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Design of Prototype Supercritical CO_2 Superheater

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1. Introduction

A supercritical CO_2 (SCO_2) cycle has been emphasized as the next generation nuclear technologies because of its theoretical promise of efficiency, compactness, and moderator working temperature [1]. Therefore, Korea Atomic Energy Research Institute (KAERI) has constructed a SCO_2 Integral Experiment Loop and tested various types of turbomachineries to optimize and improve the power cycle [2-4]. In addition, as a part of a development and test on SCO_2 power cycle for high efficiency coal-fired power plants, KAERI has started to design and develop the SCO_2 superheater. In the present study, design considerations and performance simulations of the superheater heat exchanger were studied.

2. Design of Supercritical CO_2 Heat Exchanger

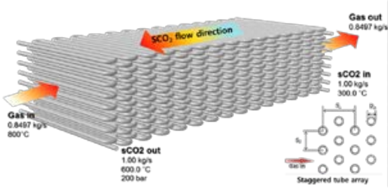
Several types of heat exchanger were considered as the superheater, such as tubular, plate fin, spiral, printed circuit, tube fin, plate, shell and plate, etc. The main consideration of the present heat exchanger is the operating condition. Table I lists the operating condition of the superheater. The operating condition indicate that the heat exchanger should endure high thermal stress, thermal shock, and structural integrity. Based on the operating conditions, the bare tube type (tubular) heat exchanger was selected as the SCO_2 heat exchanger, and design and performance simulation of the heat exchanger was conducted.

Table I: Operating condition of superheater

Mass flow rate (SCO_2)	1 kg/s
Outlet pressure (SCO_2)	200 bar
Inlet & Outlet temp. (SCO_2)	300 & 600^{o}C
Flue gas inlet temp.	800^{o}C
Outlet pressure (Flue gas)	1 bar

2.1 Heat Exchanger Specification

Fig. 1 shows the design specifications of the SCO_2 heat exchanger. S34709 (TP347H) was considered as the tube material based on the maximum allowable stress and corrosion resistance at the design pressure and temperature. In addition, commercial available tube diameter and thickness were used as the tube specification. The staggered tube array with 70 and 60 mm of the length and height pitch was considered, respectively. The tube width, height, and length were 800, 471.7, and 2086.7 mm, respectively. The estimated tube weight was 257 kg. The inlet mass flow rate and temperature of the SCO_2 were 1 kg/s and 300^{o}C, while the outlet temperature and pressure of the SCO_2 were 600^{o}C and 200 bar, respectively. The heat source of the SCO_2 was the fuel gas, which combined with liquefied petroleum gas and air. The inlet mass flow rate and temperature of the fuel gas were 0.8497 kg/s and 800^{o}C, respectively. The preliminary heat exchanger simulation was conducted using two in-house codes and the results showed that the outlet condition (600^{o}C & 200 bar) can be achieved with the present operating condition. Based on the design specification, a three-dimensional computational fluid dynamics (CFD) analysis was conducted to obtain local heat transfer coefficient and the temperature distributions for the thermal stress simulation.



Tube type	S34709
Tube	Φ 21.7 x 4.9t
Length pitch (S_L)	70 mm
Height pitch (S_T)	60 mm
Tube Width	800 mm
Tube Height	471.7 mm
Tube Length	2086.7 mm
Tube volume	1.042 m^3
Tube weight	257 kg

Fig. 1. Design specification of the SCO_2 heat exchanger.

2.2 CFD Analysis Condition

Table II lists the CFD analysis condition for the SCO_2 heat exchanger. Three domains were applied: flue gas, tube, and SCO_2. The properties of the flue gas, tube, and SCO_2 were obtained from the NIST Refprop and ASME Section II. Fig. 2 shows a 3D geometry and mesh distributions on the domain. To show the effect of staggered tube array, the half of the tube structure was considered at the top and bottom of the analysis structure. The total nodes and elements used in the CFD analysis were 9,555,606 and 10,698,900, respectively. The inlet mass flow rate and temperature for a single SCO_2 heat exchanger tube were 0.0625 kg/s and 300 ^{o}C, respectively. On the other hand, the inlet mass flow rate and temperature of the fuel gas were 0.1062 kg/s and 800^{o}C, respectively. For the fuel gas, radiation effect was considered and absorption coefficient was the parameter to control the outlet condition of the SCO_2. RNG k-ε turbulence model and smooth wall condition were used in the CFD analysis.

Table II: CFD analysis conditions

Mesh statistics			
Node #	9,555,606	Element #	10,698,900
SCO_2 condition (for a single tube)			
Inlet flow	0.0625 kg/s	Inlet temp.	300 °C
Outlet P	200 bar		
Flue gas condition			
Inlet flow	0.1062 kg/s	Inlet temp.	800 °C
Outlet P	1 bar		
Turbulence	RNG k-ε	Wall effect	Smooth

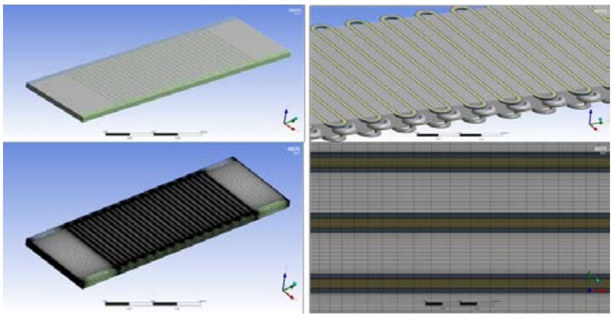
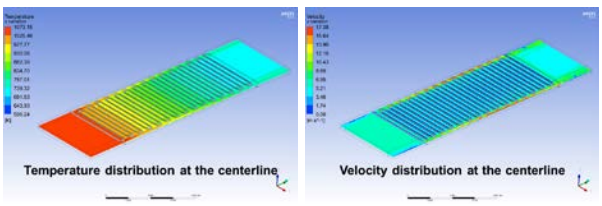


Fig. 2. 3D geometry and mesh distributions for the CFD analysis.

3. Results and Discussion

Two simulation cases were considered in the present study: (1) without radiation effect and (2) with radiation effect. The radiation effect was only applied to the flue gas. Fig. 3 shows simulation results of the superheater heat exchanger when the radiation effect was considered. When the radiation effect was not implemented, the outlet temperature of SCO_2 was calculated as 510°C. On the other hand, the outlet temperature of SCO_2 was 602°C, when the radiation effect was considered (absorption coefficient = 3.6/m). The absorption coefficient value was assumed to be a variable parameter in the CFD analysis. The pressure drop of the SCO_2 was similar for 2 cases. The outlet temperature of the fuel gas for 2 cases was 454 and 558 °C, respectively. Table III lists a summary of the CFD analysis results. By comparing with the in-house heat exchanger codes, the CFD results indicate that the radiation effect is a major parameter influencing on the outlet condition of the SCO_2.



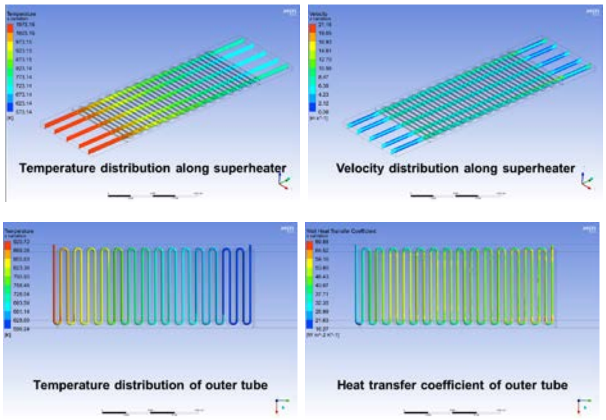


Fig. 3. CFD results (case 2: radiation effect).

Table III: CFD analysis results

	Results (w/ radiation)	Results (w/o radiation)
SCO_2 T_{out}	602 °C	510 °C
SCO_2 ΔP	0.374 bar	0.374 bar
Flue gas T_{out}	454 °C	558 °C

For the radiation effect, sensitivity study was performed by changing the absorption coefficient. In the commercial CFD code, the absorption coefficient has a unit of 1/length. The absorption coefficient is the change in radiation intensity per unit length in the selected domain. The default value of the absorption coefficient in the commercial CFD code is 1/m. However, the default absorption coefficient value did not reflect the real value of the flue gas used in the CFD analysis. Fig. 4 shows the trend of the SCO_2 outlet temperature according to the absorption coefficient. The sensitivity study indicated that the radiation effect is the main phenomenon influencing on the prediction of the SCO_2 outlet temperature. In addition, various turbulent models will be considered to optimize the CFD results.

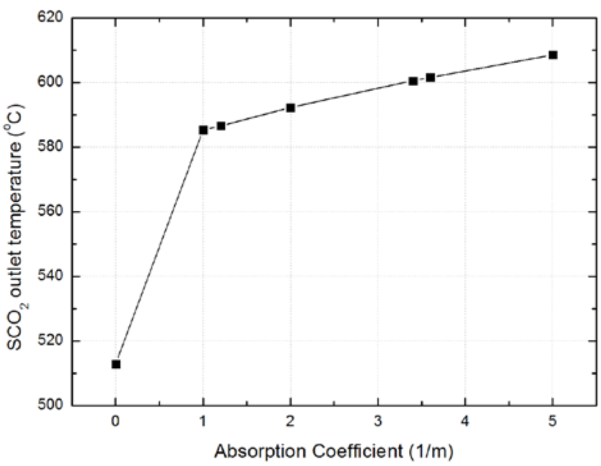


Fig. 4. SCO_2 outlet temperature according to absorption coefficient.

Fig. 5 shows an overall sectional view of the SCO_2 superheater. The total length including the combustor and the chamber (heat exchanger area) is 5,132 mm. Based on the preliminary design of the SCO_2 superheater, the manufacturing process will be performed. The possibility of manufacturing process was secured by the tube supply, the structural safety analysis of the tube bending process according to the ASME Sec. III (Minimum thickness for pipe bends for induction and incrementing bending), the thermal stress simulation at high temperature regions, etc. Additional design should be performed such as the design of tube support, header design for the uniform SCO_2 inlet mass flow rate into the heat exchanger tubes, thermal stress analysis at the welding regions, etc.

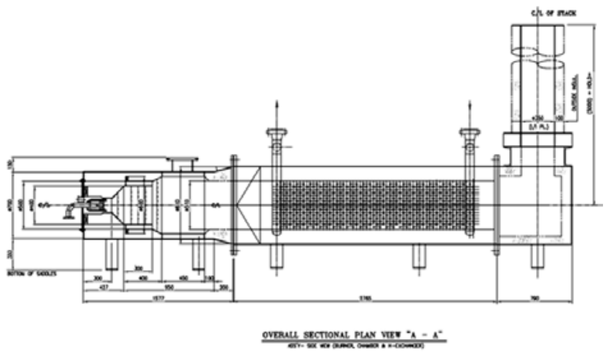


Fig. 5. Preliminary design of the SCO_2 superheater (overall sectional view).

4. Conclusions

Preliminary design and performance simulation of the superheater heat exchanger was studied. The tube specification was selected based on the maximum allowable stress and the corrosion resistance at the design pressure and temperature as well as the commercial available tube diameter and thickness. The superheater performance test was conducted using the in-house code and the commercial available CFD code. The results indicate that the radiation effect should be considered to provide the exact SCO_2 exit temperature. Further study will be conducted by considering the radiation effect on both the flue gas and the SCO_2. The detail design process will be performed to manufacture the superheater. The manufacturing process of the superheater will start next year.

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