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Power Generation Cycle with RELAP-7

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SUMMARY

Balance of plant of a High-Temperature gas-cooled Reactor – Pebble bed Module (HTR-PM) is modeled using RELAP-7. The model includes the primary helium loop where the heat produced by the core is transferred to a helical-coil steam generator and the secondary loop where superheated steam is fed to a turbine to extract power. The steam is then condensed to subcooled water and pumped back into the steam generator.

Results demonstrate that RELAP-7 has the capability to model different regimes encountered in two-phase flow with wall boiling, superheated steam, subcooled liquid and condensation. RELAP-7 also has the capability of modeling different fluids with their own specific models in a very flexible way, without any code change. This also demonstrates the capability of modeling the transfer of fission power into electrical power.

CONTENTS

1 Introduction

This report presents a balance of plant calculation for advanced reactors simulated with RELAP-7. A High-Temperature gas-cooled Reactor – Pebble bed Module (HTR-PM) is taken as an example. In the primary loop, helium transfers heat from the fuel to a steam generator. On the secondary side, subcooled water enters the steam generator and is heated up to saturation. Steam is generated and dry superheated steam is obtained at the outlet of the steam generator. The steam is fed into a turbine from which work is extracted. This work is then converted into electrical power by a generator. After passing through the turbine, the steam is routed to a condenser. The water is then pumped back into the steam generator to close the cycle.

The primary loop is modeled with the single phase flow model and the secondary loop is modeled with the two-phase 7-equation model described in Reference [1]. The HTR-PM will be shortly described before presenting the RELAP-7 model. Finally, results are presented.

2 HTR-PM advanced reactor

A detailed description of the HTR-PM plant is given in Reference [2]. The HTR-PM consists of two pebble-bed reactor modules coupled with a 210 MWe steam turbine. Each reactor module includes a reactor pressure vessel with graphite, carbon, and metallic reactor internals, a steam generator and a main helium blower. The thermal power of one reactor module is 250 MWth, the helium temperatures at the reactor core inlet and outlet are 523 K and 1023 K respectively. The steam produced at the steam generator outlet has a temperature of 840 K with a pressure of at 13.25 MPa. An outline of the plant is given on Figure 1(see Reference [3]).

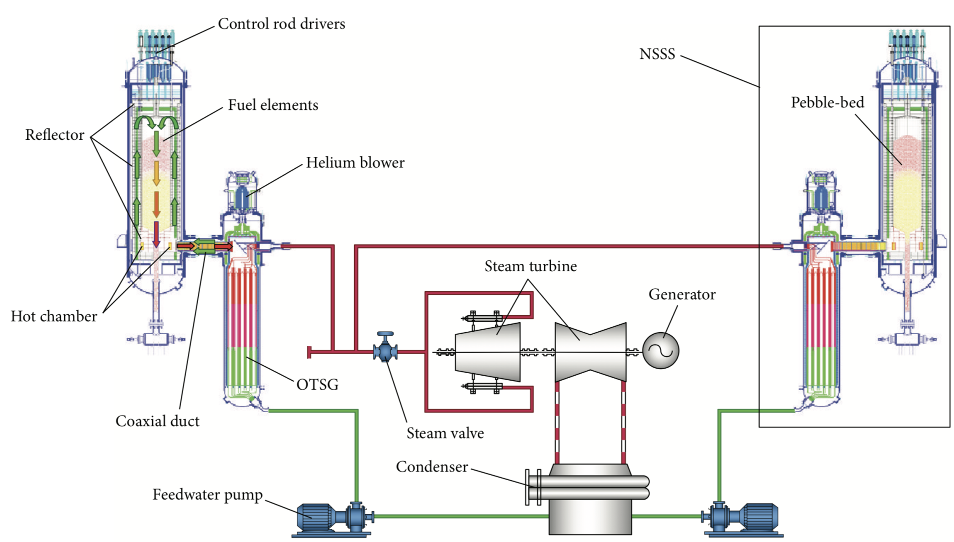


Figure 1: Outline of a HTR-PM

The steam-generator design is a vertically oriented, once-through, up-boiling, cross-counter-flow, shell and tube heat exchanger. The multiple tubes are helically wound into bundles as shown on Figure 2 (see Reference [4]). The design has an upper bundle and lower bundle. The lower bundle experiences lower temperatures and can be divided into three sections. The first section is an economizer that preheats the feedwater. The second section converts water into steam. The last section is the initial superheater that converts left-over liquid water into steam. The upper bundle experiences high temperatures and acts as the finishing superheater that completely converts saturated steam into dry steam to prevent damage to the turbine.

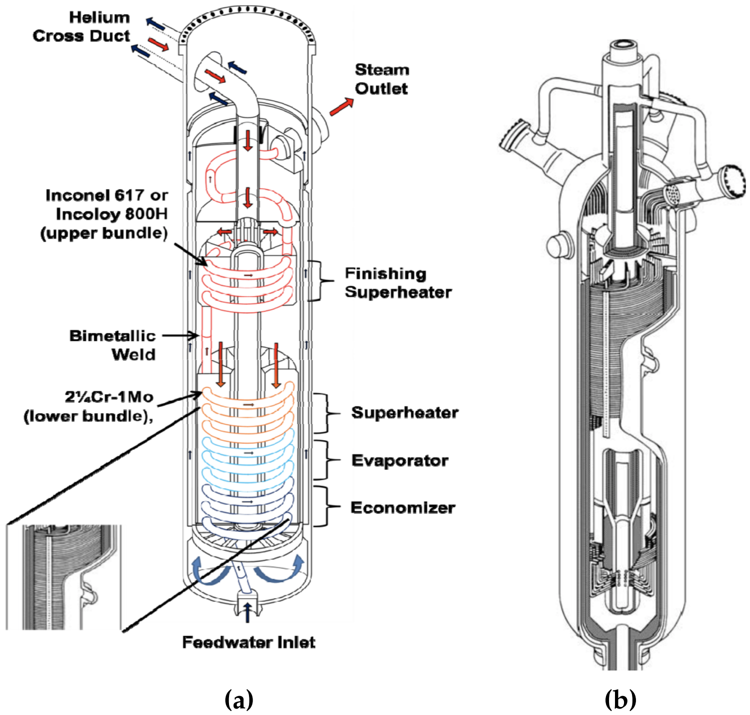


Figure 2: Helical-coil steam generator

3 RELAP-7 Model Description

The RELAP-7 model includes both the primary and secondary loops. Only one reactor module and one steam generator are included in the model. The RELAP-7 model and components are shown in Figure 3 and described in more details below.

3.1 Core

The core is modeled by coupling a heat structure and a flow channel. The fission power is deposited uniformly in a heat structure. The coolant is modeled with a single phase flow channel with helium fluid properties[5]. Specific closures for helium are used to provide wall heat transfer coefficient and wall friction. The geometry and modeling parameters used for the core are given in Table 1.

3.2 Steam Generator Model

The steam generator is a counter-current flow helical steam generator. The primary side is modeled with one single phase flow channel. The secondary side is modeled with a two-phase flow channel using two-phase water fluid properties. Constant representative values are used for the interfacial heat transfer, interfacial friction, wall heat transfer and wall friction coefficients. The temperature of onset of nucleate boiling is constant and set to 2 degrees below saturation of the

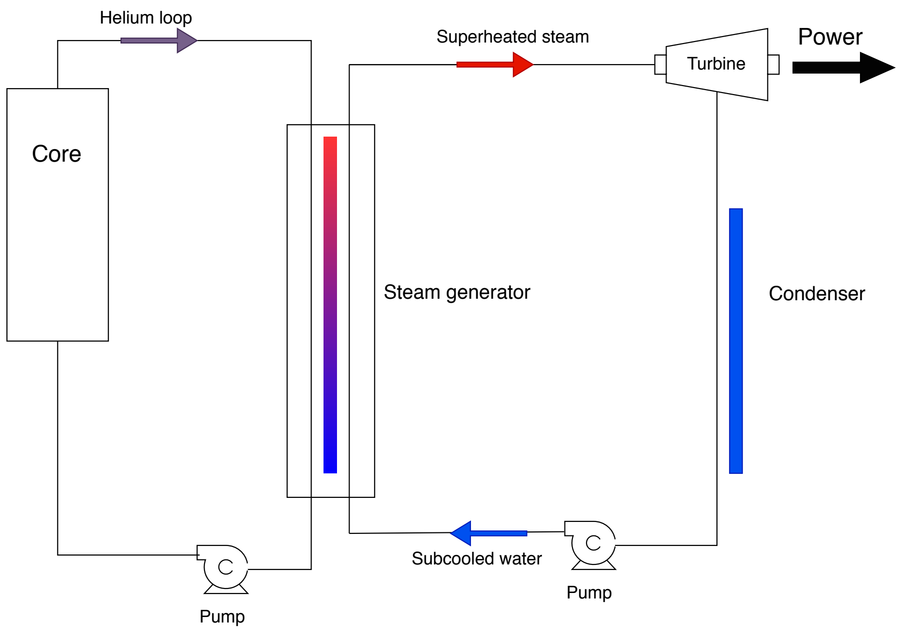


Figure 3: RELAP-7 Model of HTR-PM

Parameter	Value	Units
Total Power	250	MW
Pressure	7	MPa
Heated Length	10	m
Pump head	12750	m
Core inlet temperature	478	K
Fuel density	2000	kg/m^3
Fuel conductivity	15	W/(m-K)
Fuel heat capacity	720	J/(kg-K)

Table 1: Core modeling parameters

liquid phase when the wall temperature is above saturation. Flow area, hydraulic diameter and heated perimeter of the primary and secondary sides are calculated to match the geometry of the steam generator with bundle of tubes as described in Section 2.

The geometry and modeling parameters used for the steam generator are given in Table 2.

3.3 Pump Model

The pump is a 0D component based on the two-phase volume junction described in section 11.8 of Reference [1]. The pump head is provided by the user through the input file. The corresponding momentum and energy source terms are calculated using the following equations.

$$\boldsymbol{S}^{\boldsymbol{k}}_{\boldsymbol{Mom}} = \frac{1}{2}\rho_k g h A_{ref}\boldsymbol{d} \tag{1}$$

$$S^k_{Energy} = \frac{1}{2}\rho_k g h \boldsymbol{u}_k \cdot \boldsymbol{d} A_{ref} \tag{2}$$

Parameter	Value	Units
Length	13.5	m
Fuel conductivity	15	W/(m-K)
Fuel heat capacity	720	J/(kg-K)
Number of tubes	381	-
Primary side		
Pressure	7	MPa
Flow area	0.8715	m^2
Hydraulic diameter	0.0093	m
Heated Perimeter	374.95	m
Inlet temperature	1023	K
Mass flow rate	101	kg/s
Secondary side		
Pressure	13.24	MPa
Flow area	0.185	m^2
Hydraulic diameter	$2.48 \cdot 10^{-2}$	m
Heated Perimeter	97.72	m
Inlet temperature	1023	K
Mass flow rate	186	kg/s
Wall heat transfer coefficient, liquid phase	$1.1 \cdot 10^4$	W/(m^2.K)
Wall heat transfer coefficient, vapor phase	$4.31 \cdot 10^3$	W/(m^2.K)
Wall friction coefficient	0.01	-

Table 2: Steam generator modeling parameters

Where ρ_k is the density of the phase k, g is the gravity magnitude, h is the prescribed head, A_{ref} is the pump reference area and $\boldsymbol{d}$ is the direction of the incoming pipe.

3.4 Turbine Model

The pump is a 0D component based on the two-phase volume junction described in section 11.8 of Reference [1]. The power $\dot{W}$ to be extracted by the turbine is provided by the user. The corresponding momentum and energy source terms are:

$$\boldsymbol{S^k_{Mom}} = \frac{\dot{W}}{||\boldsymbol{u}||}\boldsymbol{d} \tag{3}$$

$$S^k_{Energy} = \dot{W} \tag{4}$$

The turbine can be turned off to behave like a volume junction. This can be used to model the turbine bypass when the incoming fluid is not pure steam.

3.5 Condenser

The condenser is modeled as a two-phase flow channel with a fixed wall temperature. The geometry and modeling parameters used for the condenser are given in Table 3.

Parameter	Value	Units
Length	13	m
Wall temperature	478	K
Flow area	0.49	m^2
Hydraulic diameter	$2.48 \cdot 10^{-2}$	m
Heated Perimeter	78.54	m
Wall friction coefficient	0.01	-
Liquid wall heat transfer coefficient	$1 \cdot 10^4$	$W/(m^2.K)$
Vapor wall heat transfer coefficient	$5 \cdot 10^3$	$W/(m^2.K)$

Table 3: Condenser modeling parameters

4 Results

The power and pump heads have been ramped up to the desired values. Once super-heated steam is generated in the secondary side, the turbine is turned on and work is extracted. The final steady state results for each relevant component are described below.

4.1 Core

The power deposited in the fuel results in a 445 K temperature rise across the core and the resulting mass flow rate in the core is 101 kg/s. The temperature distribution is shown in Figure 4.

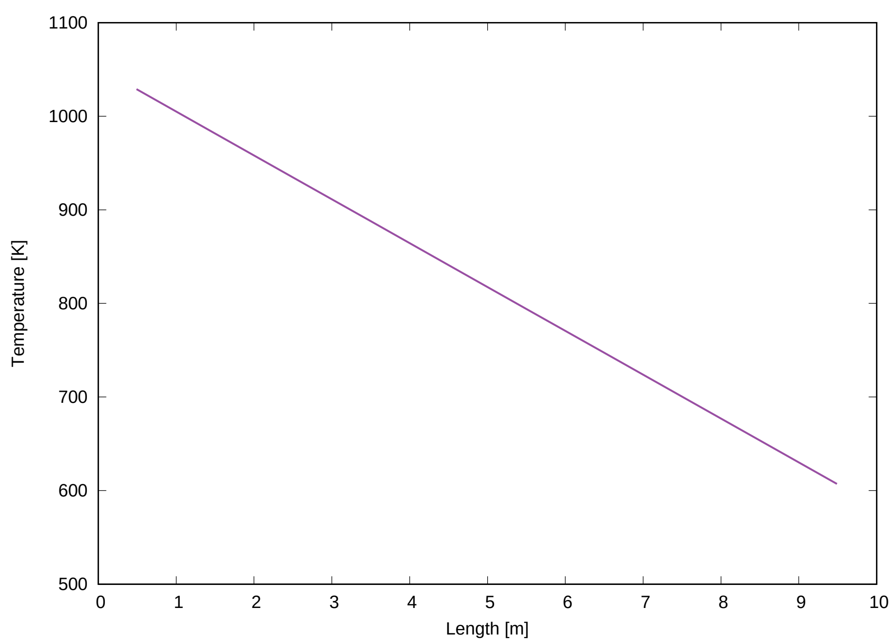


Figure 4: Temperature distribution in the core

4.2 Steam generator

On the primary side, heat was removed from the helium resulting in a 500 K temperature drop for the helium. The temperature and void fraction distribution on the secondary side on shown in Figure 5.

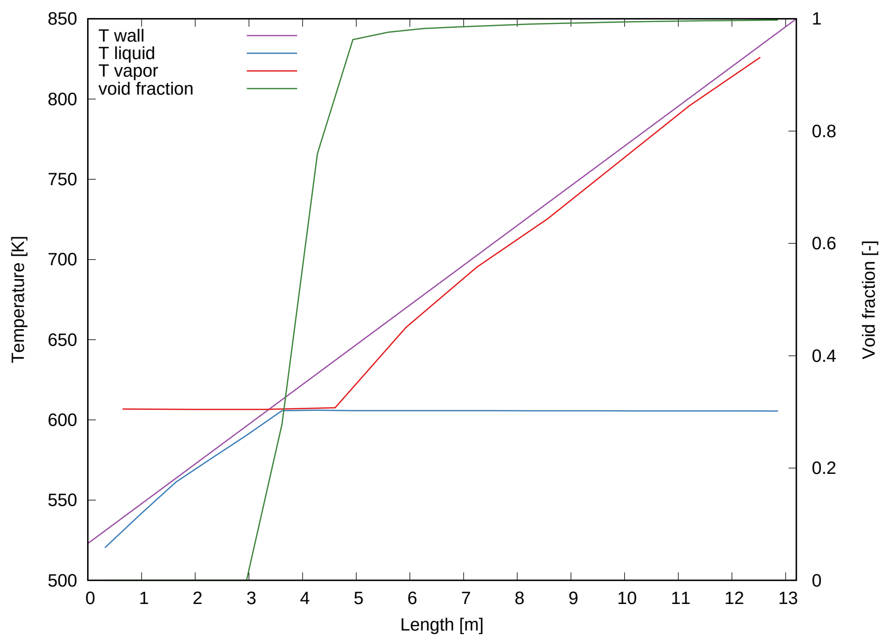


Figure 5: Temperature and void distribution in the secondary side of the steam generator

Subcooled liquid water is heated up to saturation, steam is generated and as void fraction approaches 1, the steam temperature rises above the saturation temperature. The steam outlet temperature is 830 K.

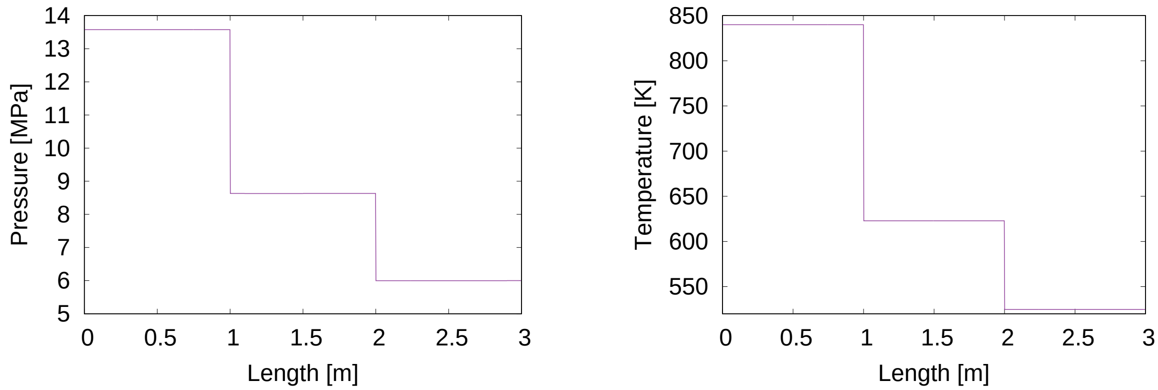
4.3 Rankine cycle

The Rankine cycle is also properly simulated. As work is extracted in the turbine, pressure and temperature drops are observed across the turbine. The steam is then condensed to pure liquid. High subcooling is obtained at the outlet of the condenser.

4.3.1 Steam Line

The steam line was modeled with 2-stage turbine using two turbine components that were placed one after the other. The pressure and temperature distribution is shown in Figure 6.

Pressure and temperature drop of approximately 7 MPa and 320 K respectively was obtained by extracting the total of 185 MW through a 2-stage turbine.



(a) **(b)**

Figure 6: Pressure (a) and temperature (b) in the steam line

4.3.2 Feedwater Line

The feedwater line included a simple pump with prescribed head of 1000 m. The pressure distribution is shown in Figure 7.

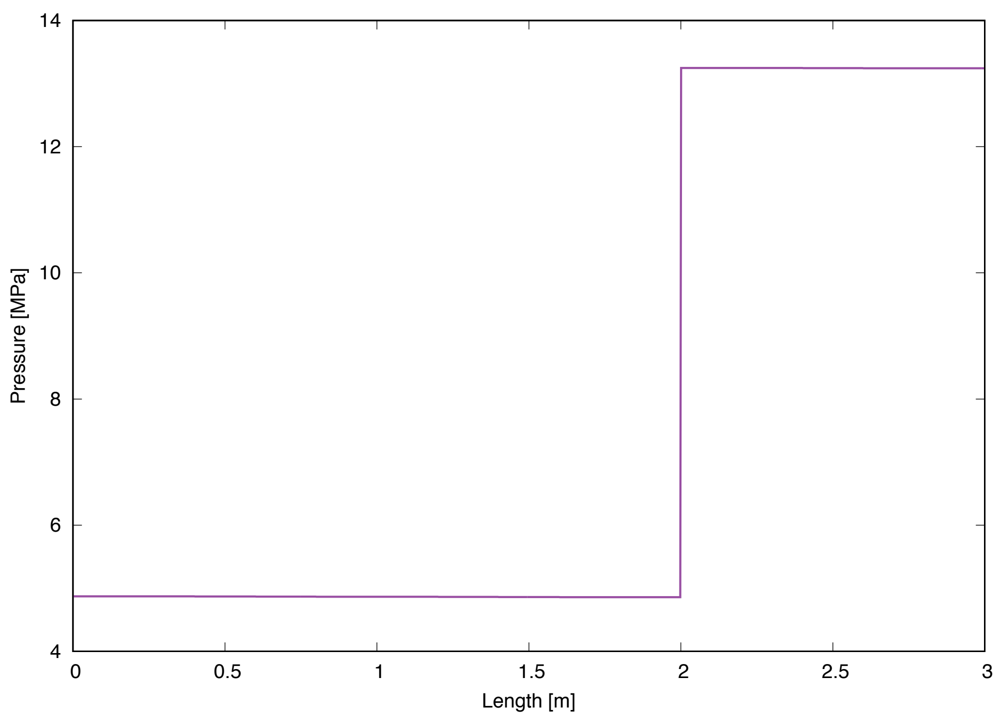


Figure 7: Pressure increase in the feed water line

Pressure increase of approximately 7 MPa was obtained.

5 Conclusion

The primary and secondary loops of on HTR-PM have been modeled with RELAP-7. Results demonstrate that RELAP-7 has the capability to model different regimes encountered in two-phase flow, including wall boiling, superheated steam, subcooled liquid and condensation. RELAP-7 also has the capability of modeling different fluids with their own specific models and can model the transfer from fission power to useful mechanical power.

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