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Effect of high pressure vessel size on compressed CO_2 energy storage for nuclear power plant to complement renewable energy

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1. Introduction

Since the invention of power conversion of heat energy, we have been facing an enormous increase of electricity demand for industries, household, and transportation. To cope with this rising demand, people have developed many types of power plants with various heat sources. Especially, nuclear power plant has played a critical role in producing baseload electricity due to its large power capacity and reasonable fuel economics, which are appropriate for base electricity generation. However, an introduction of renewable energy is likely to add intermittency problem to the electrical grid.

Thus, it is required for even a large size power plant to have load following capacity as more and more renewable energy penetrates the market. In case of a nuclear power plant, it is not easy to perform load following operation because of safety concerns. One alternative solution can be thermodynamically storing energy as shown in Fig. 1. Among them, a compressed air energy storage (CAES) system has been gaining popularity. CAES has a large capacity and fast response with moderate round-trip efficiency compared to conventional battery, but has geographic limitation for installation because CAES requires a large size underground reservoir [2, 3].

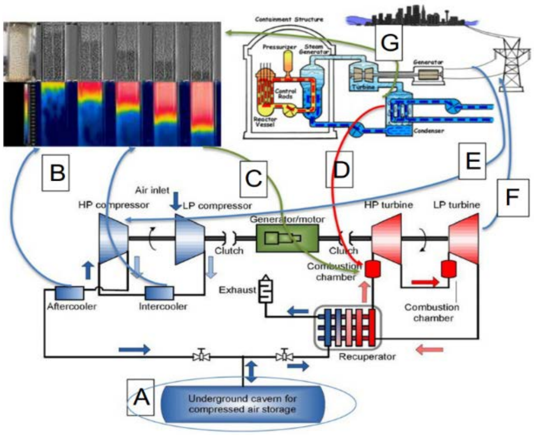

Fig. 1. Integration of energy storage system to nuclear power plant [1]

In an attempt to overcome the limitation of CAES, a compressed CO_2 energy storage (CCES) system was proposed using pressure vessel, because the high density of CO_2 makes it plausible to store compressed CO_2 more easily than air. So far many researches are ongoing for CCES layout. However, relatively little effort has been made for components of CCES. Among them, pressure vessel is one of the key components, because the performance of CCES is heavily dependent upon maximum pressure of the system, which is pressure in high pressure vessel. In this paper, the relations between the maximum pressure and the size of vessel are presented due to yield strength limitation of material. Then, its impact on the performance of CCES is discussed.

2. Simple CCES layout

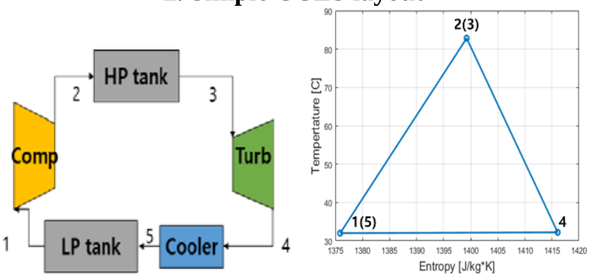

Fig. 2. Simple CCES layout and its T-S diagram

Basic components of CCES are compressor, turbine, high pressure tank, low pressure tank, and cooler as shown in Fig. 2. When electricity generation exceeds electricity demand, CO_2 is compressed from the low pressure tank to the high pressure tank so that this compressed CO_2 can be used to drive turbine when demand is larger than generation.

The performance of CCES can be generally evaluated with round-trip efficiency (RTE) and power density [3]. The power density is further classified into charging and discharging power densities. High round-trip efficiency means minimal energy loss for storing energy, and high power density indicates the system can store more energy within the same size pressure vessel.

$$\text{Round trip efficiecy} = \frac{\text{Expansion work}}{\text{Compression work}}$$

$$\text{Power density} = \frac{\text{Expansion or Compression work}}{\text{Volumes of high and low pressure tank}}$$

To observe the performance change of a simple CCES, parametric study was conducted. It is widely known that compression work can be greatly reduced when compression occurs near the critical point of CO_2 [4]. Accordingly, the first layout of CCES operates in the supercritical region as shown in Fig. 2.

Round-trip efficiency (RTE) and power density variations are presented with respect to changes of compressor inlet and outlet pressures, respectively, in Figs. 3-6. Particularly, as further away from the critical point, one can observe drastic changes of RTE in Fig. 3, and the maximum power density occurs near the critical point in Fig. 4.

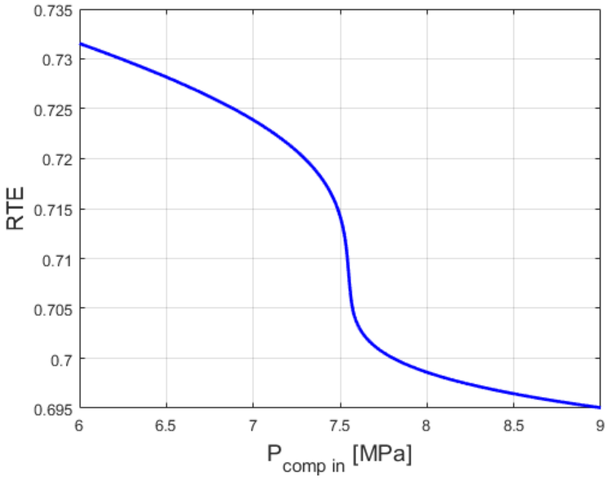

Fig. 3. Round-trip efficiency variation with respect to compressor inlet pressure

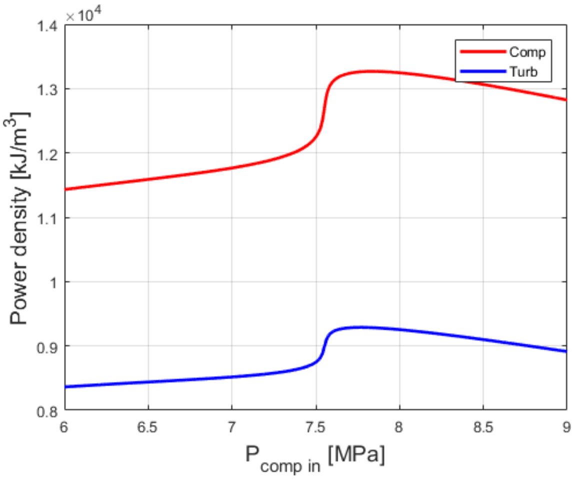

Fig. 4. Power density variation with respect to compressor inlet pressure

On the other hand, Figs. 5 and 6 show the continuous rise of RTE and power density as compressor outlet pressure increases. However, it is not possible for pressure vessel to endure extreme pressure, so compressor outlet pressure should be determined with a realistic constraint.

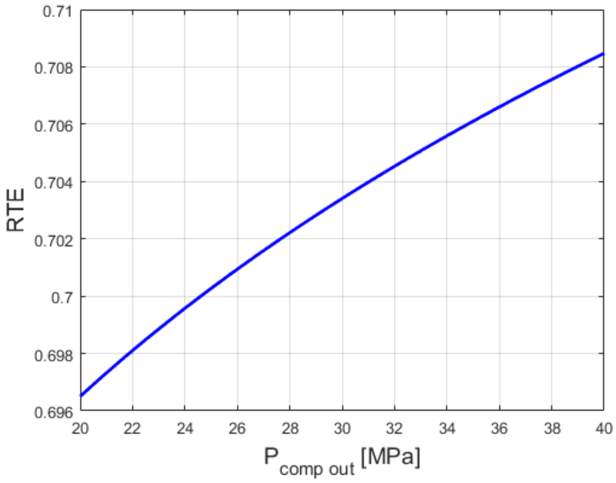

Fig. 5. Round-trip efficiency variation with respect to compressor outlet pressure

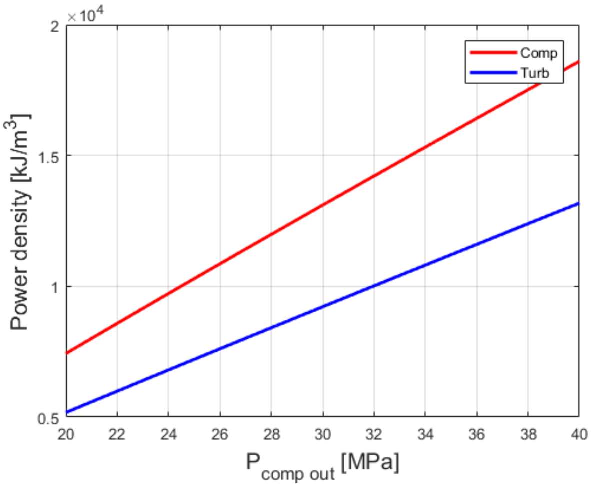

Fig. 6. Power density variation with respect to compressor outlet pressure

3. Sizing of pressure vessel

In section 2, it was pointed out that the system maximum pressure, which is the pressure in high pressure vessel, has a critical effect on the performance of CCES, and its increase always benefit RTE and power density. Thus, it is necessary to find a realistic constraint of system maximum pressure. In this section, the sizing of pressure vessel with structural limitation is conducted, by observing the relations between the size of single pressure vessel and pressure inside the vessel.

It is assumed that the shape of a pressure vessel is cylinder with 2:1 ellipsoidal head. The principle stress can be calculated with Lame's equation for thick pressure vessel [5]

$$\sigma_r = \frac{p_{in}r_{in}^2 - p_{out}r_{out}^2}{r_{out}^2 - r_{in}^2} + \frac{r_{in}^2 r_{out}^2 (p_{in} - p_{out})}{r^2 (r_{out}^2 - r_{in}^2)} \quad (1)$$

$$\sigma_\theta = \frac{p_{in}r_{in}^2 - p_{out}r_{out}^2}{r_{out}^2 - r_{in}^2} - \frac{r_{in}^2 r_{out}^2 (p_{in} - p_{out})}{r^2 (r_{out}^2 - r_{in}^2)} \quad (2)$$

$$\sigma_z = \frac{p_{in}r_{in}^2 - p_{out}r_{out}^2}{r_{out}^2 - r_{in}^2} \quad (3)$$

p indicates the pressure. Subscript in and out denote the inner and outer side of pressure vessel, respectively. Applying these principle stresses into Von Mises criterion produces equation (4). Additionally, the volume can be calculated with equation (5).

$$r_{in} = r_{out}\sqrt{1 - \frac{\sqrt{3}\,(p_{in} - p_{out}) * S}{\sigma_y}} \quad (4)$$

$$V_{int} = \pi r_{in}^2 h + \frac{2}{3}\pi r_{in}^3 \quad (5)$$

In the viewpoint of design, thickness of the vessel and yield strength of a material should be specified. Yield strength is assumed as 250MPa. With respect to thickness of vessel and inner radius, the maximum allowable pressures inside a vessel and their total volumes are shown in Fig. 7 and Fig 8, respectively. Fig. 7 implies that a large pressure vessel can contain more CO_2 for given volume, but its maximum pressure should be lowered because of the material limitation.

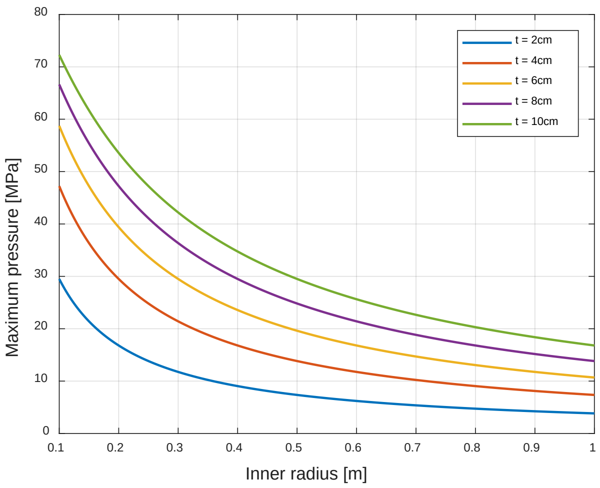

Fig. 7. Maximum pressure changes for pressure vessel

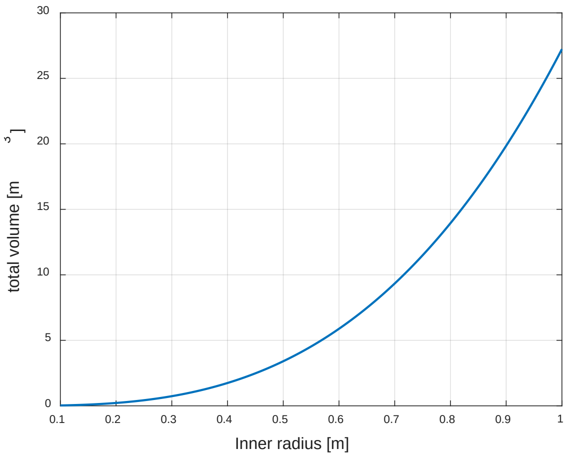

Fig. 8. Volume change of pressure vessel

4. Total stored work

To observe the performance change with respect to the maximum pressure and the volume of a pressure vessel, parametric study is performed. Assumed parameters are summarized in Table 1. Especially, the maximum pressures varied from 20MPa to 40MPa, and the vessel volumes are derived with the method described in section 3.

Table. 1. Summary of analysis parameters

Comp efficiency	80%
Turb efficiency	85%
$T_{comp,in}$	32℃
$P_{comp,in}$	7.6MPa
$P_{comp,out}$	20-40MPa
Thickness of wall	10mm
Yield strength	250MPa
Safety factor	1.5
Height : Diameter	4:1

For example, when the maximum pressure is set to be 30MPa, the information for performance prediction are tabulated in Table 2. The pressure changes between 30MPa and 7.6MPa for charge and discharge of CO_2. In Figs. 7 and 8, one can derive a specified vessel volume for the maximum pressure of 30MPa. By using density and volume, masses of the fully charged and discharged cases are determined. Then mass change can be calculated, which is the practically available amount of mass for charging and discharging. When this mass change is multiplied by compression and expansion works, the total work for charge and discharge process can be estimated.

Table. 2. Example of total work estimation for 30MPa

	Initial	Final
Pressure	30MPa	7.6MPa
Temperature	82.8℃	32℃
Density	733.6kg/m^3	524.4kg/m^3
Mass	2336kg	1670kg
Vessel volume	3.18m^3	
Mass change	666.1kg	
Comp work	4.14 E04 J/kg	
Turb work	2.91 E04 J/kg	
RTE	70.3%	
Total work (charge/discharge)	27.6MJ/19.3MJ	

Figs. 9-11 show the performance variation with respect to P_{max}. In Fig 6, it is shown that RTE becomes large as P_{max} increases, but it may reduce the total charging or discharging energy. In other words, although increasing P_{max} facilitates energy storage with least irreversibility, the scale of system is reduced. The discussion here is only focusing on a single pressure vessel. Thus, one can tell that multiple pressure vessels are required to apply a large scale CCES with high RTE and power density to a large nuclear power plant.

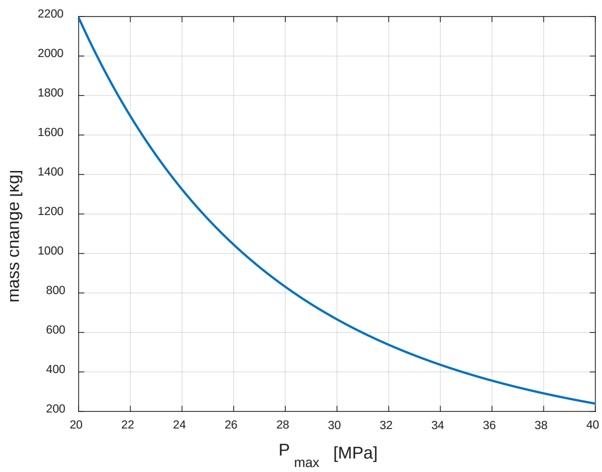

Fig. 9. Mass change variation with respect to P_{max}

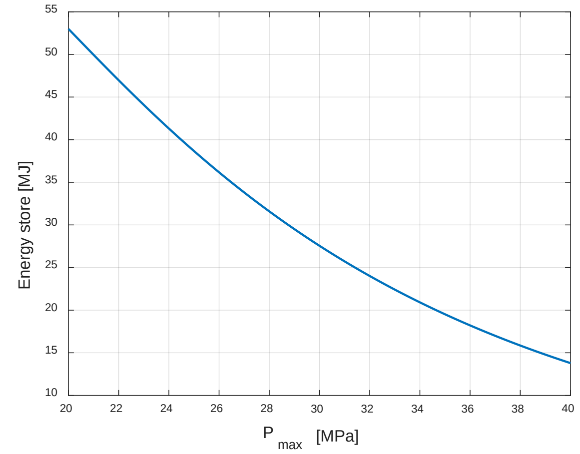

Fig. 10. Charging energy change with respect to P_{max}

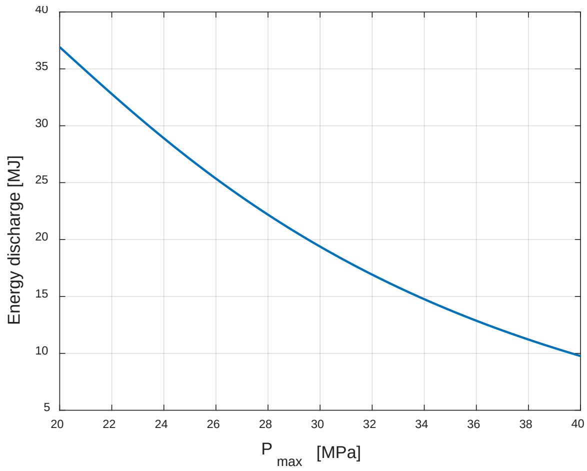

Fig. 11. Discharging energy change with respect to P_{max}

5. Summary and conclusions

In this study, characteristics of a simple CCES was investigated. Parametric study revealed that the performances of the CCES are heavily dependent on the cycle maximum pressure, which is compressor outlet pressure and the pressure inside a high pressure vessel. Especially, no optimum value for the performance was observed for the maximum pressure. However, it is not possible to apply such high pressure condition for a real pressure vessel. To set the realistic constraint, sizing of a pressure vessel was conducted, and its impact on CCES was discussed. In short, increasing the maximum pressure is good for RTE and power density, but the pressure vessel can store smaller energy. Thus, to cope with a large scale nuclear power plant, it is necessary to adopt multiple pressure vessels. After choosing a proper scale of CCES for nuclear power plant, its maximum pressure, size of a vessel and number of vessels need to be optimized in the future.

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