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Comparison of two models for a pebble bed modular reactor core coupled to a Brayton cycle

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Abstract

The pebble bed modular reactor (PBMR) plant is a promising concept for inherently safe nuclear power generation. This paper presents two dynamic models for the core of a high temperature reactor (HTR) power plant with a helium gas turbine. Both the PBMR and its power conversion unit (PCU) based on a three-shaft, closed cycle, recuperative, inter-cooled Brayton cycle have been modeled with the network simulation code Flownex.

One model utilizes a core simulation already incorporated in the Flownex software package, and the other a core simulation based on multi-dimensional neutronics and thermal-hydraulics. The reactor core modeled in Flownex is a simplified model, based on a zero-dimensional point-kinetics approach, whereas the other model represents a state-of-the-art approach for the solution of the neutron diffusion equations coupled to a thermal-hydraulic part describing realistic fuel temperatures during fast transients. Both reactor models were integrated into a complete cycle, which includes a PCU modeled in Flownex.

Flownex is a thermal-hydraulic network analysis code that can calculate both steady-state and transient flows. An interesting feature of the code is its ability to allow the integration of an external program into Flownex by means of a so called memory map file.

The total plant models are compared with each other by calculating representative transient cases demonstrating that the coupling with external models works sufficiently. To demonstrate the features of the external program a hypothetical fast increase of reactivity was simulated.

1. Introduction

Advanced reactors such as the high temperature gas cooled reactor have aroused special interest over the last few years. The main field attracting attention has been that of the high temperature gas cooled reactors with a direct helium gas turbine. Considerable attention was given to the possibility to directly connect the gas turbine and the high temperature reactor, resulting in a very economical generation of electrical power.

The development of improved technologies of high temperature gas cooled reactors emerged at the design pebble bed modular reactor (PBMR) in South Africa as a world wide international association between Eskom the national utility and other industrial partners. The PBMR aims to achieve the goals of safe, efficient, environmentally acceptable and economic production of energy at high temperature for the generation of electricity and industrial process heat applications (Matzner, 2004).

This high temperature gas cooled reactor is based on the recuperative inter-cooled closed loop Brayton cycle using helium as coolant (see in Fig. 1) (Greyvenstein and Rousseau, 2002). With reference to Fig. 1, starting at state 1, helium at a relatively low pressure and temperature (1) is compressed by a low pressure compressor (LPC) to an intermediate pressure (2) after which it is cooled in an inter-cooler to state 3. A high pressure compressor (HPC) then compresses the helium to state 4. From states 4 to 5 the helium is preheated in the recuperator before entering the reactor, which heats the helium to state 6. After the reactor, the hot high pressure helium is expanded in a high pressure turbine (HPT) to state 7 after which it is further expanded in a low pressure turbine (LPT) to state 8. The high pressure turbine drives the high pressure compressor whereas the low pressure turbine drives the low pressure compressor. After the low pressure turbine the heated helium is further expanded in the power turbine, which drives the generator, to the pressure at state 9, which is approximately the same pressure as at state 10 and at

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Nomenclature

API	application programming interface
BPV	bypass valve
GCBV	gas cycle bypass valve
HPC	high pressure compressor
HPT	high pressure turbine
HTR	high temperature reactor
IPCM	implicit pressure correction method
LPC	low pressure compressor
LPT	low pressure turbine
PBMR	pebble bed modular reactor
PCU	power conversion unit
VHTR	very high temperature reactor

state 1. From states 9 to 10 the hot helium is cooled in the recuperator, after which it is further cooled in the pre-cooler to state 1. This completes the cycle. The heat rejected from states 9 to 10 is equal to the heat transferred to the helium from states 4 to 5.

In the meantime it was decided to redesign the PCU using a single power turbine-compressor shaft (Matzner, 2004). This implies that the turbo machines (the power turbine, low pressure compressor and the high pressure compressor) and the generator are coupled to the same shaft. The power turbine and the compressors run at the same speed and subsequently it is possible to manipulate the shaft speed and all the turbo machines speeds using a single controller. Thus the control system in case of load trip is less complex than for the three-shaft design.

The complexity associated with the thermal-flow design of the cycle requires the use of a variety of analysis techniques and simulation tools. These range from simple one-dimensional models that do not capture all the significant physical phenomena to large-scale three-dimensional CFD codes that, for practical reasons, cannot simulate the entire plant as a single integrated model (Botha and Rousseau, 2002). Furthermore, the treatment of the coupled neutronics and thermal-hydraulics in the reactor core coupled to the PCU network is a complex part, which requires a realistic connection of a detailed core model with the network model.

One of the most prominent codes, especially for HTR applications is the thermal-flow network simulation code Flownex.

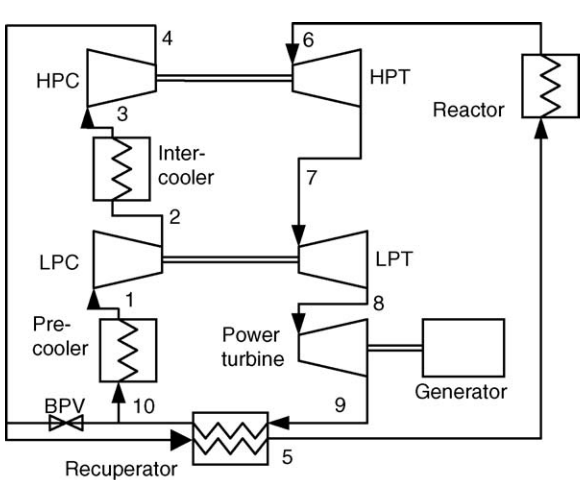

Fig. 1. Schematic diagram of the PBMR high temperature gas cooled reactor Brayton cycle (Greyvenstein and Rousseau, 2002).

2. Description of Flownex

Flownex is a network simulation code, which encompasses the ability to perform detailed analysis and design of complex thermal-fluid systems such as power plants. Flownex solver, described elsewhere (Greyvenstein, 2002), is based on the implicit pressure correction method (IPCM) that solves the momentum equation at each element and the continuity and energy equations at each node in large arbitrary structured networks for both steady-state and dynamic flow. The solver can deal with both fast and slow transients. Fast simulation speeds, on standard desktop computers, allow for real time simulations to be performed. The code has been validated against other codes as well as with experimental data.

With the network approach, a complex thermal-fluid system is represented as a network of one-dimensional elements connected at common nodes (see Fig. 2). In this figure, elements are denoted by cycles and nodes are denoted by squares. Elements represent components such as pipes, compressors, turbines, heat exchangers, control valves or the pebble bed reactor core.

The code features the ability to simultaneously solve multiple gas and liquid networks that are connected through heat exchangers. It also enables the user to construct re-usable models of complex components or sub-systems such as gas-cooled nuclear reactors and heat exchangers. The reactor and the heat exchangers are not treated as lumped systems but as distributed systems. The code can also deal with conductive heat transfer through solid structures.

Advanced rotating model allows for stage-by-stage modeling of compressors and turbines. Other features of the code are its ability to design PID controllers and control systems.

The software can be directly linked with other external computational codes, which can be externally coupled to it.

3. Characterization of Flownex core model

The reactor model introduced here is a two-dimensional reactor model, which does not incorporate a fixed center column. The pebble bed reactor core is made up of fuel spheres and

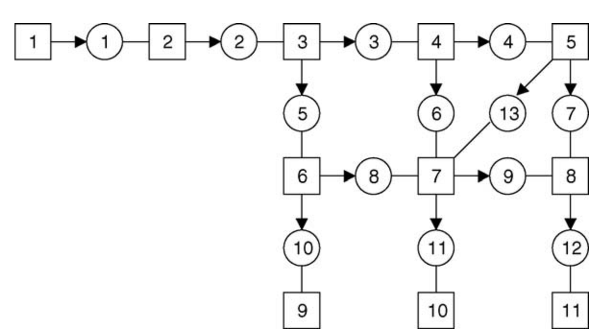

Fig. 2. Example of Flownex network representation (Coetzee et al., 2003).