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Modeling a Gas-Cooled Microreactor Balance of Plant for the Virtual Test Bed

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INTRODUCTION

High-temperature gas-cooled reactors (HTGRs) are one of the technologies considered for microreactor designs because of their high performance and technological maturity, and several designs are being developed [1]. These microreactor cores are each connected to a power conversion system through a heat exchanger. For transient analysis, the feedback of the power conversion system or primary loop can be important; therefore, it is necessary to develop robust models for the balance of plant that can be coupled to a core model.

This work presents and demonstrates a balance of plant model using the Multiphysics Object-Oriented Simulation Environment (MOOSE) Thermal Hydraulics module, THM, for startup and load-follow transients. This model will be made available on the Virtual Test Bed [2] and can be seamlessly coupled with any MOOSE-based multiphysics core model using the MOOSE multi-app approach [3].

MODEL DESCRIPTION

Microreactor balance of plant description

The system is a primary loop with a high-temperature gas-cooled reactor coupled to an open-air recuperated Brayton cycle through a heat exchanger. A diagram of the system is given in Fig.1.

The core design is taken from Ref [1] and consists of 55 hexagonal assemblies, using a graphite matrix, which acts as a moderator. The core is 2 m long, and the sides of the hexagonal assemblies measure 0.11 m. Two types of channels are inserted within the graphite matrix: 42 fuel channels of tristructural isotropic (TRISO) particles in a graphite matrix and 18 coolant channels. The design uses helium as a coolant which extracts heat from the core and releases it in the heat exchanger. Finally, a pump compensates for the loss of pressure.

The secondary loop is a recuperated open-air Brayton cycle. Air is pumped in the loop by a compressor. It is then heated by the exhaust gases in the recuperator and then in the heat exchanger. The gas goes through a turbine, transfers a part of its residual heat to the recuperator, and is finally released outside. Energy is extracted from the hot air by the turbine to spin the generator shaft and produce electricity. A motor starts the shaft rotation. When the turbine torque is high enough to compensate for the compressor and generator torque, the motor is turned off. The operating conditions are given in Table I, the overall efficiency is 14%.

Modeling strategy

THM is an open-source MOOSE module and is used to model the system described above. It solves the mass, momentum, and energy conservation equations for single-phase, variable-area (one dimensional), inviscid, compressible flow. THM also models the conjugate heat transfer between the flow channel and heat conduction in solid heat structures.

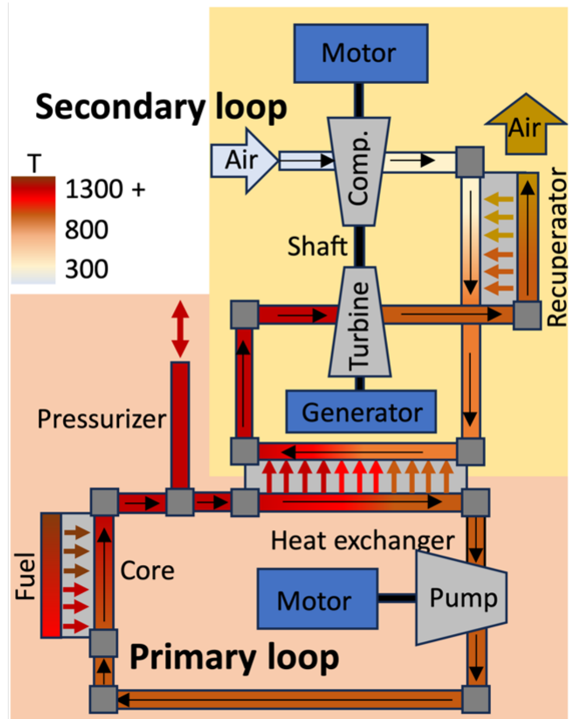

Fig. 1. System diagram.

For simplicity, the core is modeled using a single flow channel combining all the cooling channels coupled with a representative heat structure. The core power is prescribed: a constant 15 MWth value is imposed using a constant power density. The pump in the primary loop is modeled using the homologous performance curves. A motor is connected to the same shaft, and the motor torque is controlled using a Proportional–Integral–Derivative (PID) controller to match the nominal mass flow rate in the loop.

The core is connected to a heat exchanger modeled as a 2-m-long shell-tube heat exchanger with counter-current flow. It is modeled by coupled primary and secondary channels that are replicated 20,000 times and separated by a 1 mm steel wall.

On the secondary side, the compressor, turbine, and generator share the same shaft. The performance curves for the compressor and turbine are taken from Ref [4]. The rated conditions are adjusted to match the operational conditions listed in Table I. The generator is modeled using a negative torque, proportional to the shaft speed. The torque and inertia of each component connected to the shaft make contributions to the shaft speed equation.

TABLE I. Operating conditions

Operating Conditions	
Total core power	15 MWth
Primary mass flow rate	9.4 kg/s
Core inlet temperature	890 K
Core outlet temperature	1190 K
Primary system pressure	9 MPa
Secondary mass flow rate	20 kg/s
Secondary heat exchanger inlet temperature	490 K
Compressor pressure ratio	8.9
Turbine pressure ratio	4.2
Generator power	2 MWe

The Fanning friction factor in all the pipes and cooling channels is calculated using the Churchill formulation:

$$f = 2.0\left(\left(\frac{8}{Re}\right)^{12} + \frac{1}{(a+b)^{1.5}})\right)^{\frac{1}{12}} \tag{1}$$

$$\text{with } a = \left(2.457\ln\left(\frac{1.0}{(7/Re)^{0.9}}) + \frac{0.27\epsilon}{D_h}\right)\right)^{16}$$

$$b = \left(\frac{37\ 530}{Re}\right)^{16}$$

where ϵ is the wall roughness, D_h is the hydraulic diameter, and Re is the Reynolds number.

For conjugate heat transfer, the Nusselt number is calculated using the Dittus-Boelter correlation:

$$Nu = 0.023Re^{4/5}Pr^{0.4} \tag{2}$$

The air and helium gas fluid properties are calculated using the ideal gas assumption.

RESULTS

Startup transient

The temperature of each component is initially fixed at 400 K, which is close to the outlet temperature of the compressor during the steady state. This common initial temperature avoids irregular effects at the beginning of the simulation due to the difference in temperature between the two loops in the heat exchanger. The initial pressure is fixed at 90 bar in the primary loop, which is the steady-state pressure, and at 1 bar in the secondary loop, because it is open to the atmosphere. Finally, the initial velocities are fixed at zero.

The shaft of the turbine and compressor is initially at rest. Its rotation is initiated by a motor controlled by a PID controller: the motor torque is controlled with a set point for the rotation speed of the shaft, with the target value being a bit smaller than the rated shaft speed value. The final rotation speed must avoid exceeding the rated value to avoid damaging the equipment. As shown in Figure 2, the motor torque increases dramatically during the first few seconds. Then the turbine is launched upon initiating power transfer from the primary to the secondary loop. Thus, the motor torque decreases to avoid exceeding the rotation speed limit. The motor is then slowly turned off.

The startup transient is run for 50,000 s. The steady state is reached approximately at 20,000 s because of the core thermal inertia, as shown in Figures 3, 4, and 5. It reaches the operating values given in Table I.

Figure 3 shows the power transfers. As expected, the powers transferred in the core and in the heat exchanger increase from zero to the operating value of 15 MW (which is imposed in the fuel). At the same time, the power extracted by the generator increases from zero to 2 MW.

The pressure evolution in the secondary loop is plotted in Figure 4. At steady state, the pressure drastically increases in the compressor, decreases from 5.5 to 5.0 bar in the heat exchanger, and decreases significantly in the turbine. At the turbine outlet, the pressure value is 1.14 bar. It is a bit bigger than the atmospheric pressure, but the turbine outlet is separated from the secondary loop outlet by a pipe and the recuperator. In these components, a supplemental pressure drop occurs.

The pressures in the components of the primary loop are not shown, but they are close to 90 bar due to the pressurizer.

Figure 5 presents the temperatures in the core and in the secondary side of the heat exchanger. At steady conditions, helium is heated in the core from 890 to 1190 K and exchanges heat with the secondary side fluid in the heat exchanger, heating it from from 490 to 1170 K. The wall temperature stays under 1300 K.

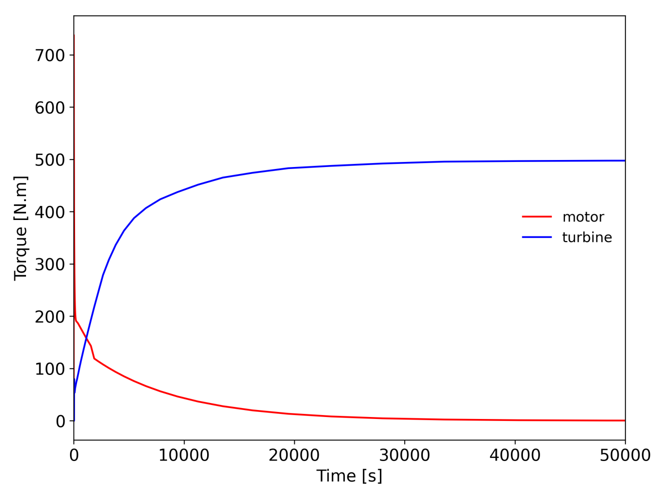

Fig. 2. Startup transient—Motor and turbine torques.

Load-follow transient

The goal of this simulation is to study how the steady-state system reacts to a power modulation. This type of transient occurs when the electricity production needs to be adapted to the grid demand.

The steady state reached in the previous simulation is used for initial conditions. From the beginning to 50,000 s, the core power is maintained at 15 MW, and then it is decreased to 80% of this value. From 100,000 s to the end, it is reset

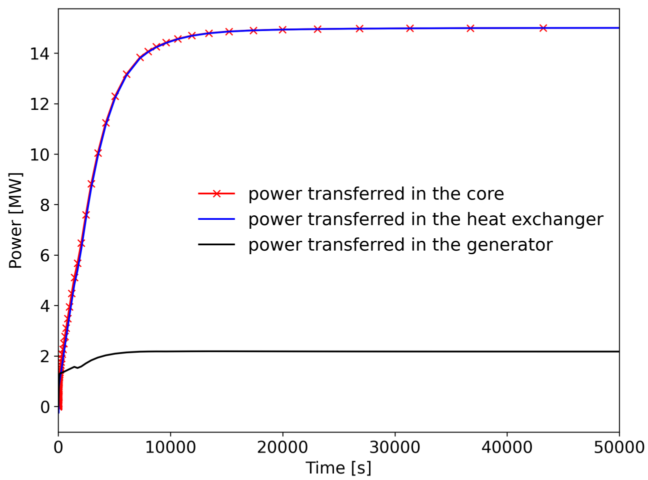

Fig. 3. Startup transient—Power transfers.

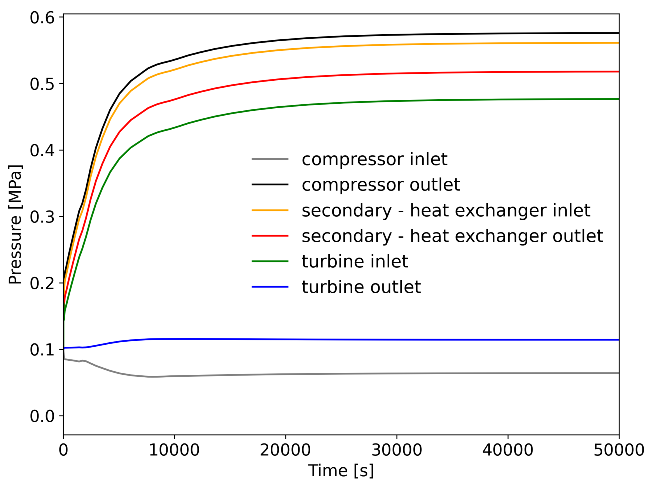

Fig. 4. Startup transient—Pressures in the secondary loop.

to its nominal value. In each of the following figures, a new steady state is reached approximately 10,000 s after the power modulation at 50,000 s and 100,000 s.

Figure 6 shows the effect of this modulation on the extracted power in the core, in the heat exchanger, and by the generator. The extracted powers are equal in the core and heat exchanger and, after the first modulation, reach a steady state at 12 MW. The generator extracts approximately 1.6 MW. After 100,000 s, a new steady state is reached with the same values as the beginning of the simulation.

The pressures in the secondary loop are plotted in Figure 7. The steady-state values after the first modulation are lower than when the core delivers 100% of its nominal power, as expected. The pressure is about 5.15 bar out of the compressor and 1.06 bar out of the turbine. Another steady state, equivalent to the initial values, is then obtained after the second modulation.

Figure 8 shows the temperatures in the core and in the secondary side of the heat exchanger. Once again, a new steady state with lower temperatures is obtained after the first

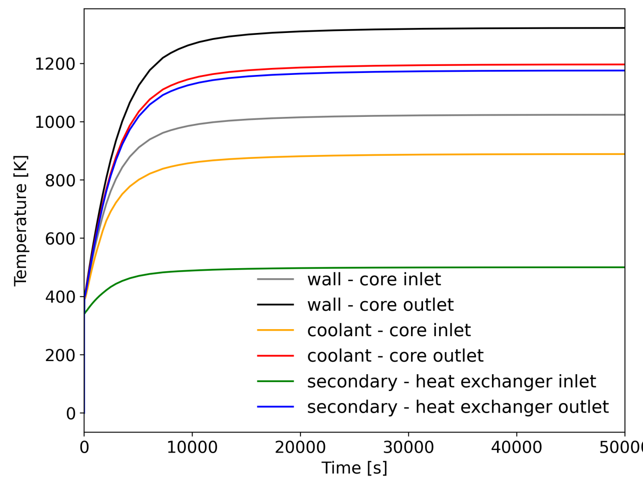

Fig. 5. Startup transient—Temperatures.

modulation. The helium flow is heated in the core from 855 to 1090 K and exchanges heat with the secondary side air in the heat exchanger, heating it from 480 to 1080 K.

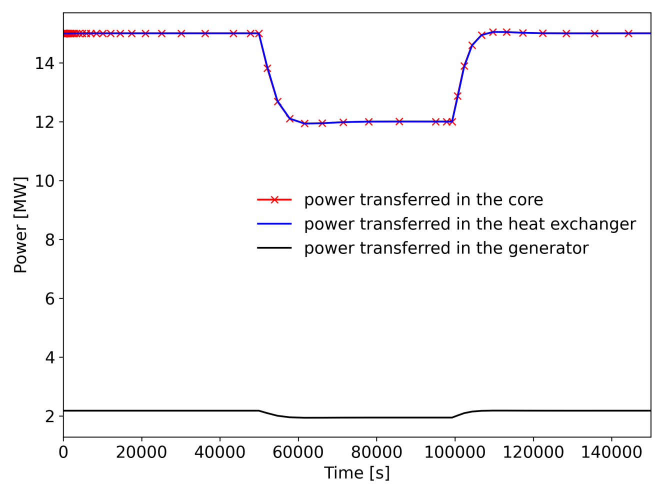

Fig. 6. Load-follow transient—Power transfers.

CONCLUSIONS

A balance of plant model of a gas-cooled microreactor was developed using the MOOSE Thermal Hydraulics module. A startup transient and a load-follow transient were simulated, demonstrating that the model can start from rest, transition to nominal conditions, and adjust the core power to match the demand. This model will be expanded to include a high-fidelity core model using other MOOSE-based tools and be made available in the Virtual Test Bed [2].

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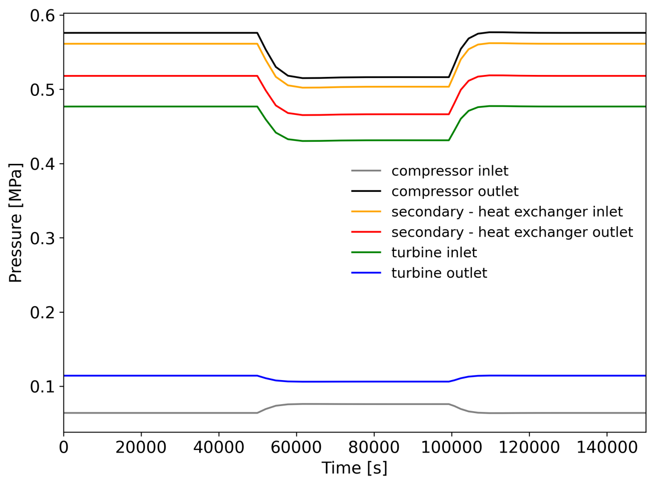

Fig. 7. Load-follow transient—Pressures in the secondary loop.

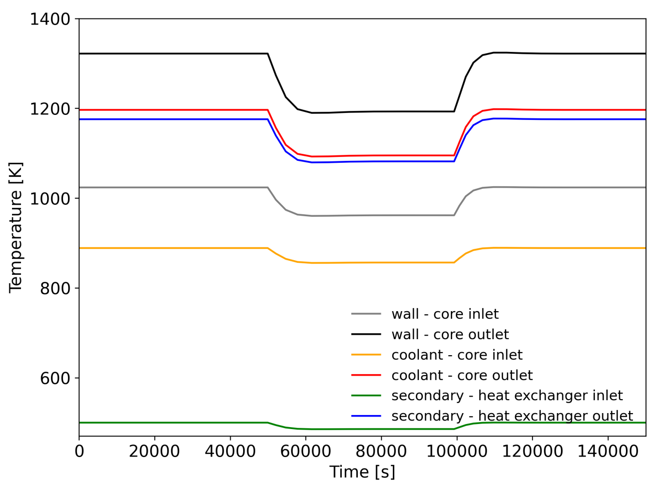

Fig. 8. Load-follow transient—Temperatures.

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