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Storage Tank Design and Dynamic Analysis of sCO_2 Power Conversion System for Thermal Energy Storage System

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1. Introduction

The Thermal Energy Storage (TES) systems are considered a promising alternative among Energy Storage Systems (ESS) due to their strength such as relatively few installation restrictions, eco-friendly, long-term energy storage, long life, and economical efficiency. As a storage material of the TES system, sodium could operate at temperature above 600°C due to its high temperature stability and could expect high power generation efficiency when combined with a supercritical CO_2 power cycle. The supercritical CO_2 brayton cycle offers a more efficient, significantly simpler and more compact alternative to the superheated steam cycle [1]. In the previous study, the heat balance and efficiency of cascade cycle and partial heating cycle were derived under the operating conditions of a two-tank TES using sodium as the storage material [2]. It was concluded that the partial heating cycle was more suitable for two-tank TES using sodium.

In this study, the capacity of a carbon dioxide storage tank is designed as a conceptual design of the partial heating cycle. To validate the design, the inventory control performance concerning electric power variation is evaluated.

2. Methods and Results

In the power operation mode, the overall control strategies for the TES and power conversion system (PCS) are described in reference [3]. During the power operation mode, the control systems of the power conversion system consist of a Turbine Bypass Controller, Turbine Throttle Valve Controller, Inventory Controller, and Cooling Water Flow Controller. Among these, the Inventory Controller on the PCS side performs the function of controlling the pressure of the CO_2 storage tank to the set pressure programmed according to the load on the power grid. When the pressure in the CO_2 storage tank is higher than the set pressure, the injection valve is opened to reduce the tank pressure, simultaneously injecting CO_2 into the PCS. Conversely, when the pressure in the storage tank is lower, the discharge valve is opened to increase the tank pressure, and CO_2 from the PCS is recovered. Through this control of injecting and

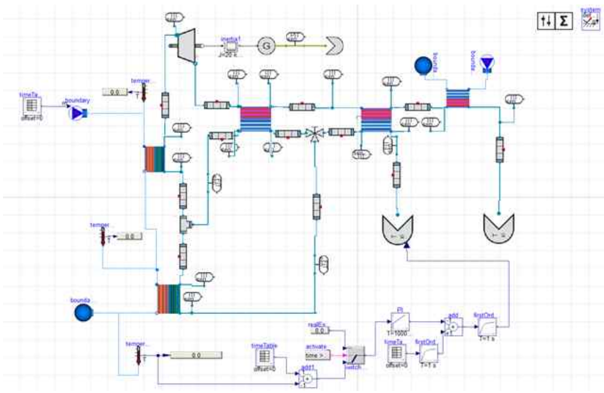

Fig. 1. Dymola model for calculating CO_2 inventory in the PCS at partial load

reducing CO_2 on the PCS, the inventory on the PCS side changes, regulating the generated power to meet the demand on the power grid. This section summarizes the design method of the CO_2 storage tank and the dynamic analysis with the applied control system.

2.1 CO_2 Storage Tank Design

The volume of the CO_2 storage tank is determined by the inventory of CO_2 that needs to be accommodated during power changes, as well as the pressure and temperature of the storage tank. The volume of the storage tank is set through the following processes:

1) Calculate the inventory of CO_2 that needs to be accommodated by performing calculations for partial load on PCS side.
2) Set the pressure of the CO_2 storage tank, ensuring no pinch occurs when reducing or injecting CO_2 within the system.
3) Ultimately, determine the volume of the CO_2 st orage tank by setting the operating temperature of the tank.

To calculate the inventory of CO_2 and pressure within the system during partial load, an analysis of partial load operation was conducted. In Fig. 1, a Dymola model is shown for determining CO_2 inventory and pressure within the PCS at partial load operation. At 100% power with a sodium flow rate of 156.02 kg/s, the high-pressure side pressure was 29.1 MPa, and at 50% power

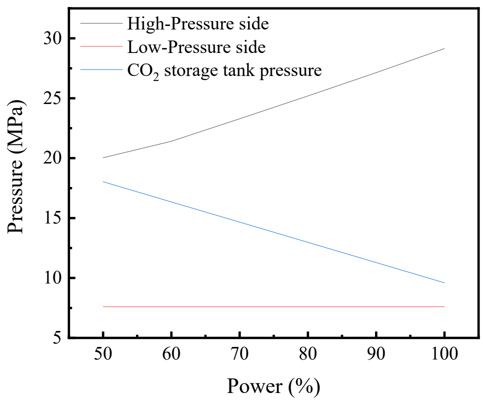

Fig. 2. The pressure of high-pressure side, low-pressure side of PCS, and CO_2 storage tank at partial load

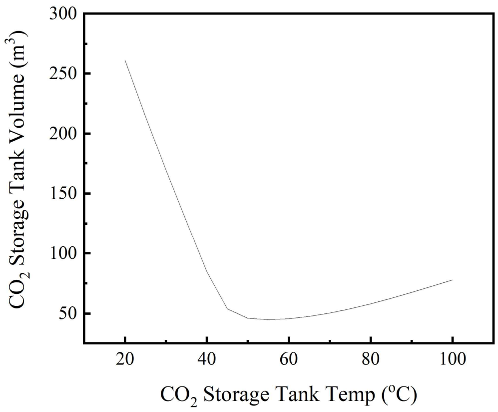

Fig. 3. CO_2 storage tank volume according to operating temperature

with a sodium flow rate of 78 kg/s, the high-pressure side pressure was derived to be 20.0 MPa.

At the minimum load conditions of 50% power, CO_2 is injected into the CO_2 storage tank from the PCS, reaching its maximum pressure. If the CO_2 storage tank pressure becomes equal to or higher than the high-pressure side of PCS, pinch occurs, preventing further transfer of CO_2 from the PCS to the tank. Conversely, at 100% power condition, if the tank pressure becomes equal to or lower than the low-pressure side of PCS, CO_2 supply to the PCS becomes impossible. Therefore, the tank pressure must be maintained at a certain pressure difference at minimum and maximum power conditions, respectively. In this study, the pressure difference of 2 MPa has been set.

In Fig. 2, the pressure in the PCS and the set pressure of the CO_2 storage tank are shown concerning power during power operation mode.

The CO_2 inventory that the CO_2 storage tank must accommodate during load changes in the PCS is equal to the change in CO_2 within the PCS at each partial load, which can be calculated from the system volume and density at each partial load. The weight of CO_2 inventory in the PCS is 42,667.6 kg at 100% power and 29,825.5 kg/s at 50% power. Therefore, the minimum inventory that the CO_2 storage tank must accommodate the difference between these two weights, which is 12,842 kg. To ensure control performance at power operation mode, there should be sufficient margin in the CO_2 inventory; hence, considering a 50% margin, the weight of CO_2 inventory, which the CO_2 storage tank needs to accommodate, is set to 19,263 kg.

When CO_2 is charged or discharged within the CO_2 storage tank, compression and expansion occur. Therefore, to match the mentioned inventory and pressure, appropriate volume and temperature of the CO_2 storage tank should be set. The volume of the CO_2 storage tank can also be minimized based on temperature. To calculate the volume of the CO_2 storage tank, applying the ideal gas state equation at 100% and 50% power gives the following equations.

$$P_{100\%}V = M_{100\%}RT \quad (1)$$

$$P_{50\%}V = M_{50\%}RT \quad (2)$$

Subtracting equation (2) from equation (1) yields the volume of the tank, expressed as a function of inventory and density as follows.

$$V = \frac{(M_{100\%} - M_{50\%})}{(P_{100\%} - P_{50\%})}RT = \frac{\Delta M}{\rho_{100\%} - \rho_{50\%}} = \frac{-19,263}{\rho_{100\%} - \rho_{50\%}} \quad (3)$$

Using equation (3) to illustrate the required storage tank volume based on the operating temperature of the CO_2 storage tank yields Fig. 3. The volume of the storage tank is minimized when the operating temperature is in the range of 50 to 60°C. To mitigate the rapid increase in power consumption on the heater side at higher temperatures, 50°C is chosen as the operating temperature, resulting in a required storage tank volume of 46 m³. Assuming a tank diameter of 3 m, the tank length is calculated to be 6.52 m.

2.2 Dynamic Analysis of Inventory Control

A model of the PCS and control was established for the evaluation of the control performance of the Inventory Controller, as depicted in Fig. 4. The assumptions for the TES include PCHE1 and PCHE2 inlet temperatures and flow rates as boundary conditions. The control performance evaluation of the Inventory Controller was conducted for a linear load variation with a slope of 5%/min, transitioning from 100% to 50%.

The boundary conditions on the sodium side varied over 600 seconds, changing from the flowrate corresponding to 100% power of 156.02 kg/s to that of

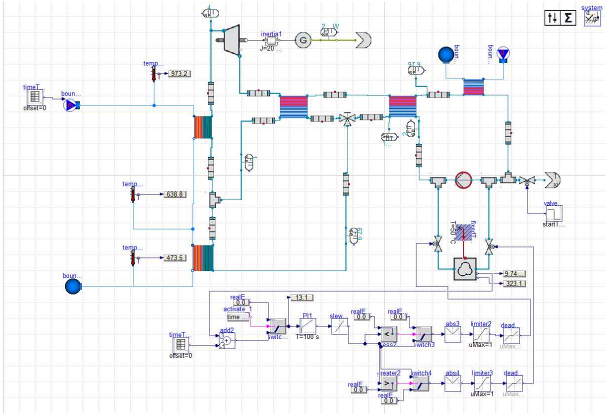

Fig. 4. Dymola model for inventory control performance evaluation

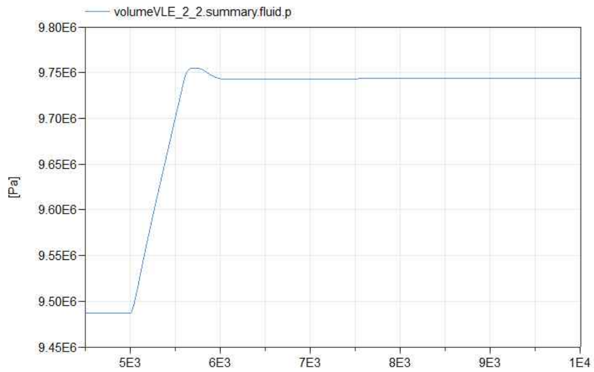

Fig. 5. CO_2 storage tank pressure transient when load linearly changes from 100% to 50%

50% power of 78 kg/s. Concurrently, the pressure setpoint for the CO_2 storage tank in the Inventory Controller was input as varying from the 9.487 MPa at 100% conditions to the 9.743 MPa at 50% conditions.

Fig. 5 to 7 illustrate the changes in CO_2 storage tank pressure, pressure control valve opening, and turbine power during a linear load reduction from 100% to 50%. It can be seen that the CO_2 storage tank pressure shown in Fig. 5 increases as it receives CO_2 from the PCS to reduce the system load from 100% to 50%. The final converged pressure precisely matched the setpoint of 9.743 MPa. A slight overshoot of approximately 0.01 MPa was observed in the pressure response, and the settling time due to this overshoot was approximately 400 seconds.

Fig. 6 illustrates the opening of the pressure control valve, showing the operation of both the high-pressure and low-pressure valves. In Fig. 7, the turbine power is displayed, revealing an overshoot from 52.2 MW at 100% power to 26 MW at 50% output. Similar to the CO_2 storage tank pressure and the pressure control valve, there is an overshoot in the turbine power for about 400 seconds. This overshoot is expected to be mitigated when operating in conjunction with the turbine bypass control.

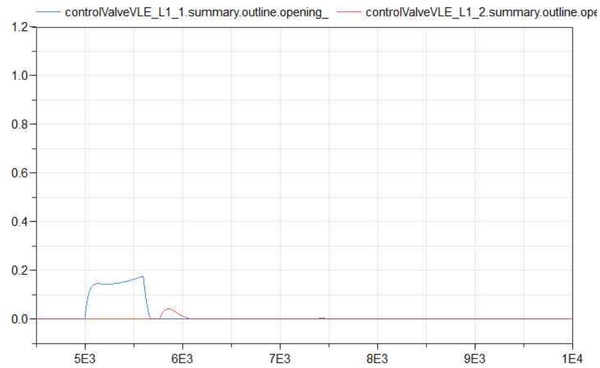

Fig. 6. The transient of pressure control valve opening of the CO2 storage tank when load linearly changes from 100% to 50%

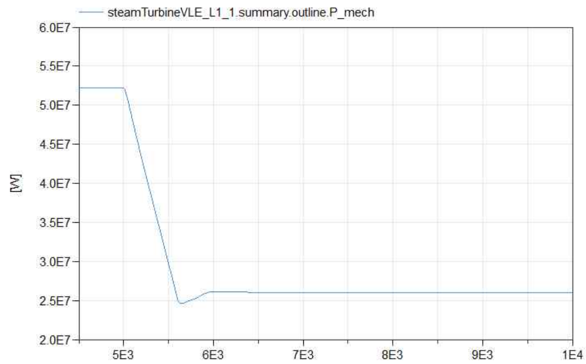

Fig. 7. The turbine power transient when load linearly changes from 100% to 50%

3. Conclusions

In this study, we have described the design method for the CO_2 storage tank in a sCO_2 PCS for TES. To validate the design concept and evaluate the performance of the inventory control, dynamic analysis was conducted for a linear load reduction from 100% to 50%. The analysis results confirmed that the CO_2 storage tank pressure responded stably to the target pressure during changing in the thermal source power. Additionally, the turbine power was observed to change stably from 100% to 50% power.

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