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Preliminary Study of S-CO_2 cycle simulation using MARS

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1. Introduction

The supercritical carbon dioxide Brayton cycle has become a strong candidate for use in the next generation nuclear reactors. To test the cycle under many different conditions an apparatus named SCO_2PE has been built in KAIST. The experimental data is to be compared with simulation results from a code named MARS.

2. Apparatus

2.1 SCO_2PE [1]

SCO_2PE is an apparatus built to test CO_2 under supercritical conditions. This device is designed to see how efficiently the low pressure ratio compressor works in given conditions. Although there is a lot of data regarding pumps for water and compressor for normal gas, there is still insufficient data for supercritical CO_2. Additionally we can test how efficiently the heat and mass are transferred through the system. The device consists of a heat exchanger, a canned motor pump type compressor, and a globe valve. The heat sink is consisted of a water tank, circulator, and a chiller. Also an air compressor, booster compressor, and vacuum pump and many other instruments exist.

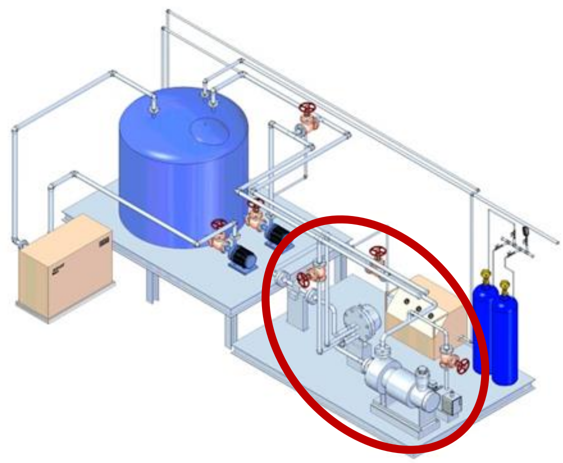

Fig. 1. 3D model of SCO_2PE [1]

The red circle in Fig.1 shows the part of the facility we will simulate. It is the closed CO_2 loop. Fig.2 shows a clear diagram of the CO_2 loop which we will nodalize and simulate on MARS.

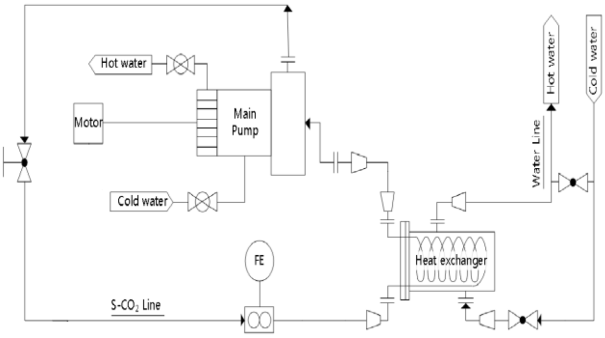

Fig. 2. A schematic diagram of the main CO_2 loop

2.2 MARS Code [2]

MARS Code is a thermal hydraulic system analysis code developed by KAERI. It was designed as an integration of RELAP5/MOD3 and COBRA-TF codes. It is mainly designed for the analysis of water but CO_2, D_2O, He, Be, and Na can also be tested.

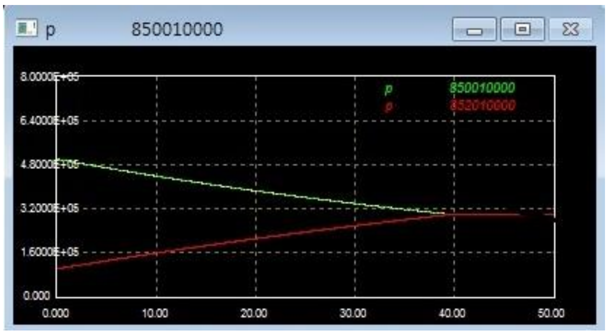

Fig. 3. A random pressure graph drawn from a MARS simulation (not a simulation of the SCO_2PE)

3. Literature Review

3.1 Argonne National Laboratory (ANL)

A lot of research regarding the next generation reactors is going on in ANL. S-CO_2 cycles that can be used for VHTR and SFR are being studied by A. Moisseytsev and J. J. Sienicki. On the year 2009, they showed that an ordinary S-CO_2 cycle will have low cycle efficiency if used directly on a VHTR. This is due to the mismatch of temperature difference in the primary and secondary cycle. To overcome this they have proposed two approaches. The first is to use three separate cycles to match the big temperature difference requirement of the VHTR. The second is increase the pressure ratio in the turbine to match the temperature difference of the helium and also adding a compressor to retain minimum compressor work in the main compressor. However, in case of the SFR, the temperature difference matches each other so the standard recompression cycle fits well. Furthermore, the Plant Dynamics Code has been modified so that it can be applied to any type of system that uses a S-CO_2 cycle.

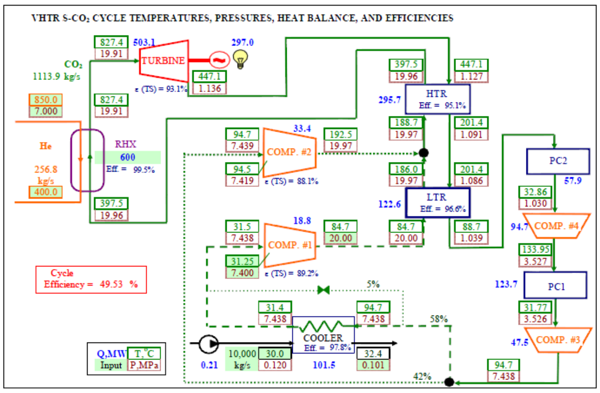

Fig. 4. Schematic Diagram of SCO_2 cycle with two-stage precooling [3]

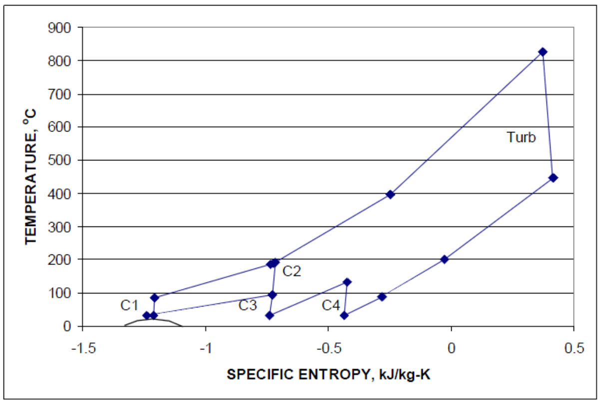

Fig. 5. T-s Diagram of SCO_2 cycle with two-stage precooling [3]

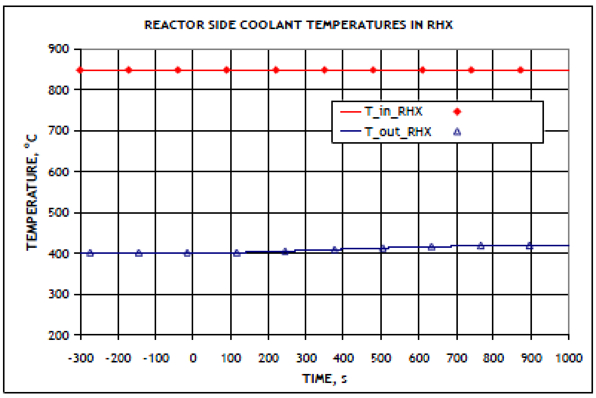

Fig. 6. Transient Control Analysis of VHTR [3]

3.2 Massachusetts Institute of Technology (MIT)

Research on SCO_2 cycle control has been done in MIT. Using the GAS-PASS/CO_2 code, an analysis on the SCO_2 recompression cycle, including part-load operations and loss-of-load events, has been done. Typically, four control methods are used for part-load operations: inventory control, temperature control, throttling, and bypass. Inventory control was observed to be the best choice regarding efficiency and range of operation. However, it has a big disadvantage of slow response time. Loss-of-load transient is a condition when the generator disconnects from the grid and a rapid loss of load is experienced. In the S-CO_2 recompression cycle, this would bring turbine failure because of acceleration in tip speed. A bypass valve between the IHX and turbine can prevent such failure. Simulation results show that the valve should be opened completely within 0.4 seconds to maintain shaft speed under 130% of its nominal speed. Shaft speed reaches maximum around 3 seconds. [4]

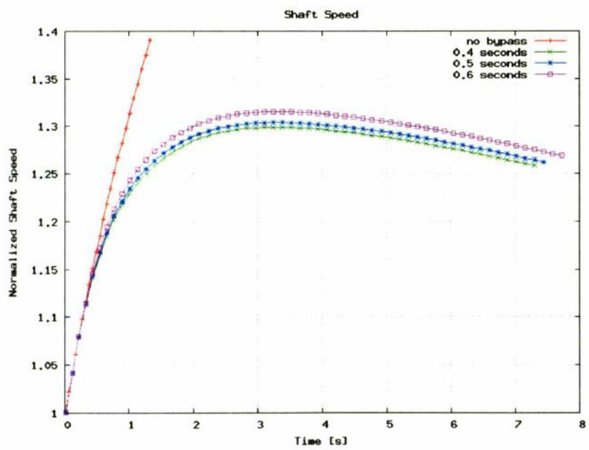

Fig. 7. LOL Transient: Normalized Shaft Speed – Time [4]

3.3 Knolls Atomic Power Laboratory (KAPL)

A S-CO_2 Brayton cycle test facility named Integrated Systems Test (IST) is being built in KAPL. To test the turbo-compressor first, the SNL Gen IV Test Loop was used. However, due to excessive focus on avoiding surge, the flow in the turbine stopped or even reversed leading to thrust bearing overload. By changing the valve lineups and optimizing initial fluid conditions to avoid surge and maintain forward flow in turbine, the device ran smoothly. Results were compared to TRACE modelling results. As turbine inlet temperatures rose, the TRACE calculations were closer to the test data because TRACE is based on ideal gas and the fluid shows properties close to that of ideal gas in high temperatures. Due to this test, more accurate test setup is possible even in low mass flow rate regions. Surge can be avoided while sustaining turbine forward flow.

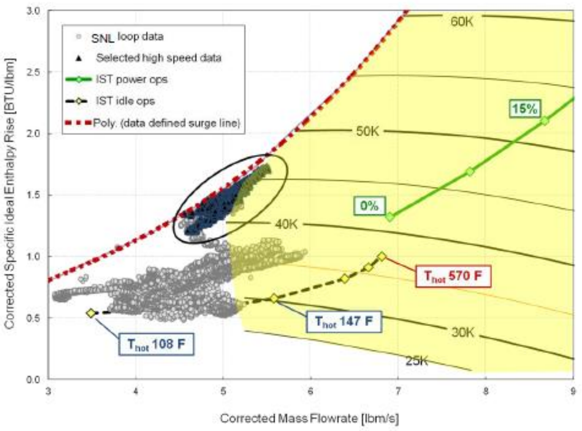

Fig. 8. IST compressor performance data [5]

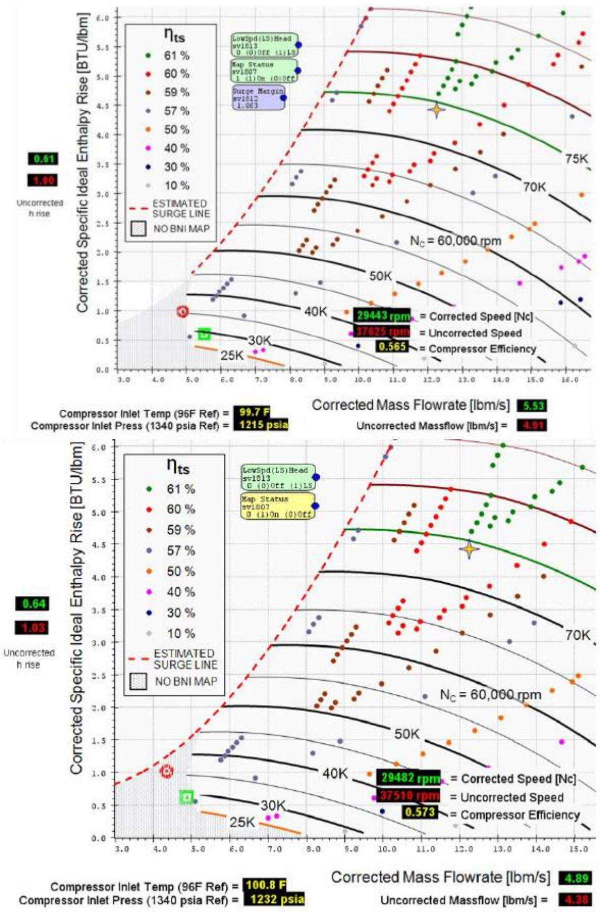

Fig. 9. Compressor model prediction before (top) and after (bottom) surge line extension [5]

4. Simulation

The SCO_2PE mainly consists of three cycles but for simplicity we will only simulate the CO_2 section.

4.1 Pipe Lines

The Input requires the pipe length, area, vertical angle, roughness, loss coefficient, pressure, temperature, etc.

The flow area of 1 1/2 (80) pipe was calculated to be 0.00114 m^2.

The length is determined by the change of flow. Whenever there is an elbow, the corresponding loss coefficient is applied to the junction and the pipe is divided into two. The longest single pipe is measured to be 1.017m

Vertical angle is 0 for most of the time. All angle changes are 90 degrees. Maximum elevation change is 530mm.

Loss coefficient in 90 degrees elbows can be approximated to 0.3 for a flanged elbow. [6]

Pressure must be above the critical point of CO_2 which is 7.39MPa. Pressures slightly under critical point may also be studied for trans-critical cycle studies.

Temperature must be above the critical point of CO_2 which is 304.25K. Temperatures slightly under critical point may also be studied for trans-critical cycle studies.

4.2 Globe Valve

The simulation and experiment is conducted in steady state operating conditions so the valve need not be modelled as a valve. The corresponding loss coefficient may be calculated according to how much the valve is open. The coefficient is 10 when fully open. (Must be tested for S-CO_2 conditions.) [6] Thus the calculated value may be inserted in a junction between two pipe lines. The loss coefficient is strongly dependent on the opening size therefore an accurate calculation is needed when condition is specified.

4.3 Heat Exchanger

The Heat exchanger is a spiral tube heat exchanger. This can be simplified as a pipe passing through a volume of water. The pressure drop is 48kPa and heat transfer area totals up to 2.022m^2. 20 tubes with outer diameter of 9.525mm are present in the heat exchanger but it may be simplified as one big pipe with the given inputs.

The coolant side is actually connected to a water pump which is again connected to a chiller. The temperature is dependent on the temperature of the CO_2 cycle. However we have simplified the problem to have a constant temperature coolant such that incoming and exiting volumes were modeled as a time dependent volume. The heat exchanger inlet temperature of coolant is given as constant temperature of 281.8 K. The pump is capable of flowing water at rates up to 80L/min so the corresponding mass flow will come through the time dependent junction and also flow out.

4.4 Compressor

The compressor is a canned pump type customized compressor with a capacity of 4.49kg/s. The junction area of the inlet is 0.001905m^2. The outlet junction area is 0.00114m^2. The operating pressure at the inlet is maintained at 7.49MPa which is slightly above the critical point. Pressure ratio is 1.18. Temperature of pump inlet is given as 305.35K which is also slightly above the critical point. Maximum rotation speed of pump is given as 4620rpm. The motor driver's capacity is given as 56kW. Impeller diameter is 234mm. However, since the compressor used in the facility is a derivative from the pump technology, it will be modeled as a pump in MARS.

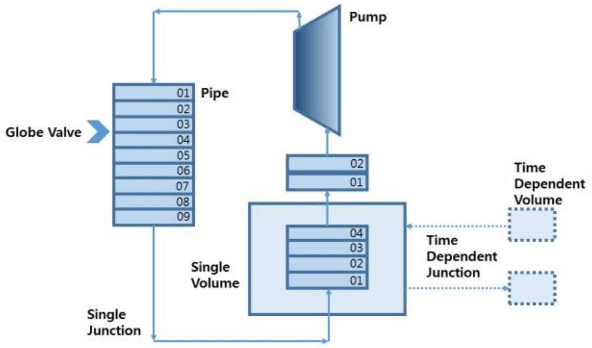

Fig. 4. Model of SCO₂PE CO_2 for MARS Simulation

5. Further Works

Once the CO_2 thermodynamic data and the right version of MARS Code are acquired, we will carry out the simulation and compare results with the actual experimental data. The differences will show if there's any mistake in the input file, which we can modify to match the conditions more accurately, or it may show the engineering community's lack of information on supercritical CO_2. If it is the latter, we may actually go further and organize more experiments and simulations to study the properties of supercritical CO_2 Brayton cycle.

Additionally, upgrade of the facility may bring more studies to do.

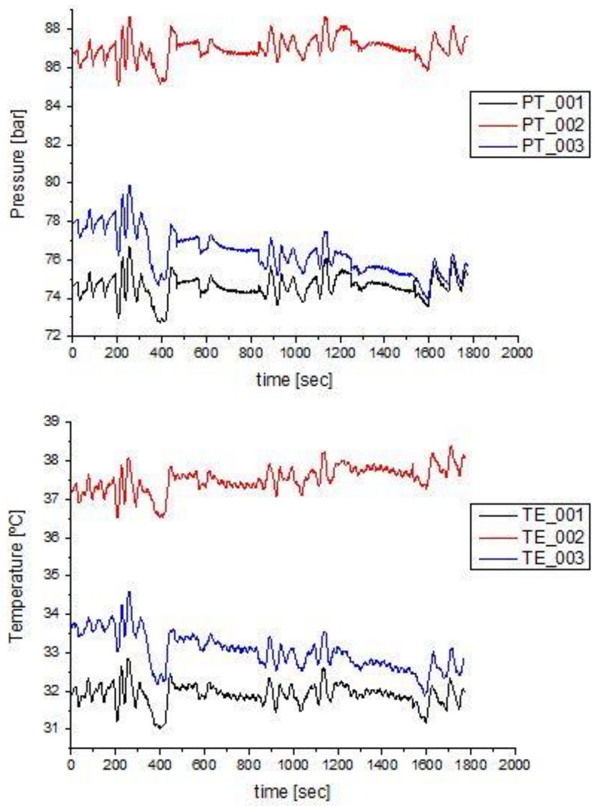

Fig. 5. Experimental results.
PT_001, TE_001: Compressor Inlet, Heat Exchanger Outlet
PT_002, TE_002: Compressor Outlet
PT_003, TE_003: Heat Exchanger Inlet

6. Conclusions

The pipelines, globe valve, heat exchanger, and pump have been nodalized as written above. Using the work done so far, we will be able to simulate the experiment as soon as the right version of MARS arrives. Once we have the simulation results, we may improve the simulation result by adding more realistic features to the input and study the missing gap for the accurate simulation of S-CO_2 system.

ACKNOWLEDGEMENT

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