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Studies of S-CO_2 Power Plant Pipe Design

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1. Introduction

Further development of nuclear energy is required to address the global warming issue while overcoming the difficulty of meeting the constantly growing demand of energy. As the nuclear energy does not only reduce the carbon dioxide emission but also attain sufficient and stable electricity supply, this is considered as one of the most clean and sustainable energy sources. The Sodium-cooled Fast Reactor (SFR) is a strong candidate among the next generation nuclear reactors. However, current SFR design may face difficulty in public acceptance due to the potential hazard from sodium-water reaction (SWR) when the current conventional steam Rankine cycle is utilized as a power conversion system for SFR. In order to eliminate SWR, the Supercritical CO_2 (S-CO_2) cycle has been proposed. Although many S-CO_2 cycle concepts are being suggested by many research organizations, pipe selection criteria for S-CO_2 cycle are one of the areas that are not clearly established. As one of the most important parts of the plant design is economical fluid transfer, this paper will discuss how to select a suitable pipe for the S-CO_2 power plant compared to steam Rankine cycle.

2. S-CO_2 Power Plant Pipe Design

2.1. S-CO_2 Brayton cycle layout and properties

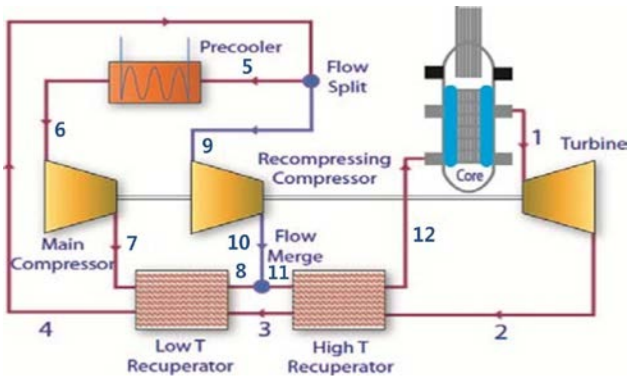

Fig. 1 S-CO_2 recompressing cycle layout

The major advantages of S-CO_2 cycle are: 1) prevention of SWR by substituting the working fluid, 2) relatively high efficiency under moderate turbine inlet temperature(450~750℃), 3) physically compact power plant size because of small turbomachinary and heat-exchangers due to high operating pressure and density.[2]

Table. 1 Design specification of the S-CO_2 recompressing cycle[1]

Net output (MW)	21.43	Cycle Thermal Efficiency (%)	47.8
Maximum pressure (MPa)	20.00	Turbine efficiency	0.94
Main Compressor efficiency	0.86	Recompressing Compressor Efficiency	0.85
CO_2 mass flow (kg/s)	200.61	Flow split ratio	0.42

The S-CO_2 recompressing cycle shown in Fig. 1 reduces the waste heat and increases the recuperated heat by recompressing some portion of the flow without heat rejection to increase the thermodynamic efficiency of the cycle.

The KAIST research team developed an in-house code to calculate the S-CO_2 recompressing cycle performance, and the fluid properties are obtained from NIST database. The design specifications of the S-CO_2 cycle system are given in Table. 1. With the in-house code developed by KAIST research team, the properties at each station are shown in Table. 2.

2.2. Determination of pipe diameter and thickness for S-CO_2 cycle

There are several factors that should be considered at the same time when determining the pipe diameter.

Table. 2 Properties at each station in 20MWe S-CO_2 recompressing cycle

Section Condition	T (℃)	P (MPa)	ρ (kg/m3)	h (kJ/kg)	s (kJ/kg-K)
①Turbine Inlet	650.00	19.40	106.91	1160.4	2.8906
②HT Recuperator HS Inlet	530.82	7.90	51.519	1021.7	2.9034
③ LT Recuperator HS Inlet	162.97	7.82	105.22	597.96	2.2026
④LT Recuperator HS Outlet	68.67	7.72	166.65	476.97	1.8901
⑤Precooler Inlet	68.51	7.72	166.88	476.71	1.8893
⑥MC Inlet	32.00	7.69	598.81	306.81	1.3483
⑦LT Recuperator CS Inlet	60.18	20.00	722.55	324.95	1.3477
⑧LT Recuperator CS Outlet	158.01	19.98	312.53	536.16	1.9102
⑨RC Inlet	68.51	7.72	166.88	476.71	1.8893
⑩RC Outlet	152.42	19.98	322.26	527.22	1.8893
⑪HT Recuperator CS Inlet	157.98	19.98	312.58	536.12	1.9100
⑫IHX Inlet	489.09	19.92	134.89	959.92	2.6469

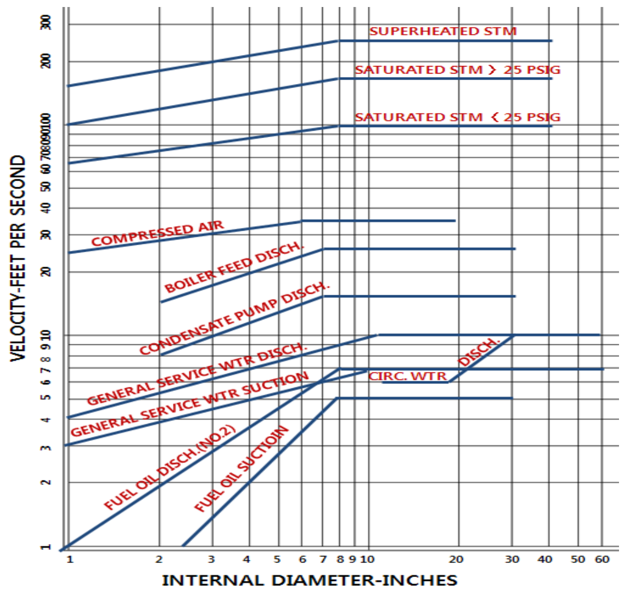

Fig. 2 The optimal flow velocity of various piping systems [4]

Typical considerations are as follows: Energy costs, Corrosion, Erosion, Noise, Vibration, System requirement (pump inlet/outlet etc.), pressure loss, and diverse project experience [3].

Determining the pipe diameter after reviewing all the above considerations requires a lot of effort and time. Therefore, to minimize this effort, most of the engineering companies establish the criteria of proper flow velocity for design guidelines. Fig. 2 shows the optimal flow velocity criterion applied to the pipe design in KEPCO E&C. Thick solid line shown in Figure 1 is the maximum recommended pipe velocity of each design application. To offer proper flow velocity to the designers for design guidelines in the preliminary design stage, KEPCO E&C uses this diagram. Although there is an optimal flow velocity for water, a similar value is not determined for S-CO_2 cycle.

Table. 3 The pipe design of 20MWe S-CO_2 cycle in MIT report

S.C.	ṁ (kg/s)	v (m/s)	D (m)	Minimum Thichness(m)	Pressure drop per 1m (kPa)
①	200.61	37.03	0.2540	0.5496	160.1
②	200.61	30.02	0.4064	0.4738	18.64
③	200.61	19.20	0.3556	0.3800	20.41
④	200.61	23.76	0.2540	0.3823	102.7
⑤	116.6	13.79	0.2540	0.2930	34.65
⑥	116.6	10.67	0.1524	0.2888	297.2
⑦	116.6	8.85	0.1524	0.4029	235.0
⑧	116.6	3.76	0.3556	0.3236	2.321
⑨	84.02	9.94	0.2540	0.2650	17.99
⑩	84.02	5.15	0.2540	0.4441	10.60
⑪	200.61	6.46	0.3556	0.4470	6.869
⑫	200.61	14.97	0.3556	0.0162	15.92
Total pressure drop (kPa)					922.4

Table. 4 The flow velocity and diameter of 20MWe S-CO_2 cycle from MIT report after applying the Ronald equation

S.C.	ṁ (kg/s)	v (m/s)	D (m)	μ (Pa-s)/10^5	Re*10^6	Minimum Thichness(m)
①	200.61	7.140	0.5785	4.0236	10.97	0.04076
②	200.61	8.888	0.7469	3.5617	9.602	0.01644
③	200.61	7.174	0.5817	2.2518	19.50	0.01556
④	200.61	6.250	0.4952	1.9689	26.20	0.02252
⑤	116.6	6.247	0.3774	1.9688	19.98	0.01776
⑥	116.6	4.258	0.2413	4.4401	13.86	0.01222
⑦	116.6	4.025	0.2259	5.9896	10.97	0.01174
⑧	116.6	5.175	0.3030	2.9384	16.68	0.01941
⑨	84.02	6.247	0.3203	1.9688	16.96	0.01545
⑩	84.02	5.128	0.2544	2.9624	14.19	0.0167
⑪	200.61	5.175	0.3974	2.9386	21.87	0.02153
⑫	200.61	6.659	0.5333	3.5685	13.42	0.02677

To define the pipe dimensions for S-CO_2 cycle, following equation was first applied and tested. The equation is an empirical formula suggested by Ronald W. Capps. [5]

$$V = f_{pv} / \rho^{0.3} \qquad (1)$$

V : optimal flow velocity [m/s]

f_{pv} : pipe velocity factor [$m(kg/m^3)^{0.3}/s$]

ρ : density of flow [kg/m^3]

In the case that the diameter of pipe is larger than 6 in, optimal velocity factor is 29. As a result of calculating the diameter of 20MWe S-CO_2 cycle pipes of MIT report shown in Table. 3, the pipe velocity of turbine inlet is 37.03 m/s, which seems very high for fluid flowing in a pipe. However, it is very straightforward to expect that after applying the equation suggested by Ronald W. Capps the diameter and the flow velocity will be very different from the initial MIT result. As shown in Table. 4, flow velocity and diameter are calculated from Eq. (1) and mass flow rate. Because the maximum diameter is suitable for ASME standard, this cycle can be designed [7].

To determinate the pipe diameter and thickness in accordance with the ASME standard, temperature and pressure should be considered. In addition, as the selection of pipe material affects the minimum thickness and cost of pipe, the overall economy of the pipe material selection has to be studied further. The procedure to comply with the ASME standard is as follows:

① After obtaining the average diameter by optimal velocity, calculate the minimum required thickness.

The equation of minimum required wall thickness is as follows [6]:

Table. 5 The optimal diameter and thickness in accordance with the ASME standard (S-CO_2)

S.C.	Nominal Pipe Size	External Diameter(m)	Internal Diameter(m)	Schedule No.	Thickness(m)
①	24	0.610	0.5307	100	0.03967
②	32	0.813	0.7780	40	0.01748
③	26	0.660	0.6250	20	0.01748
④	22	0.559	0.5113	60	0.02383
⑤	18	0.457	0.4158	60	0.02062
⑥	14	0.3556	0.3238	60	0.01588
⑦	12	0.3238	0.2920	60	0.01588
⑧	14	0.3556	0.3144	80	0.02062
⑨	14	0.3556	0.3238	60	0.01588
⑩	12	0.3238	0.2857	80	0.01905
⑪	18	0.457	0.4093	80	0.02383
⑫	24	0.610	0.5528	60	0.02858

$$t_m = \frac{PD_o}{2(SE+Py)} + A \quad (2)$$

t_m: minimum required wall thickness [m]
P: internal design pressure [Pa]
D_o: outside diameter of pipe [m]
S: maximum allowable stress [Pa]
E: weld joint efficiency
Y: coefficient
A: additional thickness [m]

② set the outside diameter and thickness in accordance with the ASME standard by selecting the proper material.

③ In the case that the flow velocity is more than the optimal velocity, select larger outside diameter pipe and check whether it is on the ASME standard.

④ re-examine the diameter and thickness of pipe after the change whether the minimum required thickness is newly defined by internal diameter.

The actual diameter and thickness in accordance with ASME standard of 20MW S-CO_2 cycle pipes are shown in Table. 5.

Table. 6 The optimal diameter and thickness in accordance with the ASME standard (Water)

S.C.	Nominal Pipe Size	External Diameter(m)	Internal Diameter(m)	Schedule No.	Thickness(m)
①	24	0.610	0.5338	80	0.03810
②	30	0.762	0.7270	30	0.01748
③	18	0.457	0.4316	30	0.01270
④	18	0.457	0.4158	60	0.02062
⑤	14	0.3556	0.3238	60	0.01588
⑥	12	0.3238	0.2920	60	0.01588
⑦	12	0.3238	0.2920	60	0.01588
⑧	14	0.3556	0.3144	80	0.02062
⑨	12	0.3238	0.2920	60	0.01588
⑩	12	0.3238	0.2857	80	0.01905
⑪	18	0.457	0.4093	80	0.02383
⑫	20	0.508	0.4603	60	0.02383

All the additional thicknesses of pipes are 2.5mm for the safety. The used materials are high nickel Alloys and carbon steel and all the figures of S, E, y are found in the ASME B31.1 and B36.10M [7].

2.3 Comparison between S-CO_2 and water pipe for pressure drop

If the same mass flow rate, temperature and pressure of S-CO_2 cycle are assumed for a water-cooled system pipe, the result is shown in Table 6. The optimal velocity factor of water and superheated steam are 14 and 68, respectively. Pressure drop in each path is calculated by using the next expression

$$\Delta p = f \cdot \frac{L}{D} \cdot \frac{\rho V^2}{2} \quad (3)$$

where Δp is pressure drop[Pa], f is friction factor, L is length of pipe [m], D is internal diameter of pipe [m], ρ is density of flow [kg/m^3], and V is optimal flow velocity [m/s].

Friction factor is calculated by a Colebrook equation which is a function of Reynolds number and surface roughness.

$$\frac{1}{\sqrt{f}} = -1.8 log[(\frac{\varepsilon / D}{3.7})^{1.11} + \frac{6.9}{Re}] \quad (4)$$

where ε is roughness, and Re is Reynolds number of pipe. Also, it was assumed that there are two 90° bends in ⑦ section, one 45° bend in the ⑧ section and one 90° bend in the ⑪ section. So the minor losses should be considered. Minor losses in each path is calculated using the expression

$$\Delta p = K_L \cdot \frac{L}{D} \cdot \frac{\rho V^2}{2} \quad (5)$$

Where K_L is loss coefficient. As each of the K_L figures is 0.3(90°) and 0.2(45°) [8], the total pressure drop of the S-CO_2 cycle is 25.11kPa. The total pressure drop compared to the overall system pressure is 0.126% unlike the MIT report result which showed 4.612%. The under-estimated diameter and over-estimated velocity from MIT report result in higher pressure drop in the system.

The comparison of pressure drop between S-CO_2 and water is shown in Table 7. As shown in Table 7, S-CO_2 pressure drop per unit length is smaller than water in ①, ②, ③, ⑥ and ⑫ sections. If these pipes were designed longer and the others were designed more compact as much as possible, the S-CO_2 piping cost can be cheaper.

Table. 7 Comparison of pressure drop between S-CO_2 and water

Section Condition	Pressure drop per unit length (kPa)		Pressure drop in the cycle (kPa)		
	S-CO2	Water	Pipe length (m)	S-CO2	Water
①	*1.8458*	*3.8799*	1.00	1.8458	3.8799
②	*0.4147*	*1.4041*	0.36	0.1493	0.5055
③	*0.7203*	*0.7375*	1.93	1.3903	1.4234
④	1.4728	0.8535	1.84	2.6953	1.5704
⑤	1.6963	1.3058	2.74	1.1704	3.5779
⑥	*3.1452*	*3.3358*	3.33	6.8708	8.9869
⑦	3.7703	2.7474	1.17	11.5780	3.1625
⑧	4.9216	1.6712	0.56	5.7582	0.9359
⑨	3.9894	1.2804	0.69	2.2341	0.8835
⑩	5.2688	1.8346	0.80	4.3749	1.5234
⑪	2.9423	0.9992	1.37	4.0310	1.3690
⑫	*1.1505*	*6.5986*	1.00	1.1505	6.5986
Total	31.338	26.648	16.79	43.2486	34.4169

3. Conclusions

The main advantages of S-CO_2 cycle are: 1) prevention of no SWR by changing the working fluid, 2) relatively high efficiency with 450~750℃ turbine inlet temperature, 3) physically compact size.

Additional study for larger system such as 300MW class system in MIT report will be conducted. From the preliminary estimation when the S-CO_2 system becomes large than the pipe diameter may exceed the current ASME standard. This means that more innovative approach will be needed for the S-CO_2 pipe design.

To economically design the pipe of S-CO_2 recompressing cycle, optimal flow velocity for S-CO_2 that can be obtained through the process engineering should exist. Although the Ronald W. Capps equation offers an optimal flow velocity while considering safety, capital cost, operating cost and life-cycle cost, this equation is optimized for water or steam system. As S-CO_2 cycle is not commercialized yet and it is being developed actively at present, procedure for the S-CO_2 pipe design is not fully established. Thus, further study and accumulation of operating experiences are salient for the further development and realization of the S-CO_2 cycle.

ACKNOWLEDGEMENT

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