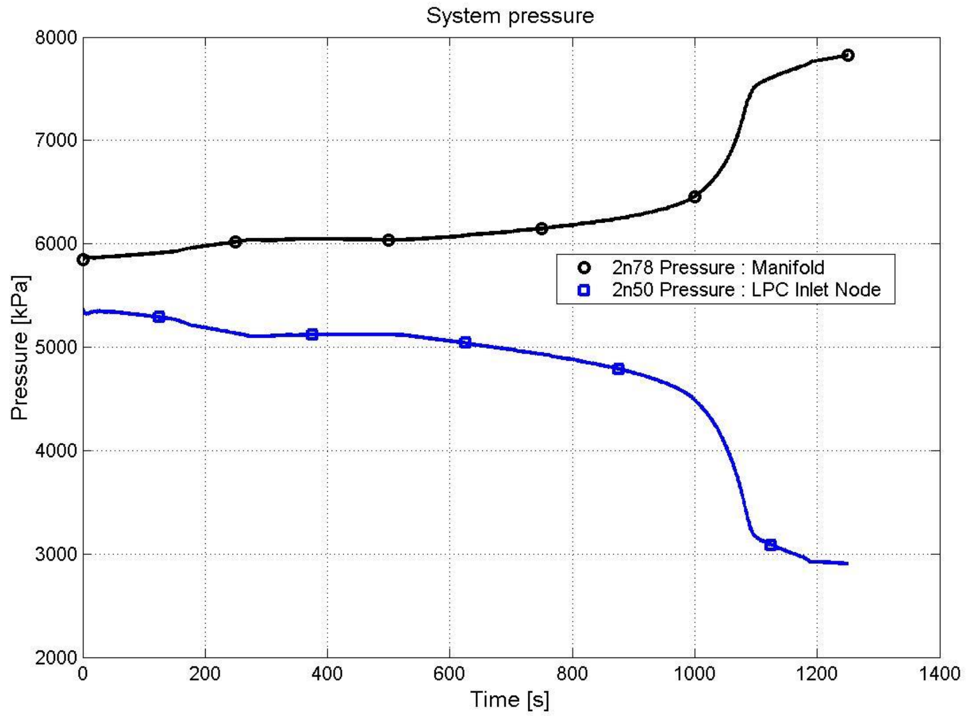

Figure 3: Start-up transition - System Pressure

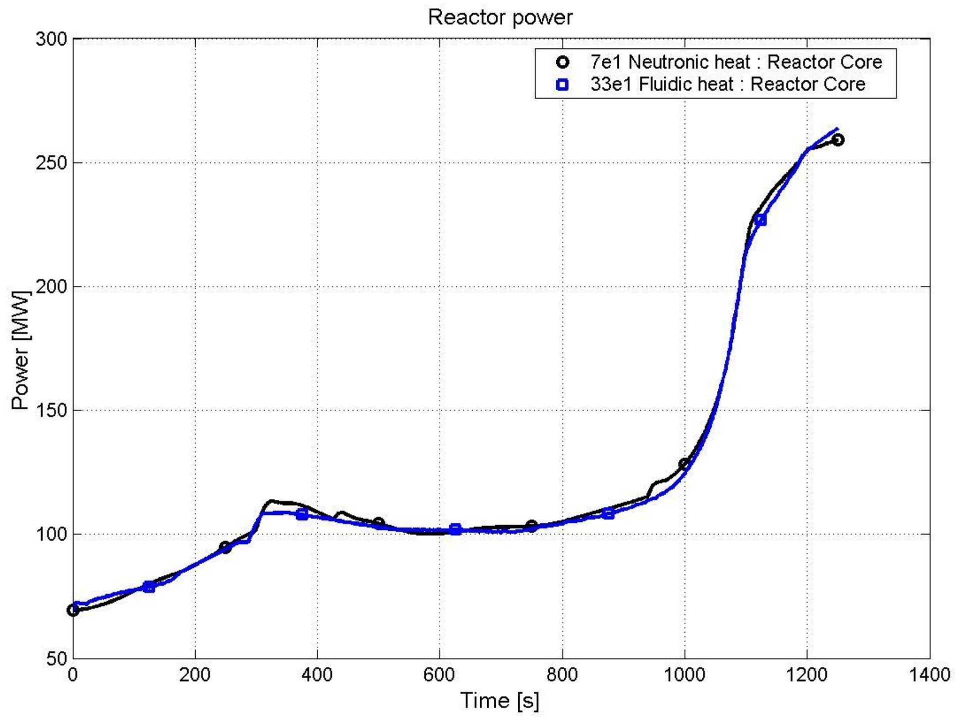

Figure 4: Start-up transition - Reactor Power

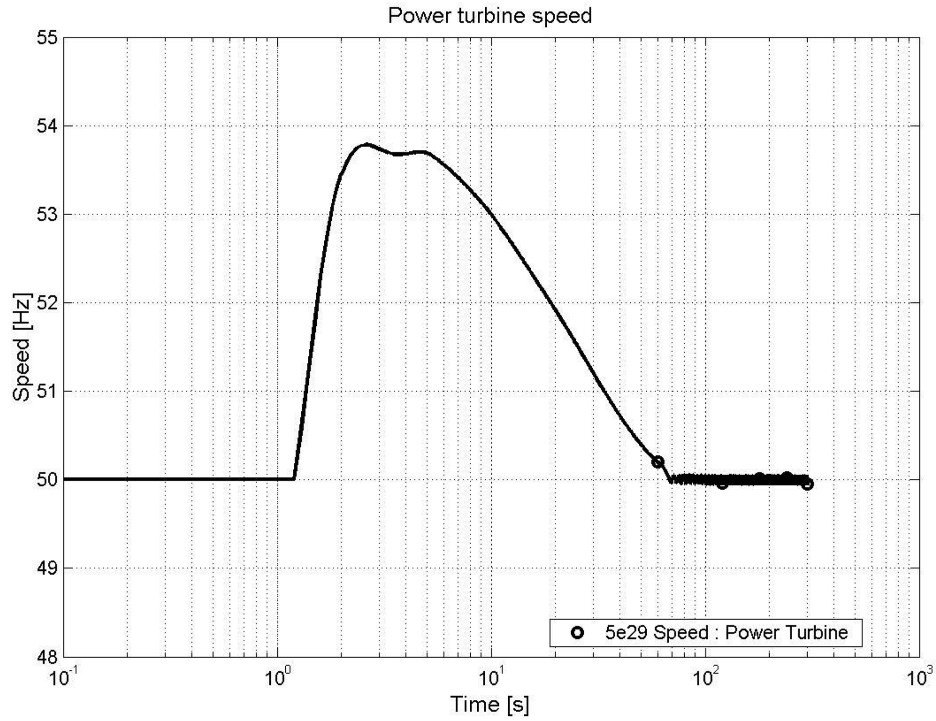

Figure 5: Loss of load transient - Power turbine speed

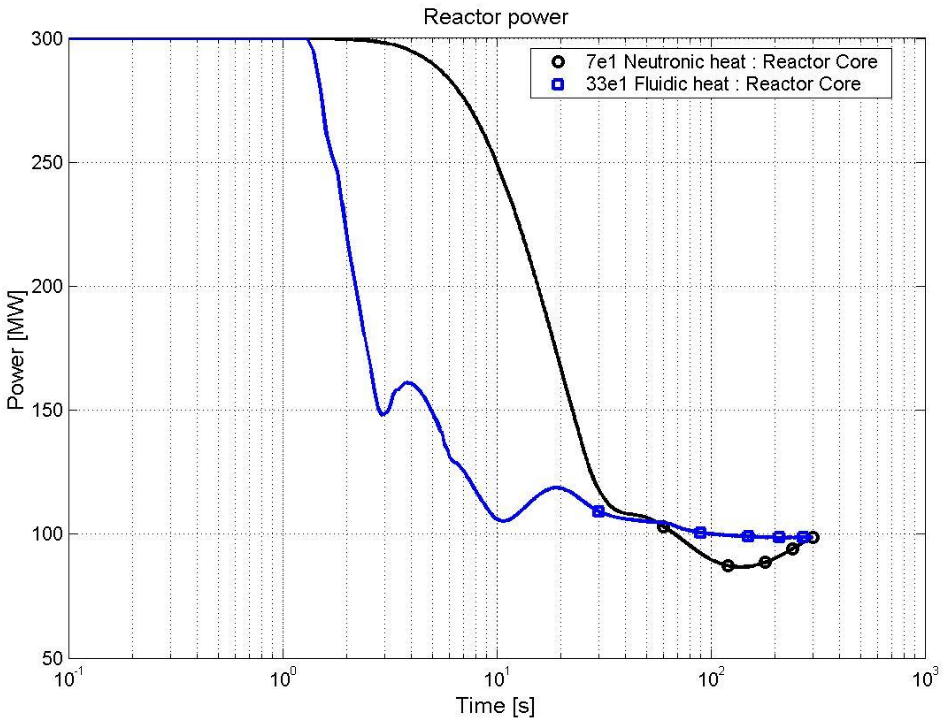

Figure 6: Loss of load transient - Reactor power

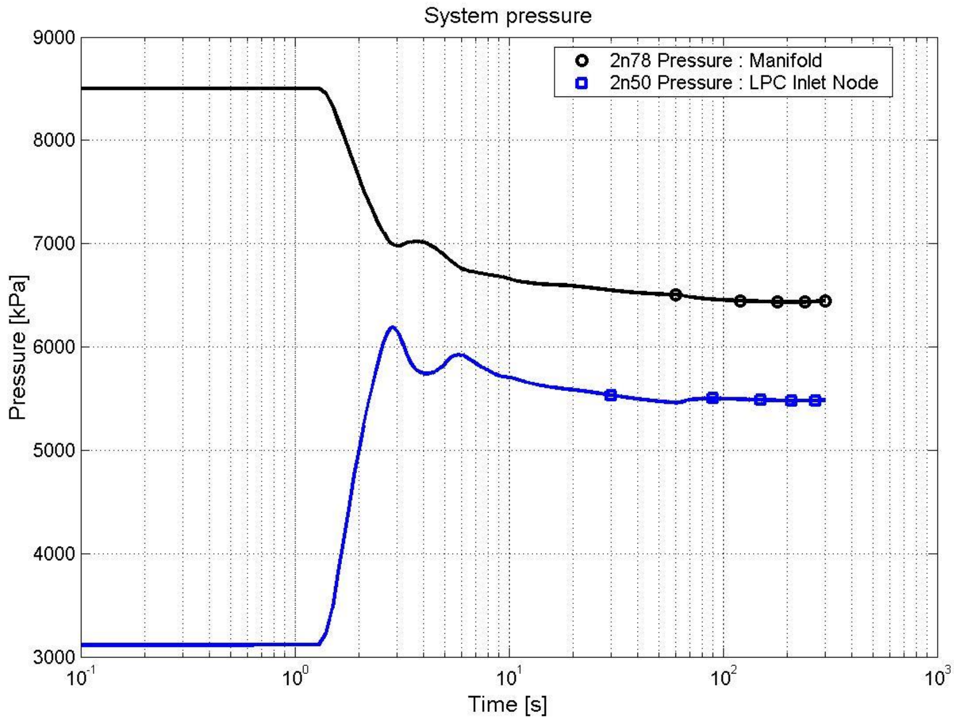

Figure 7: Loss of load transient - System pressure

4. CONCLUSION AND REMARKS

An accurate simulator is essential in order to accurately determine the transient response of a closed Brayton cycle. By making use of Flownet, which is based on first principles, PBMR is capable of transient simulations of the reactor unit coupled to the power conversion unit.

The use the simulator connected to Simulink (Matlab) enables interactive control development and simulation of the plant dynamics with the control systems actively controlling the plant. These simulations forms an essential part in the design of the system as well as providing loading catalogues for the various components in the system. The plant simulator together with the controllers can subsequently be used as an integral part in the training simulator and as an engineering simulator for analysis during commissioning, testing and operation of a PBMR plant.