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Simulation of the TerraPower Direct-Cycle sCO_2 Pascal Reactor with the ANL Plant Dynamics Code

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ABSTRACT

Under a U.S. Department of Energy's Technology Commercialization Project, Argonne National Laboratory and TerraPower are jointly developing the Argonne's Plant Dynamics Code to be able to provide design and transient analysis of the sCO_2 reactor applications, including the Pascal reactor. TerraPower has developed a Pascal reactor concept that uses a direct sCO_2 cycle, where the cycle working fluid also serves as the primary reactor coolant, without a need for an intermediate heat exchanger. This paper presents the progress on the Pascal reactor modeling with the PDC, including simulation of the Pascal split-expansion cycle, comparison of the components and cycle performance predictions with the design calculations performed by TerraPower, and the development of the reactor module in the PDC.

INTRODUCTION

Argonne National Laboratory has been developing the Plant Dynamics Code (PDC) [1] for design and transient analysis of supercritical carbon dioxide (sCO_2) Brayton cycles. The philosophy for PDC creation and development has always been a requirement to address and accurately calculate the specific features of sCO_2 cycles, such as CO_2 properties variations close to the critical point, and the effect of those properties variations on the performance of the cycle components, such as compressors and coolers, as well as on the integrated performance of the entire cycle. PDC has been used extensively for analysis of sCO_2 cycles, mostly in application to nuclear reactors, such as sodium-cooled fast reactors [e.g., 2,3,4]. The code has also been extensively validated using experimental data from integral lops [e.g., 5] and individual component testing.

In 2020, U.S. Department of Energy awarded a Technology Commercialization Fund (TCF) project to Argonne and TerraPower to bring the Plant Dynamics Code to commercial market. The TCF project is funded by U.S. DOE with 50% cost share from TerraPower. The main focus of the TCF project, which started in Spring of 2021 and will last for two years, is to extend the application base and the code usability by developing the capabilities to be able to simulate reactor systems with direct sCO_2 cycles. In previous analyses with PDC, only indirect sCO_2 cycles, where the heat is being added through a heat exchanger, such as sodium-to-CO_2 HX, were analyzed. Adding possibility to analyze direct cycles would significantly increase the applicability range of the code and remove one of the main barriers in adopting the code by the industry. These new capabilities are being developed in application to the TerraPower's Pascal reactor concept.

Pascal reactor

Pascal is the name of a heavy water gas turbine reactor (HWGTR) developed by TerraPower. It features a direct-cycle architecture in which sCO_2 used for reactor cooling also serves as the working fluid in an sCO_2 power cycle. As illustrated in Figure 1, the reactor employs vertical pressure tubes and heavy water moderation, which provides a reliable heat sink in case primary cooling is lost. Addition information about the HWGTR and its power cycle can be found in [6].

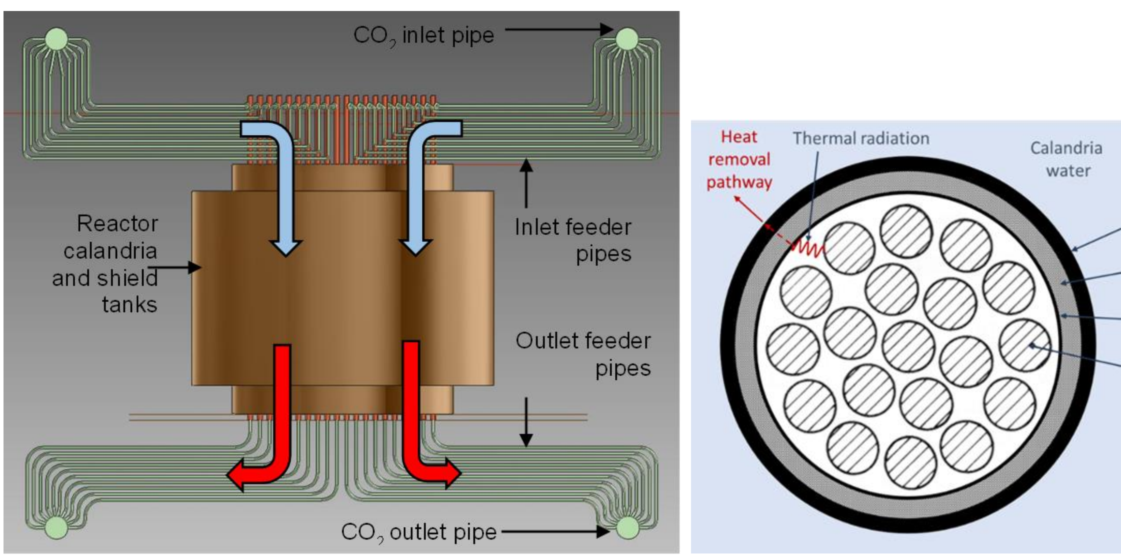

Figure 1. Pascal Reactor and Chanel Structure

The Pascal HWGTR features two unique elements not typically found in analyses of sCO_2 power cycles. First is direct coupling to the reactor core, which necessitates modeling of heat transfer between the sCO_2, fuel, pressure tubes, and moderator fluid. Next is the use of a split-expansion cycle, illustrated in Figure 2 and described in [7], in which a turbine upstream of the reactor reduces reactor operating pressure below the maximum pressure of the cycle. This reduces the strength requirements for reactor components and broadens reactor design space.

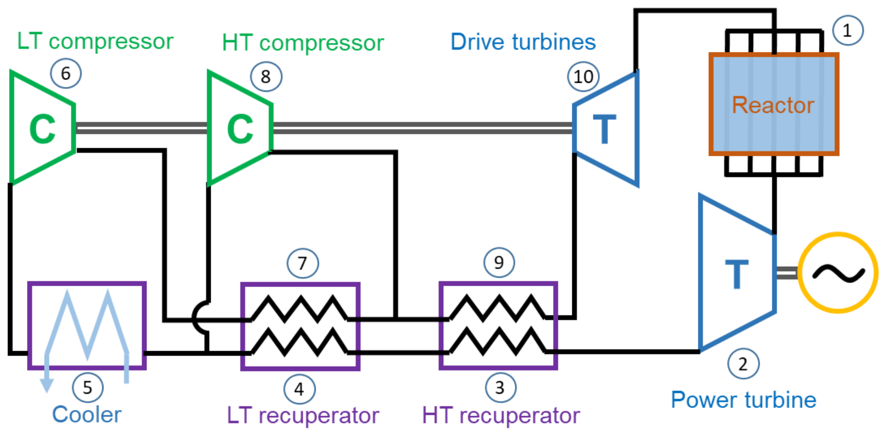

Figure 2. Pascal Split Expansion Cycle

RESULTS AND DISCUSSION

The first task in the TCF project was simulation of the Pascal sCO_2 split expansion cycle in PDC to establish a baseline for future transient simulations. The results of this simulation are presented in Figure 3. The cycle was modeled with three turbomachinery shafts, two parallel shafts for drive turbines (DT) and compressors (C) – low temperature (LT) and high temperature (HT), – and a shaft with a power turbine (PTurb) and a generator. Given by the Pascal configuration, the simulated cycle includes two recuperators, high- and low-temperature (HTR and LTR, respectively), a cooler (Cool), and a reactor (Rx) located between the drive and power turbines. The input for the PDC simulation also included the boundary cycle conditions, such as 550 °C reactor-outlet temperature, 22.3 MPa maximum cycle pressure, and low temperature compressor inlet conditions (inputs are highlighted in green in Figure 3). Note that in the Pascal sCO_2 cycle, while the minimum pressure is above the critical value, the minimum temperature goes below critical, meaning that there would be a pseudo-critical transition somewhere in the cooler.

The PDC results in Figure 3 were obtained with the heat exchangers (cooler and recuperators) designs provided by TerraPower. The performance of these compact diffusion-bonded heat exchangers predicted by PDC is close to the TerraPower design calculations. For example, the recuperator effectiveness is around 95% for both units. The cooler effectiveness is more than 98%, as a close approach at the cold end is required in this cycle to achieve the specified compressor-inlet conditions. One of the interesting results from this PDC simulation is the temperature profiles inside the cooler shown in Figure 4. Due to CO_2 properties variations, the results in Figure 4 shown a double pinch-point characteristic of the cooler temperature profiles. The first pinch point, at around 0.6 m, is calculated when CO_2 goes through a pseudo-critical point transition and experiences a condensation-like behavior at almost constant temperature. The second pinch point is calculated at the CO_2 outlet (z=0), where CO_2 is being cooled below its pseudo-critical temperature and approaches water inlet temperature.

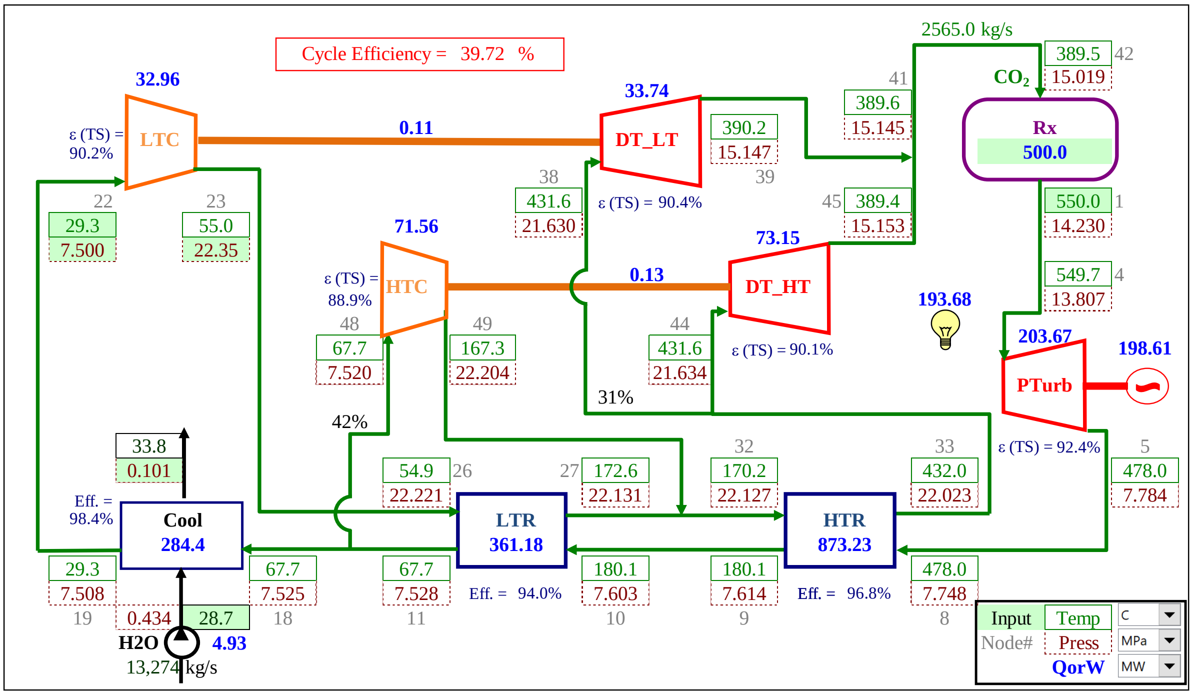

Figure 3. PDC Results for Pascal sCO_2 Cycle.

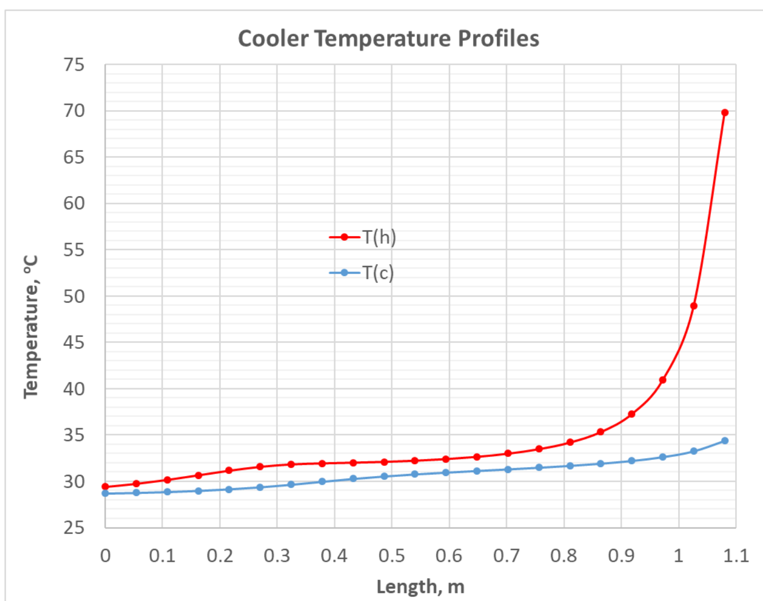

Figure 4. PDC Results for Pascal sCO_2 Cycle.

The turbomachinery results in Figure 3 were obtained with the internal PDC design subroutines. The inputs for these calculations include the component type, - centrifugal compressors and axial turbomachinery, rotational speeds (60 rev/s for power turbine and low temperature drive shaft and 120 rev/s for high temperature drive shaft), and inlet/outlet conditions obtained from other cycle calculations. The results of the turbomachinery design calculations are again close to the Pascal specifications. The compressor and drive turbine total-to-static efficiencies are close to 90%, while the efficiency of the power turbine is slightly higher than 92%. The PDC turbomachinery design calculations also provide the turbine and compressor dimensions, like wheel diameters, blade heights, etc.

Cycle efficiency in Figure 3, 39.7%, predicted by PDC is also close to the TerraPower design calculations of 40%.

With completion of the baseline cycle modeling, the attention of the PDC work has focused on development on the reactor component modeling. The previously existed electrical heater module (which in turn was based on shell-and-tube heat exchanger design) has been modified to simulate the Pascal channel-type reactor. The implemented code modifications include:

- Organization of reactor geometry in a number of parallel channels, each with a number of fuel pins, as shown in Figure 1. The input file structure has been modified to provide all necessary input for the reactor geometry.

- Simulation of heat transfer from the channel tube to the calandria water moderator, which is modeled as a constant temperature heat sink. This heat transfer is expected to play an important role in safety analysis of the Pascal reactor.

- Addition of the unheated inlet and outlet sections in the reactor outside the reactor core. Here, only the pressure drop effects are calculated and included in the model.

- Possibility to provide power profile along the fuel pin length. This axial profile is important in predicting peak fuel and cladding temperatures, both at design conditions and in transients, - a very important consideration for nuclear reactors.

- Addition of peak power-to-flow channels. The main calculations are done for reactor average conditions, such as average CO_2 flow rate per fuel pin, to calculate reactor average outlet temperature and pressure drop (which is used in cycle calculations). Simulating a number of parallel power-to-flow channels allows to also calculate local peak temperatures in the core to assess minimum safety margins in the reactor.

After the reactor module development in PDC is completed, the work will progress according to other TCF project tasks, including simulation of the Pascal decay heat removal system and dynamic modeling of accident conditions. The final goal of this analysis will be a simulation of whole-plant transients, including accident conditions for reactor safety. The ultimate goal of the entire TCF project though is to bring the Plant Dynamics Code to the level that it is ready to be used commercially by the industry for analysis of various sCO_2 systems.

REFERENCES

1. Moisseytsev, A., Sienicki, J. J., “PDC: Plant Dynamics Code for Design and Transient Analysis of Supercritical Brayton Cycles,” ANL-ART-154, Argonne National Laboratory, September 30, 2018.

2. Moisseytsev, A. and Sienicki, J. J., “Analysis of Thermal Transients for sCO_2 Brayton Cycle Heat Exchangers,” GT2019-90374, ASME Turbo Expo 2019, GT2019, Phoenix, AZ, USA, June 17-21, 2019.

3. Moisseytsev, A. and Sienicki, J. J., “Dynamic Control Analysis of the AFR-100 SMR SFR with a Supercritical CO_2 Cycle and Dry Air Cooling Part I: Plant Control Optimization”, Proceedings of 26th International Conference on Nuclear Engineering, ICONE-26, London, England, July 22-26, 2018.

4. Moisseytsev, A. and Sienicki, J. J., “Dynamic Control Analysis of the AFR-100 SMR SFR with a Supercritical CO_2 Cycle and Dry Air Cooling Part II: Plant Control under Varying Ambient Conditions”, Proceedings of 26th International Conference on Nuclear Engineering, ICONE-26, London, England, July 22-26, 2018.

5. Moisseytsev, A. and Sienicki, J. J., “Simulation of IST Turbomachinery Power-Neutral Tests with the ANL Plant Dynamics Code,” 6th International Symposium - Supercritical CO_2 Power Cycles, Pittsburgh, PA, March 27-29, 2018.

6. Petroski, R., et al., “Design of a direct-cycle supercritical CO2 nuclear reactor with heavy water moderation,” Nuclear Engineering and Technology, 2021, ISSN 1738-5733, https://doi.org/10.1016/j.net.2021.09.030.

7. Muto, Y., Kato, Y., “Optimal Cycle Scheme of Direct Cycle Supercritical CO_2 Gas Turbine for Nuclear Power Generation Systems,” International Conference on Power Engineering, Hangzhou, China, 2007.

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