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Design of Prototype Supercritical CO_2 Superheater Heat Exchanger

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ABSTRACT

Based on the present design and the simulation results of the superheater heat exchanger, the manufacturing process will be conducted.

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. Korea Atomic Energy Research Institute (KAERI) has constructed a SCO_2 Integral Experiment Loop for optimization of the SCO_2 cycle with using various types of turbomachineries [1-8]. In addition, as a part of a development SCO_2 power cycle connected with thermal power plants, KAERI has started to design the SCO_2 superheater heat exchanger for obtaining high-temperature and high-pressure heat exchange core technology. Therefore, the present study covers the design criteria of the prototype SCO_2 superheater, heat exchanger type selection, material selection, and performance simulations of the prototype SCO_2

Table 1 shows operation condition of superheater heat exchanger. The heat source of the superheater is liquefied petroleum gas (LPG) and air, which is similar to the exhausted gas from thermal power plants. The basic configuration of the superheater heat exchanger duct is a rectangular shape fed by a blower with LPG. The design of the superheater heat exchanger was performed based on the available tube specification.

Table 1. 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 bar
Flue gas inlet temp	800^oC
Outlet pressure (flue gas)	1 bar

DESIGN CONSIDERATIONS OF SUPERHEATER HEAT EXCHANGER

- Heat Exchanger Type Selection

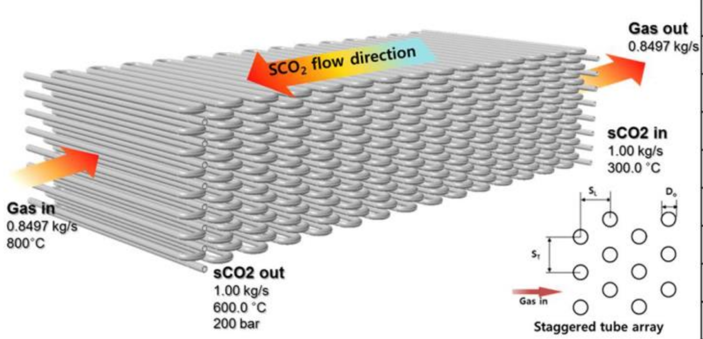
Heat exchanger type can be classified by shape and flow arrangement. Main considerations for the superheater heat exchanger are enduring high thermal stress, thermal shock, and integrity. Tubular type and printed circuit type heat exchangers are suitable for high-temperature and high-pressure condition. The maintenance and inspection of the printed circuit type is difficult because the heat exchanger was manufactured by diffusion bonding process. Therefore, tubular (bare) type was finally considered as the superheater heat exchanger. Hoopes and Rimpel [9] also used a staggered serpentine tube bundle and natural gas fired air heater for providing the required turbine inlet condition.

- Material Selection of Superheater Heat Exchanger

Material selection for the heat exchanger is based on a combination of cost, properties, fabricability, and availability. Because the operating condition of superheater heat exchanger is under high-temperature and high-pressure, material selection is important to endure the environment. Various materials were considered as candidates for the superheater heat exchanger. The major consideration was the maximum allowable stress according to temperature. The maximum heat exchanger tube temperature was assumed as 650°C: the maximum allowable stress value of the material should higher than 44.1 MPa. Based on the available experimental data, experience at similar operating condition, cost, and availability, S34709 was selected as the superheater heat exchanger material. However, the material consideration was based on the straight bare tube, additional analysis of the material integrity should be performed by considering weld spot point and tube thickness decrement due to the tube bending effect.

DESIGN OF SUPERHEATER HEAT EXCHANGER

Figure 1 shows a design specification of the SCO_2 heat exchanger. The commercial available tube diameter and thickness of S34709 material were 21.7 mm and 4.9 mm, respectively. Staggered tube array with counter-crossflow arrangement was considered. The length and height pitch were 35 mm length pitch and 60 mm height, respectively. The selection criteria of the length pitch was the minimum thickness for pipe bends for induction and incrementing bending (ASME Sec. III). The preliminary performance simulation of heat exchanger was conducted using two in-house codes and the results showed that the outlet SCO_2 condition can be achieved with the present operating condition.



Tube type	S34709
Tube	Φ 21.7 x 4.9t
Length pitch (S_L)	35 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

Figure 1. Design of prototype superheater heat exchanger

Figure 2 shows a schematic diagram of the superheater including heat source system and heat exchanger and a preliminary design of heat exchanger nozzle, header, and tube supporting structure. The total length of the superheater was calculated as 5132 mm. There are two inlet and outlet headers for the distribution of SCO_2 into the heat exchanger tubes. For the tube supporting structure, welding method (3 spots) was considered. Thermal stress analysis at the welding point should be performed to show the integrity of supporting structure. The results of in-house simulation code only present the outlet condition of the working fluid. This means that detailed thermal stress analysis is difficult with the in-house codes. Therefore, a three-dimensional computational fluid dynamics (CFD) analysis was conducted to obtain local heat transfer coefficients and the temperature distribution. Based on the 3D flow analysis, thermal stress simulation was conducted to show the tube integrity.

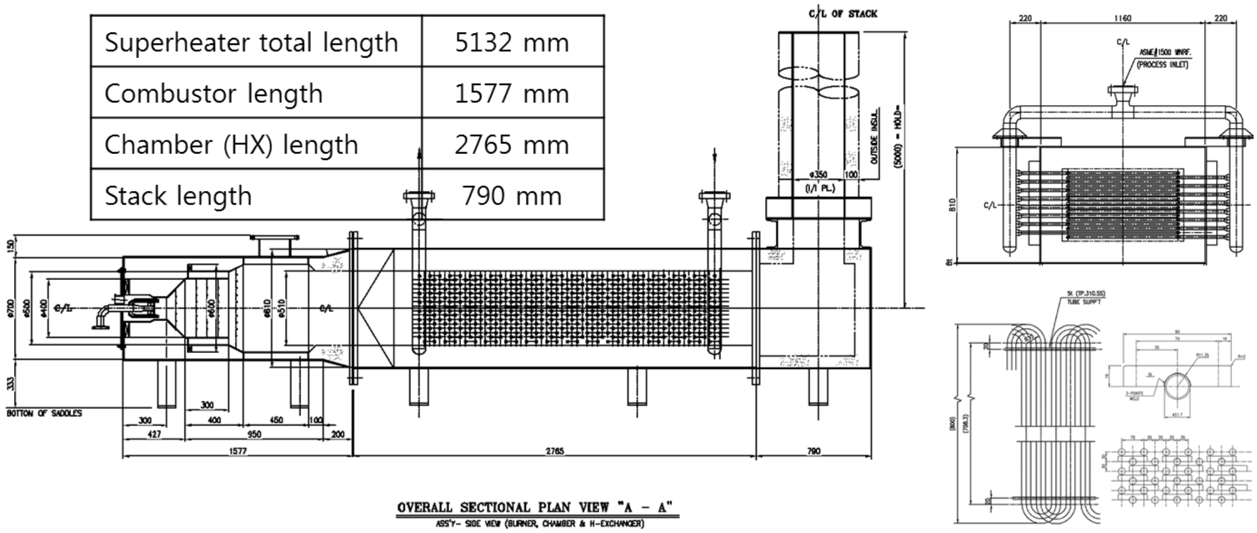


Figure 2. Schematic diagram of superheater

PERFORMANCE SIMULATIONS OF SUPERHEATER HEAT EXCHANGER

- Flow analysis

The overall simulation of the heat exchanger is difficult due to the computing power. Therefore, scaled configuration of the heat exchanger was simulated. Three domains were considered in the present simulation: flue gas, tube, and SCO_2. The properties of the flue gas and the SCO_2 were obtained from NIST REFPROP and the property of heat exchanger tube was obtained from ASME Sec. II. To reflect the staggered flow configuration, the half of the tube structure was modeled at the top and bottom of the simulation structure. The SCO_2 inlet mass flow rate and temperature for a single heat exchanger tube (center tube) were 0.0625 kg/s and 300^{o}C, respectively. On the other hand, the inlet mass flow rate and temperature of the flue gas were 0.1062 kg/s and 800^{o}C, respectively. The SST turbulence with radiation effect was considered in the present CFD analysis.

Figure 3 shows the results of temperature and velocity distributions along the heat exchange chamber. The outlet temperature of the working fluid showed similar result compared to the in-house codes. Figure 4 shows the results of temperature and heat transfer coefficients of inner and outer surfaces of heat exchange tube. Based on the temperature and heat transfer coefficients of the inner and outer surfaces of the tube, thermal stress analysis was performed.

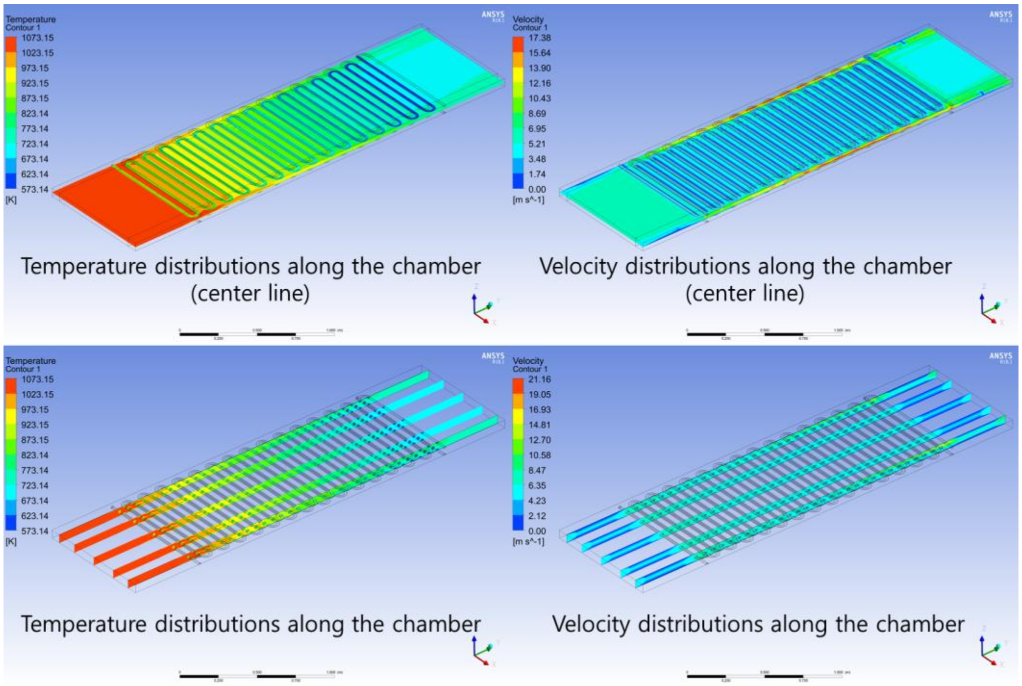


Figure 3. Temperature and velocity distributions along the chamber

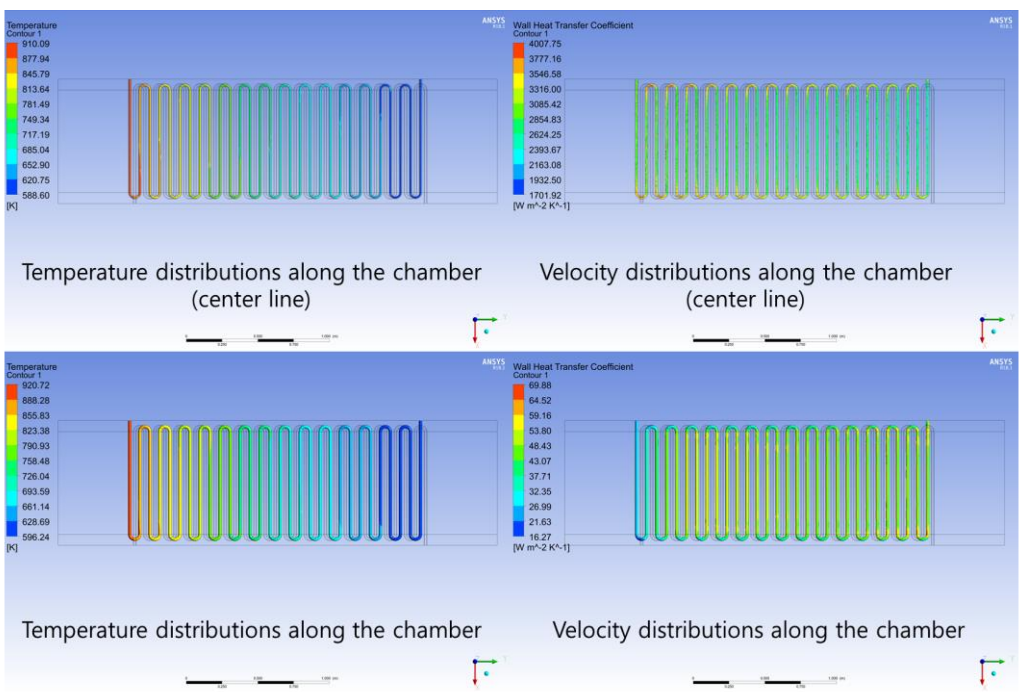


Figure 4. Temperature and velocity distributions along the chamber

- Thermal stress analysis

Thermal stress analysis of the superheater heat exchange tube was conducted with finite element method using ABAQUS. The stress analysis was performed with 3 cases: (1) heat load, (2) pressure load, and (3) heat and pressure load. 10 straight tube lines from the outlet port of the SCO_2 were modeled for the thermal stress analysis, because heat load is concentrated at the outlet of the heat exchanger tube. The maximum surface temperature was found to be 618°C, which was smaller than the value considered in the tube material selection. Based on the calculated temperature distributions of the tube, the thermal stress analysis was performed. The largest tube displacement was observed at the outlet position of the working fluid. The maximum principal strain was 0.017.

Figure 5 shows the stress analysis results. The maximum value of von-Mises stress was 52.28 MPa, 51.64 MPa, 3.55 Mpa in case of heat and pressure load, pressure load, and thermal load, respectively. This means that thermal load influenced on the tube displacement, but not the main parameter on the total stress. Based on ASME Sec. VIII, the superheater heat exchange tube satisfied the allowable stress criteria.

Membrane stress (Pm) = 28.7 MPa (Allowable stress, S = 53.9 MPa)

Membrane and bending stress (Pm + Pb) = 37.8 MPa (Allowable stress, 1.5S = 80.8 MPa)

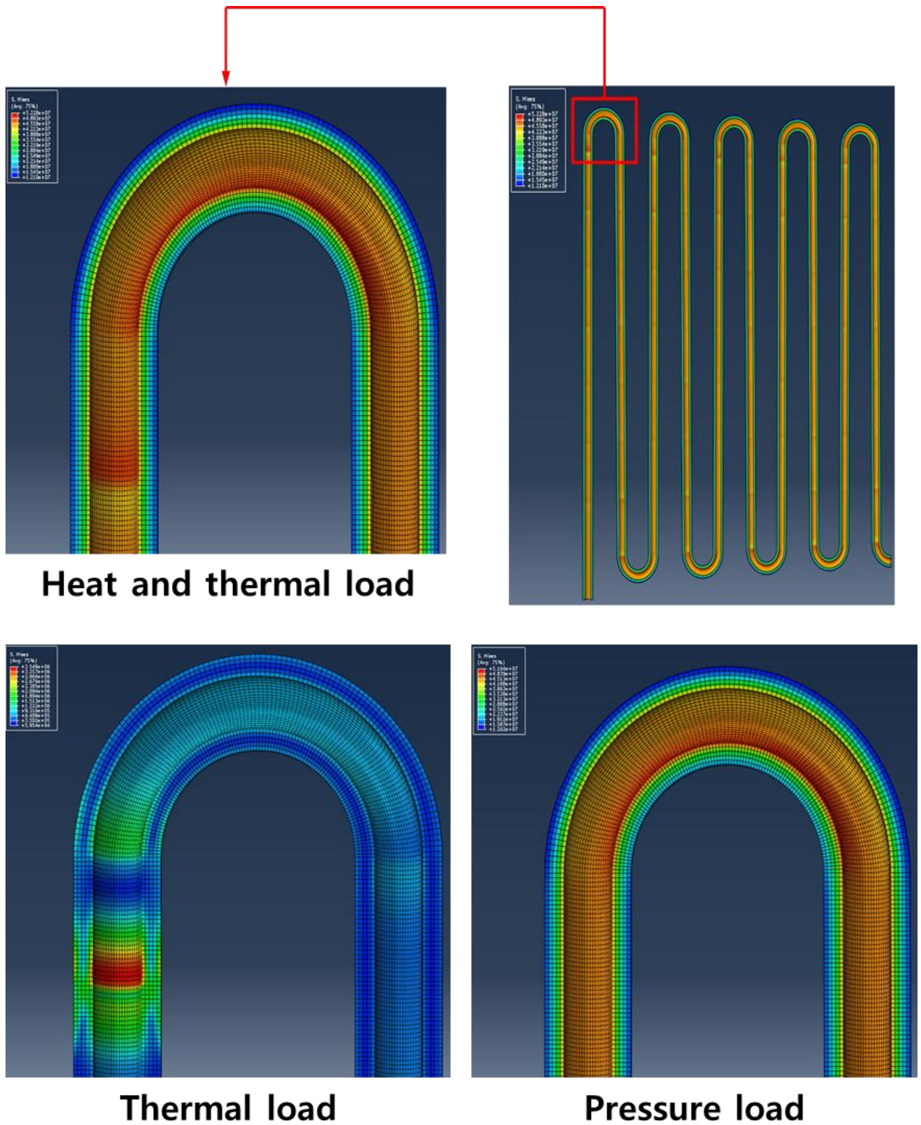


Figure 5. Maximum von-Mises stress location of the tube

CONCLUSIONS

The design of the superheater heat exchanger was conducted to secure the high-temperature and high-pressure heat exchange core technology of SCO_2. The heat exchanger performance was simulated by the in-house heat exchanger codes and the commercial available computational fluid dynamics code. The material selection of the prototype SCO_2 superheater heat exchanger was based on the maximum allowable stress and corrosion resistance. The possibility of superheater manufacturing process was verified 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), and the thermal stress simulation at high temperature regions. Detail design of the superheater heat exchanger will be performed to manufacture the heat exchanger.

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