SIMULATION OF THE TERRAPOWER DIRECT-CYCLE SCO$_2$ PASCAL REACTOR WITH THE ANL PLANT DYNAMICS CODE

Supercritical CO$_2$ Power Cycles Symposium

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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 Pascal reactor concept 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.

TCF PROJECT

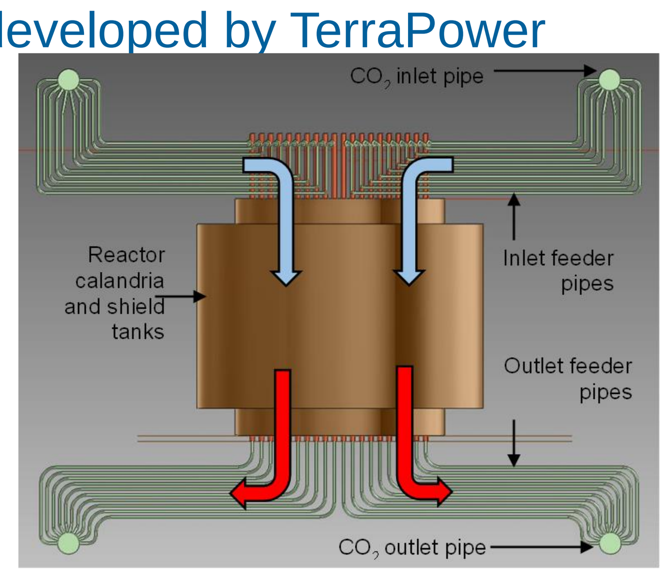
- Technology Commercialization Fund
  - Funded by U.S. DOE
  - Bring laboratory "products" to market
    - ANL Plant Dynamics Code (PDC)
- **TCF-20-21498 "Extending PDC Capabilities to TerraPower Direct-Cycle Supercritical CO$_2$ ("Pascal") Nuclear Reactor Concepts"**
  - New PDC capabilities to model direct cycles
  - Widen the PDC applicability base to include CO$_2$-cooled reactors
    - Other "direct" applications as well
- Project with TerraPower
  - Modeling of Pascal reactor concept

PLANT DYNAMICS CODE (PDC)

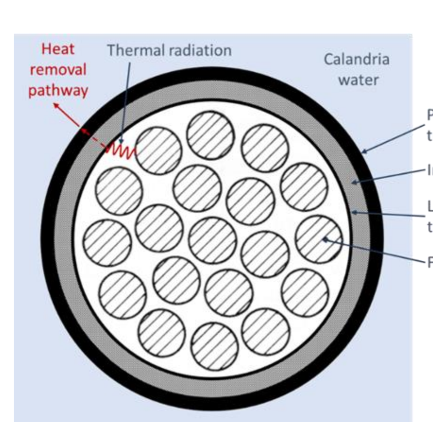
- Developed at Argonne for supercritical CO$_2$ cycles
  - Special attention to complex CO$_2$ properties
- Steady-state analysis
  - Performance of each component (HXs, TM)
  - Integrated cycle performance (efficiency)
  - Piping pressure drop
  - Integrates TM design
- Dynamic calculations
  - Cycle control mechanisms
  - HX thermal inertia and performance
- Cycle and component design and optimization
  - Cost-based optimization of HXs
- Investigation of cycle layouts and operating conditions
  - Cascading cycles, partial cooling, etc.
  - Normal operation and load following
- Analysis of accident conditions
  - Pipe break, loss-of-load, inadvertent valve closure
- Code validation
  - Component testing
  - Small-scale integral tests

PASCAL REACTOR

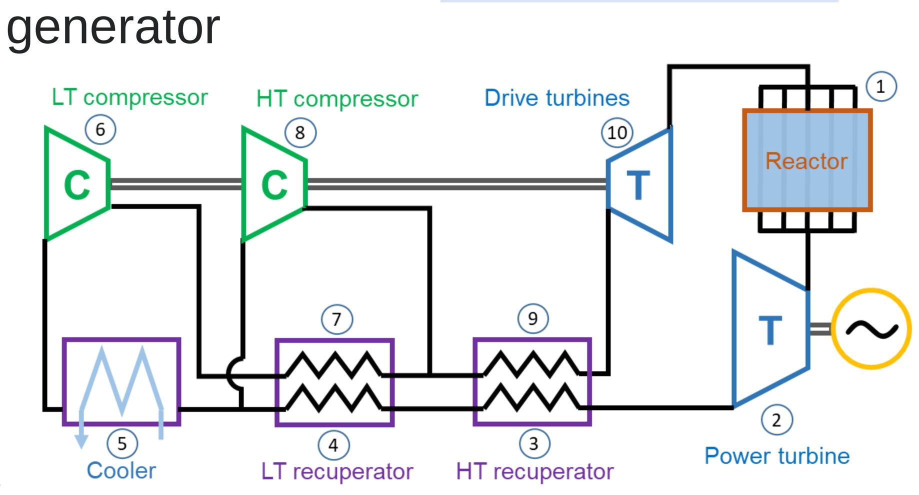
- Heavy water gas turbine reactor (HWGTR) developed by TerraPower
  - Direct cycle with sCO$_2$ reactor coolant
    - sCO$_2$ is a reactor coolant *and* cycle working fluid
  - CO$_2$ vertical pressure tubes
  - Heavy water moderator in calandria tank
    - Also serves as heat sink in emergency
  - 21 fuel rods (UO$_2$) in each channel



- Split expansion sCO$_2$ cycle
  - Reactor is located between the turbines
    - Reduces reactor pressure below maximum cycle pressure
    - Reduces strength requirements on reactor components
  - Flow split between two compressors
    - Similar to recompression cycle
  - Drive turbine provides power for compressors
  - Power turbine is connected to generator

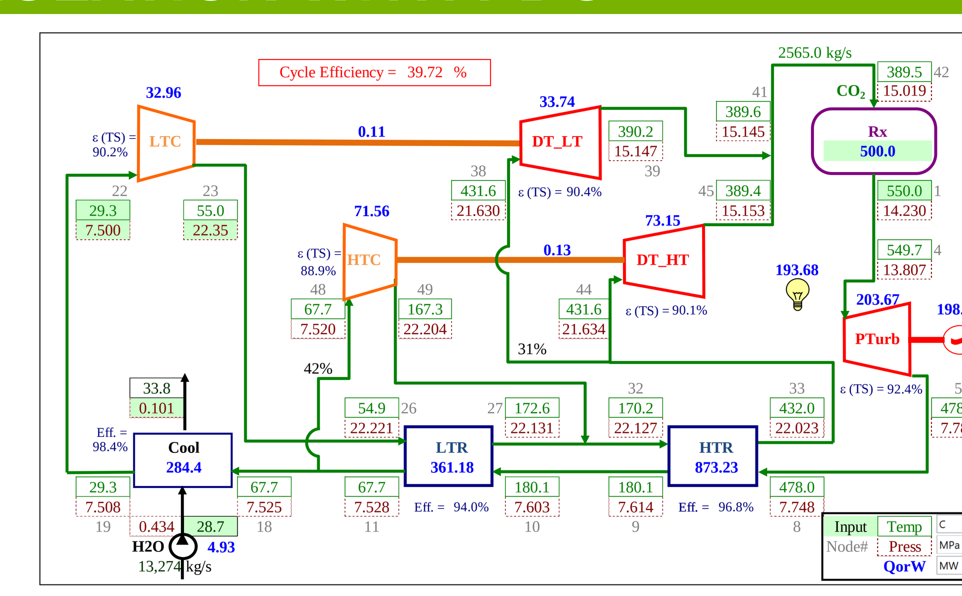


- Cycle design conditions
  - Compressor inlet conditions
    - Above critical pressure (7.5 MPa)
    - Below critical temperature (29.3 ºC)
  - Maximum pressure: 22.3 MPa
  - Reactor outlet (turbine inlet) temperature: 550 ºC
  - Cycle efficiency: 40%

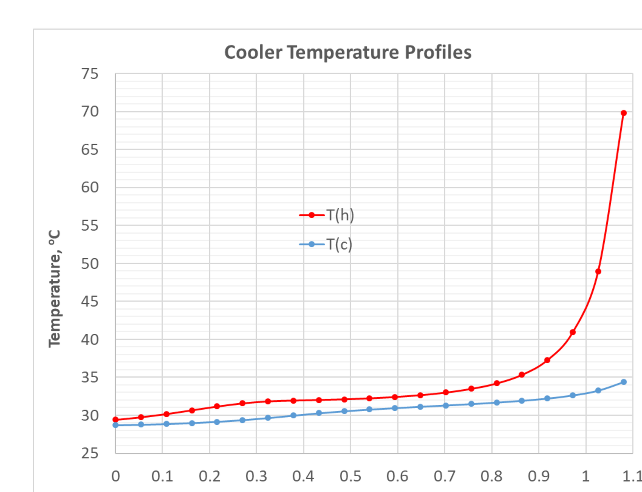


CYCLE SIMULATION WITH PDC

- Modeling of Pascal split expansion cycle
  - Reactor (Rx) located between turbines
  - Minimum cycle temperature below critical temperature
  - Compression similar to recompression cycle



- Three turbomachinery shafts
  - Low temperature drive turbine and compressor (LT_DT and LTC)
  - High Temperature drive turbine and compressor (HT_DT and HTC)
  - Power turbine (PTurb)



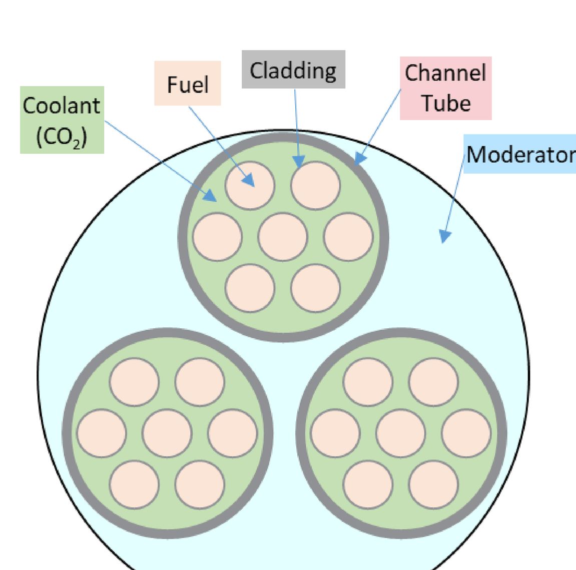
- Heat exchanger designs provided by TerraPower
  - Similar performance results in PDC
  - Double pinch point in cooler
    - Transition through pseudo-critical point
- Turbomachinery design* performed by PDC
  - Inputs by TerraPower and cycle calculations
- Cycle efficiency of 39.7%
  - Close to Pascal design value of 40%

Shaft	Power	LT Drive		HT Drive	
Speed, rps	60	60		120	
Component	PTurb	DT_LT	LTC	DT_HT	HTC
Turbine/Compressor	Turbine	Turbine	Comp	Turbine	Comp
Type	Axial	Axial	Centr.	Axial	Centr.
Blades	Shrouded	Shrouded	Unshrouded	Shrouded	Unshrouded
Number of stages	3	3	2	1	2
Min hub radius, m	0.30	0.28	0.11	0.22	0.16
Min/max blade height, cm	15.8/25.7	5.1/6.9	3.3/7.5	7.7/10.0	4.2/6.7
Max wheel diameter, m	1.11	0.69	0.8	0.64	0.66
Max diameter, m	1.11	0.69	1.29	0.64	1.53
Total length, m	1.66	0.49	0.44*	0.55	0.49*
Max Mach number	0.416	0.316	0.260	0.552	0.713
Exit speed, m/s	46.0	33.4	42.1	57.6	64.2
Eff., S-S, %	93.6	91.6	94.0	93.7	91.7
Eff., T-S, %	92.4	90.4	90.2	90.1	88.9
Power, MW	203.89	33.74	32.96	73.15	71.56

*Preliminary results

REACTOR MODULE MODELING IN PDC

- Channel-type geometry
  - Coolant channel tubes
- Heat transfer from the channel tube to the calandria water moderator
  - Modeled as a constant temperature heat sink
  - Important role in safety analysis of the Pascal reactor
- Unheated inlet and outlet sections in the reactor
  - Pressure drop only
- Power profile along the fuel pin length
  - Peak fuel and cladding temperatures
- Peak power-to-flow channels
  - Local peak temperatures and safety margins



TCF PROJECT STEPS

- ✓ Baseline PDC model for Pascal reactor
- ✓ Modeling and implementation of the reactor component
- ❑ Modeling and implementation of shutdown cooling system for the reactor safety operation,
- ❑ Carry out design analysis and transient simulation with the improved PDC, and
- ❑ Provide training to TerraPower on the PDC

REFERENCES

- 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.
- Petroski, R., et al., "Design of a direct-cycle supercritical CO$_2$ nuclear reactor with heavy water moderation," Nuclear Engineering and Technology, 2021.

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