Preliminary Study on Tank Design for S-CO_2 Power Cycle Inventory Control

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1. Introduction

A supercritical CO_2 (S-CO_2) cycle is a promising alternative power cycle for steam cycle due to high efficiency and smaller size. Various control strategies for S-CO_2 cycle has been developed. The developed control schemes usually consist of a combination of several schemes. For S-CO_2 cycle control, inventory control and bypass control are both used. In general, inventory control is used for the slow transient and bypass is used for the fast transient [1,4]. When only inventory control is actuated, the system pressure changes significantly to maintain velocity and temperature at approximately constant level [2]. For these reasons, the inventory control could maintain high thermal efficiency. Various control schemes are available in the inventory control depending on the number of tanks used and where the tanks are connected to the cycle. In general, the control scheme as presented in Fig. 1 that a tank is connected to the compressor outlet and the precooler inlet is commonly used because it is simple, and the mass transfer could occur naturally.

The transferred mass to and from the inventory tank is a parameter that determines the load change capacity of the inventory control scheme. The pressure in a tank is also an important parameter in the above-mentioned scheme because the pressure difference between the tank and the cycle is a driving force for the natural mass transfer. Thus, the authors tried to find a parametric study of the load range by comparing some methods. The initial pressure and mass in a tank are dealt as the design conditions for a tank in this paper and KAIST MMR (Micro Modular Reactor) is used as the reference system.

KAIST MMR with a tank

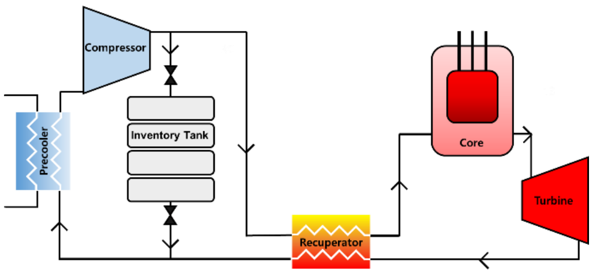

Fig. 1. Layout of MMR with a tank for a natural mass transfer

KAIST MMR is designed to have good transportability and completely modularized system. KAIST MMR is a direct cycle composed of reactor core and power conversion system. For compactness of the system, the layout is a simple recuperated cycle. The layout of MMR with a tank is shown in Fig. 1. Table I shows the design parameters of KAIST MMR in this paper [5].

Table I. Design result of KAIST MMR

Thermal power [MWt]	36.2	**Cycle Efficiency [%]**	34.09
Turbine inlet T [K]	823.15	**Turbine outlet T [K]**	713.90
Turbine inlet P [MPa]	19.93	**Turbine outlet P [MPa]**	8.161
Compressor inlet T [K]	333.15	**Compressor outlet T [K]**	415.32
Compressor inlet P [MPa]	8.001	**Compressor outlet P [MPa]**	20.0
Precooler inlet T [K]	430.94	**Core inlet T [K]**	659.68
Precooler inlet P [MPa]	8.091	**Core inlet P [MPa]**	19.98
Total external volume [m^3]	83.6	**Mass flow rate [kg/s]**	180

2. Design of inventory tank for S-CO_2

In this section, some relations and the KAIST-CCD (Closed Cycle Design) for the design of inventory tank for S-CO_2 are introduced.

2.1. Simplified relations for load range limits.

D. Bitsch and J. Chaboseau introduced the load range limits of the inventory control by natural transfer for a gas turbine loop. These are given by the following simplified relations with some assumptions [3].

Assumptions:
1. Ideal gas of equation of state.
2. Isothermal process between tank and loop.
3. High pressure is proportional to current load operation.
4. Turbomachinery pressure ratio is constant.

- Lower limit (load decrease)

$$x = \frac{\left(1+\frac{M_1}{M_0}\right)}{1+\frac{yM_1}{M_0}} \qquad (1)$$

- Upper limit (for a further load increase)

$$\mathrm{x} = \frac{\left(1 + \frac{M_1}{M_0}\right)}{1 + \frac{yM_1}{\overline{\omega} M_0}} \quad (2)$$

M_0 *and* M_1 : Initial mass of gas respectively in the gas turbine loop and in the transfer tank.
$\overline{\omega}$: Pressure ratio of the gas turbine cycle.
y : Ratio of the cycle high pressure to the initial pressure of the tank

As described in eq. (2), it is natural that the tank should have an initial pressure between the pressures of the connected pipes to reach 100% again. Thus, in this paper, the upper limit is not discussed and only the lower limit is discussed.

2.2. Consideration of S-CO_2 property characteristics

Among the assumptions in section 2.1, the authors considered that ideal gas equation cannot be applied to the S-CO_2 inventory control due to non-linearity in the property as shown in the Fig. 3. For example, the density varies non-linearly and dramatically along the constant temperature line near 333.15 K. So, the limits of the inventory control for KAIST MMR were calculated following the flow chart in Fig. 2 using NIST data [2].

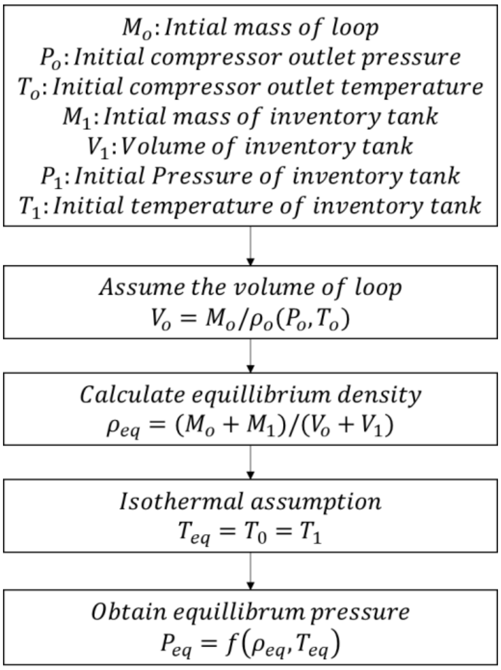

Fig. 2. Flow chart to obtain equilibrium pressure of S-CO_2 cycle

2.3. Analysis using the KAIST-CCD

KAIST-CCD an in-house code is developed for steady state cycle analysis. Thus, it does not consider any off-design performance of the component in MMR.

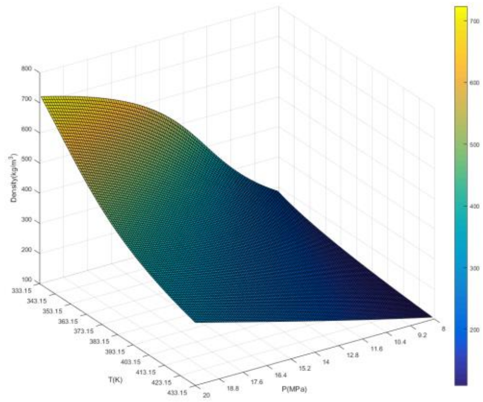

Fig. 3. Density variation of S-CO_2 near the region of the MMR compressor (8-20MPa, 333.15-433.15K)

For the analysis using KAIST-CCD, the following conditions are used. Firstly, each inlet temperature of compressor and turbine is hold at the design point. Secondly, the volumetric flow rate at turbine inlet is also assumed as constant value of the design point. The selected varying parameters are power of the core and the high pressure in the cycle. Fig. 4 shows the flow chart for analysis using KAIST-CCD.

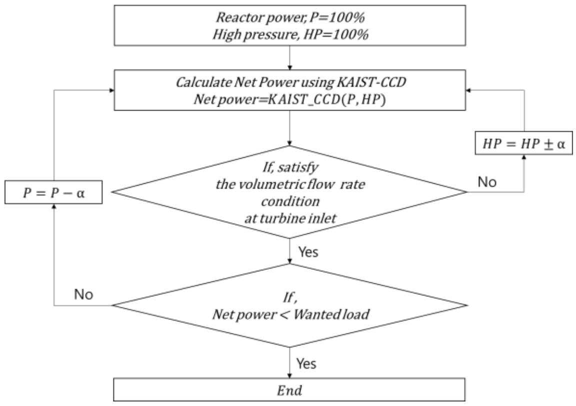

Fig. 4. Flow chart for analysis using KAIST-CCD

3. Comparison between the methods for designs of inventory tank for S-CO_2

In this section, the analysis results that have been conducting using the above methods are compared. The equilibrium pressure that corresponds to KAIST MMR conditions with a tank are calculated using eq. (1) and the flow chart in Fig. 2. And the calculated equilibrium pressure is considered as the part load without any correction following the assumption 3 in section 2.1. In other words, the ratio of the equilibrium pressure to 20MPa is considered as the part load. The tank volume is set to equal to 5% of the MMR total external volume. Fig. 5 shows the calculated results. The calculated results using eq. (1) and the flow chart in Fig. 2 are almost similar but the load limit results using KAIST-CCD are lower than them. It means that KAIST-CCD predicts that the tank needs less volume to achieve the same part load compared to other methods.

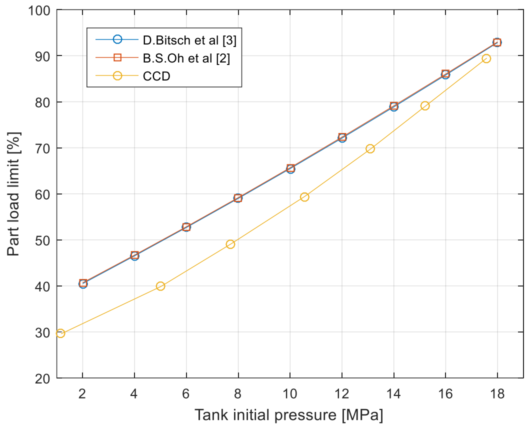

Fig. 5. The lower limits with respect to initial pressure of the tank.

The reason why the blue and red lines are similar is that these two methods do not consider the both point where the tank is connected. So, in the calculation of load decrease (lower limits) using these two methods, parameters such as pressure, temperature and density at the high-pressure part are assumed as the whole system parameters. Thus, they have similar results because the significant variation in the density of S-CO_2 does not affect much due to the assumption. But in the case of load increase, the non-linearity of the density affects the results because the considered part is the lower-pressure part and this part is closer to critical point as shown in Fig. 6.

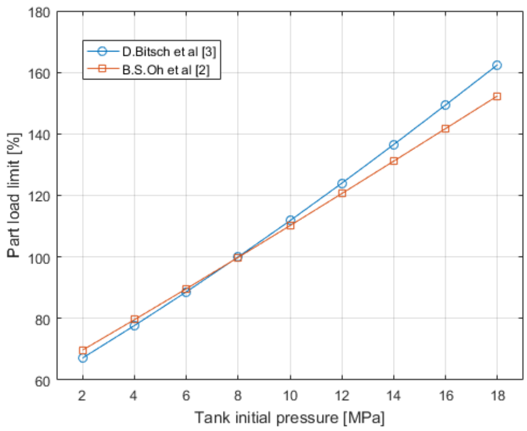

Fig. 6. The upper limits with respect to initial pressure of the tank.

The tendency that the results using KAIST-CCD is lower than the others are mainly due to the assumption 3 in section 2.1. As shown in Fig. 7, the high pressure is not linear to part load in KAIST-CCD calculations and it is higher than the values expected by the assumption 3 in section 2.1. So, the part loads using the other two methods are overestimated.

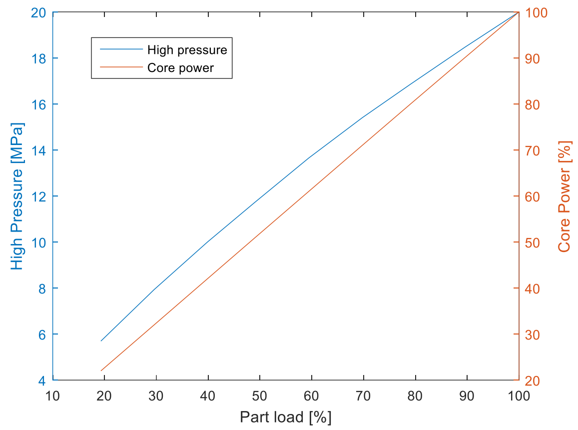

Fig. 7. The variations of the high pressure and the core power in CCD calculation respect to the part load

4. Summary and Further works

In this paper, expected lower part load limits respect to the initial pressure condition of the tank for S-CO_2 power cycle inventory control are calculated using three methods. The calculations are based on the KAIST-MMR conditions and the tank is located between the compressor outlet and the precooler outlet for natural mass transfer. From the results, it is found that the method using KAIST-CCD underestimates the tank volume for control than others.

As further works, qusai-static analysis results considering the off-design performances of the components and simulation results using MARS code will be also performed and presented in the conference to consider effects of the other parameters that does not considered in this paper.

ACKNOWLEDGEMENT

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