Steady-state simulation of a two-shaft High Temperature Gas-Cooled Reactor Nuclear Power Plant

Introduction

This case study demonstrates the steady-state simulation of a High Temperature Gas-Cooled Reactor (HTGR) nuclear power plant (NPP).

The HTGR is one of the most promising reactor concepts of the Nuclear Renaissance, offering advantages such as improved safety and economics, shorter construction times, distributed generation and high temperature availability for process heat applications such as hydrogen production.

System Description

The configuration considered in this example is a direct two-shaft closed inter-cooled recuperated Brayton cycle as shown in Figure 1. The heat source for the system is a Pebble Bed Reactor [1,2].

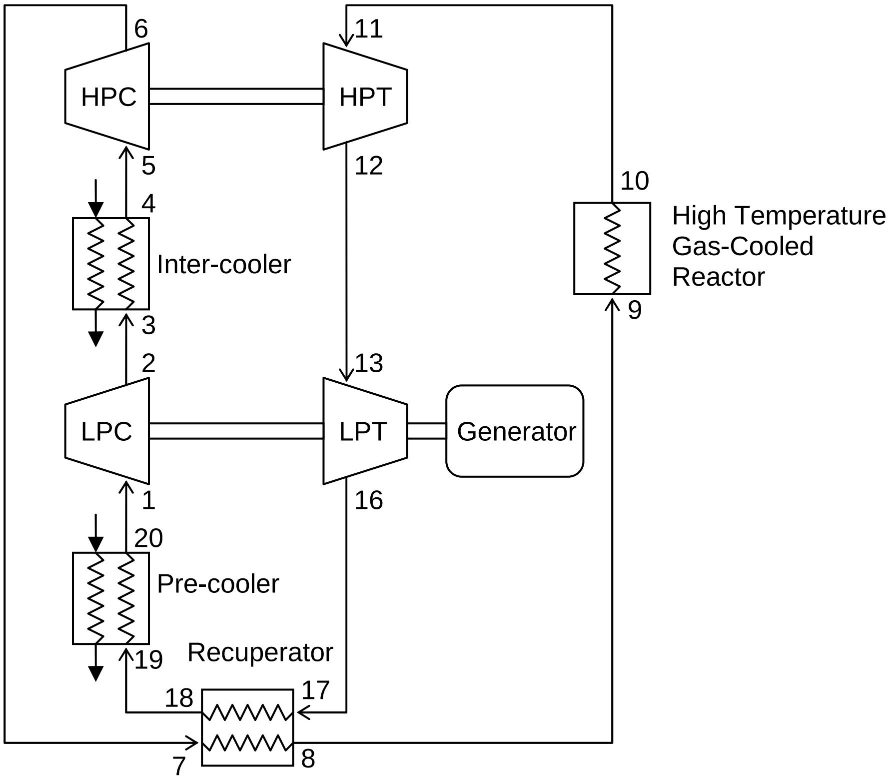

Figure 1: *Schematic layout of a two-shaft Power Conversion Unit (PCU) for a Pebble Bed type HTGR.*

Helium enters the Low Pressure Compressor (LPC) at 1 and is then compressed to state 2. From 3 to 4 the helium is cooled in the intercooler where after it is re-compressed in the High Pressure Compressor (HPC) to state 6. The helium is then pre-heated in the recuperator (7-8) and then further heated to the maximum cycle temperature in the reactor (9-10). The hot high pressure helium is expanded to an intermediate pressure in the High Pressure Turbine (HPT) (11-12), which drives the HPC. It is then further expanded in the Low Pressure Turbine (LPT) (13-16), which drives both the LPC and the generator. After the LPT the still hot helium is passed through the recuperator (17-18) where it is cooled to state 18 while at the same time pre-heating the helium leaving the HPC before it enters the reactor. The helium is then further cooled in the pre-cooler to state 20 before entering the LPC.

Objective of simulation

The objective of the simulation is to model the steady-state operation of the system given appropriate input data for all the components as well as boundary conditions. Important to mention is that speed of the LPC/LPT is fixed while the speed of the HPC/HPT shaft has to be determined as part of the simulation.

Flownex model

The Flownex model of the system is shown in

Figure 2.

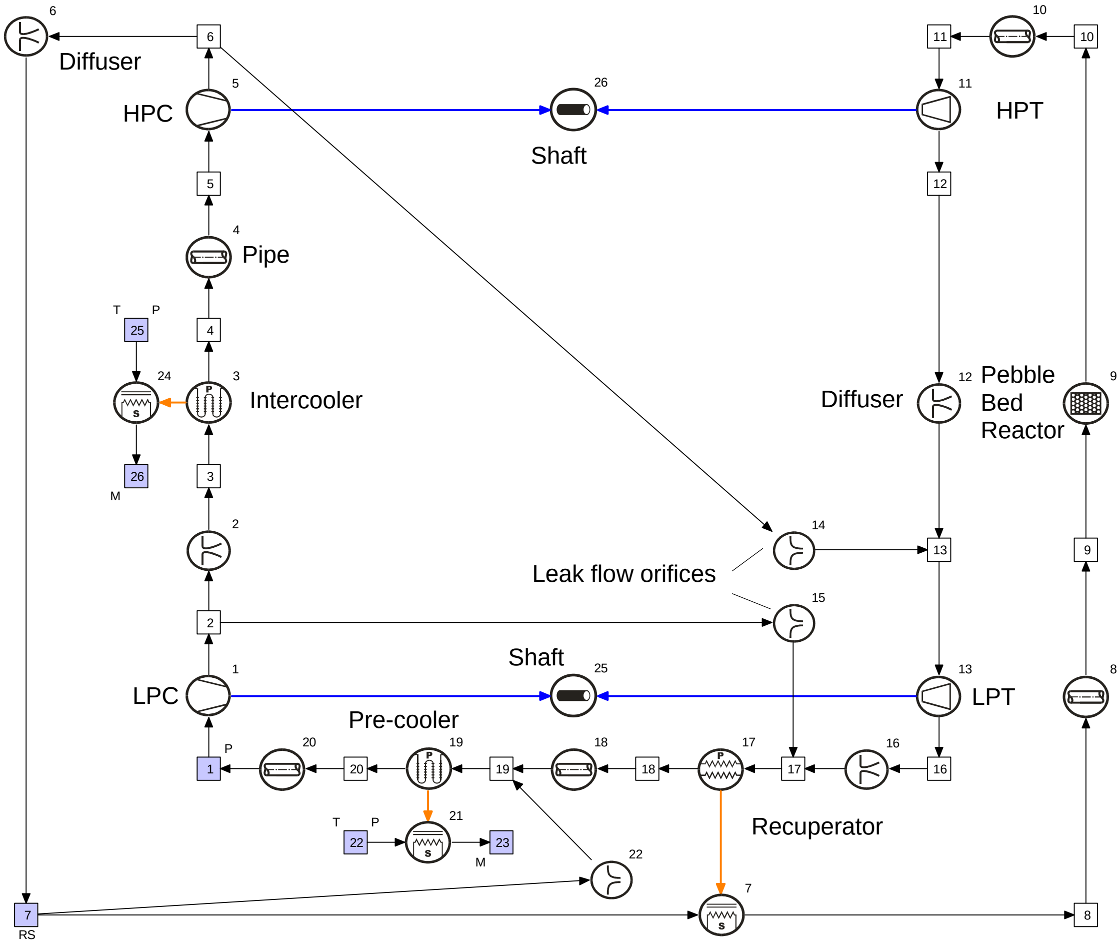

Figure 2: *Flownex network of the direct two-shaft closed inter-cooled recuperated Brayton cycle PBMR power plant.*

The specification of the system is discussed in [3] together with an explanation of how the input data for the different components were determined. This reference also gives a more detailed description of the simulation. What we want to highlight here is that the heat exchangers (pre-cooler, intercooler and recuperator), reactor and pipes are not modeled as lumped systems but as discretized systems. Figure 3 shows the discretization of the pre-cooler for example.

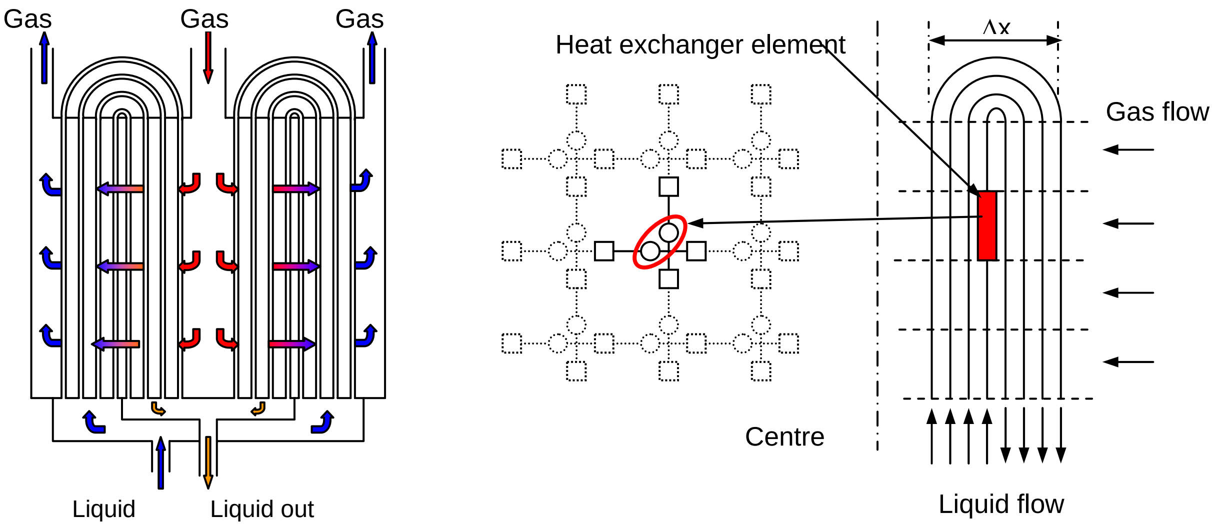

Figure 3: *Discretization of the pre-cooler.*

The recuperator is modeled with Flownex's recuperator element. This is a counter flow or parallel heat exchanger (depending on the flow direction of the two streams) divided into a number of increments in the flow direction as shown in Figure 4.

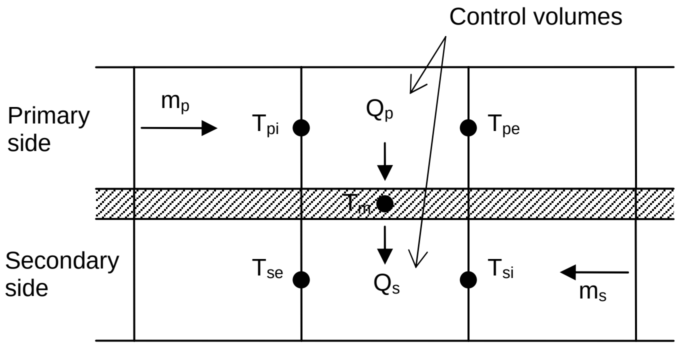

Figure 4: *Discretization of counter/parallel flow heat exchanger.*

Flownex uses a distributed model equivalent to a 2D CFD method to solve the flow, pressure and temperature distribution inside the pebble bed reactor [5]. Figure 5 shows the network representation of the staggered CFD grid with nodes representing the control volume centers and the elements representing the convective fluxes across control volume boundaries.

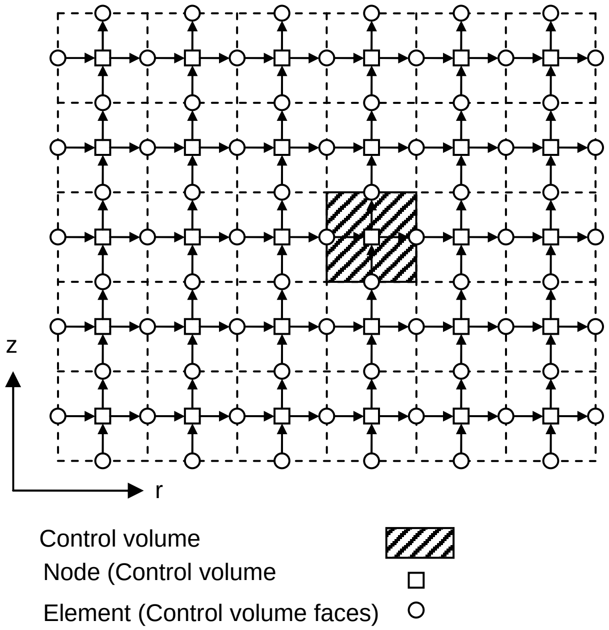

Figure 5: *Flownex network representation of staggered CFD grid.*

The fission heat released inside the pebbles is modeled with a point kinetics neutronics model [6]. The heat transfer inside the pebbles, heat transfer between the pebbles and heat transfer from the pebble surface to the gas is modeled through an additional network superimposed on the gas flow network as shown in Figure 6.

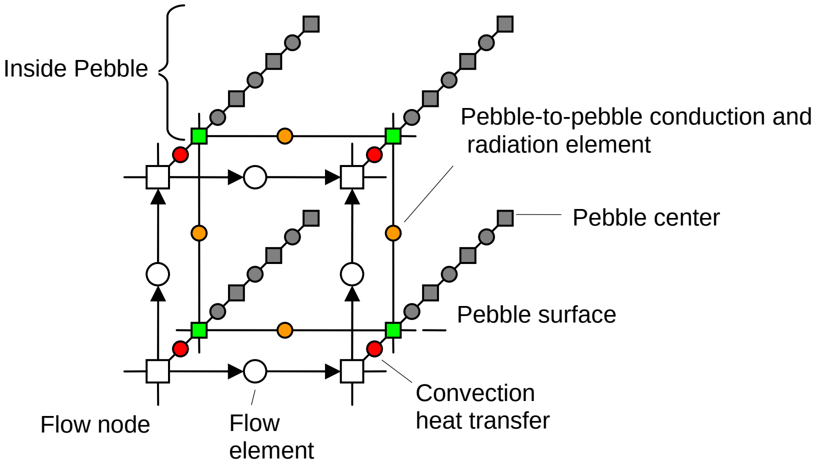

Figure 6: *Network for calculating heat transfer inside the pebbles, between pebbles and between pebbles and gas.*

A more detailed description of the reactor model can be found elsewhere [7].

Description of simulation

The only boundary condition of the gas loop is the fixed pressure of 2333.3 kPa at the inlet of the LPC (Node 1). The temperature boundary conditions of 22 ºC are set at Nodes 22 and 25, which are the water side inlets of the pre-cooler and intercooler respectively. These temperatures affect the helium temperatures through the pre-cooler and intercooler.

The initial speed of the high-pressure turbo charger is intentionally set as 7200 rpm (as apposed to the known value of 10800 rpm) to demonstrate the Flownex's shaft balancing capability. By specifying an approximate shaft speed and then selecting the appropriate option Flownex will automatically determine the shaft speed at which the power delivered by the turbine exactly matches the power required by the compressor and any additional loads.

The reactor exit temperature is fixed at 900ºC. Alternatively one can specify a fixed heat transfer.

Results

Table 1 compares some Flownex results with the second order cycle analysis results obtained with EES[1]. The agreement between the two sets of results is excellent.

Parameter	Units	Flownex	EES
Mass flow rate	kg/s	127.8	127.8
Net work	MW	126.2	126.4
Reactor heat	MW	259.8	260.0
Thermal efficiency	%	48.6	48.6
Maximum cycle pressure	kPa	6967.5	6968.5
HP turbo unit shaft speed	rpm	10793	10800
Pre-cooler heat	MW	78.1	78.3
Intercooler heat	MW	53.0	53.0
Recuperator heat	MW	240.2	240.1
LP compressor power	MW	55.1	55.1
HP compressor power	MW	52.9	53.0

Table 1: *Comparison between Flownex results and second order cycle analysis results obtained with EES.*

Conclusion

The steady-state simulation of a High Temperature Gas-Cooled Reactor (HTGR) nuclear power plant (NPP) is demonstrated in this example. Excellent agreement with the results of a second-order cycle analysis was obtained. A special feature demonstrated with this example is Flownex's ability to do turbo machine shaft speed balancing i.e. determining the speed at which the turbine power balances the compressor load.

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[1] Engineering Equation Solver, www.fChart.com

The steady state results are often used as initial conditions for transient simulations.

References

[1] Rousseau, P.G., and Greyvenstein, G.P., 2003, "Changing the face of nuclear power via the innovative Pebble Bed Modular Reactor", Proceedings of Power Generation World,16-17 March 2004, Gallagher Estate, Midrand, South Africa. (Available on Flownex website under Publications).

[2] PBMR Website. www.pbmr.co.za.

[3] "Two-shaft direct Brayton Cycle HTGR Demo" under Downloads on Flownex Website.

[4] Greyvenstein, G. P., 2006, "The application of systems CFD to the design and optimization of high-temperature gas-cooled nuclear power plants", Accepted for publication, Proceedings of ASME POWER 2006, Conference, May 2-4, Atlanta, Georgia.

[5] Patankar, S.V., 1980, Numerical Heat Transfer and Fluid Flow. McGraw Hill, New York.

[6] Rousseau, P.G., and Greyvenstein, G.P., 2003, "One-dimensional reactor model for the integrated simulation of the PBMR power plant", Proc. 1st Int. Conf. on Heat Transfer, Fluid Mechanics and Thermodynamics, Kruger Park, South Africa, April 8-10, 2002.

[7] Du Toit, C.G., Rousseau, P.G., Greyvenstein, G.P., and Landman, W.A., 2005, "A systems CFD model of a packed bed high temperature gas-cooled nuclear reactor", Int. J. of Thermal Sciences 45, pp 70–85.