Optimal Design of a Na-CO_2 Heat Exchanger with Segmental Baffles

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1. Introduction

A Na-CO_2 heat exchanger is one of the key equipments in the concept of coupling the supercritical CO_2 Brayton cycle to the KALIMER design[1]. The exchanger, like the steam generator in the KALIMER, provides supercritical CO_2 at the temperature, pressure, and flow rate required by the turbine during a normal power operation. The purpose of this study was develope the computer-based design method for a segmentally baffled Na-CO_2 heat exchanger. And using the method, a preliminary design of the optimized Na-CO_2 heat exchanger was completed through a parametric sensitivity study.

2. Na-CO_2 Heat Exchanger Concept

The Na-CO_2 exchanger is a counter current shell and tube type unit with a vertical orientation. The heat exchanger is to be designed to heat CO_2 by use of the IHTS(Intermediate Heat Transport System)coolant, which flows in the shell side with a mass flow rate of 638.34 kg/sec. CO_2 enters the heat exchanger through the nozzles at the bottom of the heat exchanger and then flows inside the straight tubes. The tube outer diameter is 10mm with a wall thickness of 3.0mm. In preliminary designing process, the major requirements for a Na-CO_2 heat exchanger are the pressure drop and shell-side maximum velocity. The permissible maximum pressure drop on the shell side is 0.4MPa. A maximum Na velocity of 2 m/sec is suggested to prevent an erosion and a maximum tube length of 10m is required because of a space consideration. In this calculation, the baffle spacing ranged from 20% to 100% of the shell diameter.

3. Calculation Procedure

Heat Transfer Coefficient

The heat transfer coefficient between the outer wall of the tubes and the shell side sodium is calculated by the Delware method[2]. In this method, the heat transfer coefficient for a pure cross flow is first calculated and then corrected for configuration, leakage, and bypass. In this paper, the correction factor is taken as 0.6, which is an adapted value for well designed heat exchanger. For a straight tube bundle, a Nusselt number, Nu_s, for an ideal cross flow of liquid metal is calculated from Eq.(1)[3], where d_o the is tube outer diameter, and P_t is the tube pitch. According to the Hsu's results, the term,(ϕ/d_o), of the above equation can be estimated, which is given by Eq.2

$$Nu_S = 0.958\left(\frac{\phi}{do}\right)^{0.5}\left(\frac{p-do}{p}\right)^{0.5} Pe_{v,max}^{0.5} \tag{1}$$

$$\frac{\phi}{do} = 7.46\left(\frac{do}{p}\right)^{3} - 4.95\left(\frac{do}{p}\right)^{2} + 1.58\left(\frac{do}{p}\right) + 1.92 \tag{2}$$

The shell side Reynolds number, Res, and the maximum velocity, V_{max}, is defined as Eq.(3) and Eq.(4)

$$Re_s = \frac{\rho_{Na} V_{max} D_o}{\mu_{Na}} \tag{3}$$

$$V_{max} = \frac{\dot{m}_{Na}}{\rho_{Na} A_{cs}} \tag{4}$$

A_{cs} is the shell side flow area and defined as Eq.(5) for triangular pitch.

$$A_{cs} = L_B\left[D_{si} - D_{tl} + \frac{D_{tl} - d_o}{P_t}(P_t - d_o)\right] \tag{5}$$

where Lb is the baffle spacing op in the center region and Dtl is the tube bundle diameter. Geometrical design values of the heat exchanger are chosen to be consistent with the recommendation of Taborek[4]. Dittus - Boelter's equation is used for the calculations of the heat transfer coefficient for the inner tubes of the supercritical CO_2 conditions.

$$N_u = 0.023\, Re^{0.8} Pr^{0.4} \tag{6}$$

Pressure Drop

The shell side pressure drop, ΔPs, can be calculated from Eq. (7)

$$\Delta P_s = (N_B - 1)\Delta P_c + N_B \cdot \Delta P_w + 2\Delta Pe + \Delta P_n \tag{7}$$

where ΔP_c is the pressure drop in the cross flow section, ΔP_w is the pressure drop in the window section, ΔP_e is the pressure drop in an end cross section, ΔP_n is the pressure drop in both inlet and outlet heat exchanger nozzles, and N_B is the number of segmental baffles. The ideal cross-flow pressure drop, ΔPc, and the pressure drop in the window section, ΔP_w, are defined as Eq.(8) and Eq.(9)

$$\Delta P_c = Nc\, K_f (0.5\, \rho_{Na} V_{max}^2) \tag{8}$$

$$\Delta P_w = \frac{(2 + 0.6Ncw)\dot{m}_s^2}{2\, A_{cs}\, A_w\, \rho_{Na}} \tag{9}$$

where K_f is the parameter given by the heat exchanger design handbook[5], Nc is the number of cross rows, Ncw is the number of cross-flow rows in the window zone, and Acw is window flow area.

4. Results and Discussion

One feature of a shell-and-tube type heat exchanger is to select the optimum inter-baffle spacing. In a E-type heat exchanger with a half-moon segmental baffle, the baffle spacing has a decisive effect on the heat transfer coefficient and pressure drop. The results are shown in Figures 1 and 2 with a shell side pressure drop and a Na maximum velocity versus the baffle numbers. It is easy to see that with on increasing number of baffles(decreasing baffle space), the shell side pressure drop and the Na maximum velocity increase simultaneously.

Fig.1 is a plot of shell side pressure drop versus number of baffles for each number of tubes. When the number of baffles is less than 10, the shell side pressure loss can be maintained below 0.3MPa which is within the recommended range. Figure 2 is a plot of the shell side maximum velocity versus the number of baffles for each number of tubes. The velocity rises almost linearly as the number of baffles increases. If the heat exchanger with 4000 tubes satisfies the requirement of 2.0m/sec, the number of baffles should be less than 8.

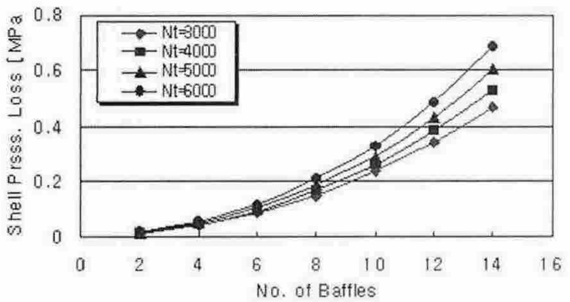

Fig. 1 Shell-side Pressure Loss Variations with respect to the Number of Baffles

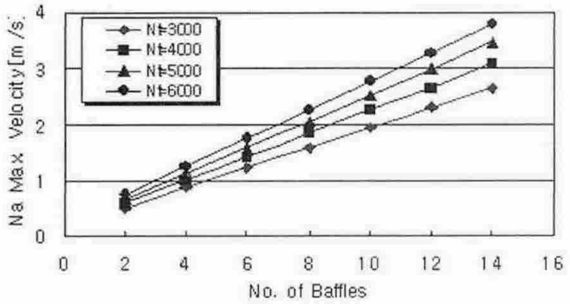

Fig. 2 Shell- side Maximum Velocity Variations with respect to the Number of Baffles

The shell diameter and tube length changes with respect to the number of tubes are shown in Figure 3. As the number of tubes increases, the shell diameter increases and the tube length decreases.

The table below summarizes the Na-CO_2 heat exchanger specification with the IHTS of KALIMER. This design meets all of the requirements as stated in section 2. As the inlet and outlet temperatures of the IHTS sodium temperature are 339 °C /511 °C in the heat exchanger of thermal capacity of 198.35 MWt, the sodium flow rate in the shell side is 901.8 kg/sec as shown in Table 3. At this condition, the sodium velocity is around 1.9 m/s and the shell side pressure loss is 0.28 MPa.

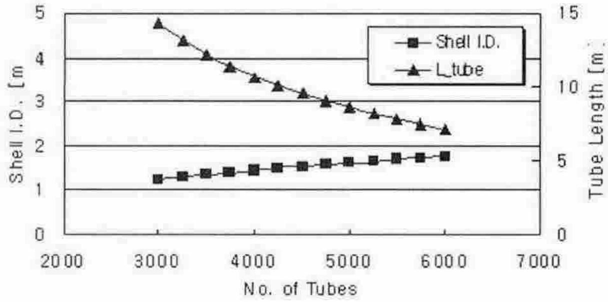

Fig. 3 Shell Diameter and Tube Length with respect to the Number of Tubes

Table 1 Design Summary of Na-CO_2 Heat Exchanger

Parameter		Parameter	Values
Thermal duty, MW	198.35	No. of tubes	4270
Na Inlet Temp. °C	511	Tube length, m	10.9
Na Outlet Temp. °C	339	HX shell I.D. m	1.49
CO_2 Inlet Temp. °C	230	Tube arrangement	Triangle
CO_2 Outlet Temp. °C	483.6	No. of baffles	8
Shell side ΔP, MPa	0.28	Baffle cut, %	25
Na max. velocity, m/s	1.9	Pitch/Tube O.D.	1.5
Baffle space/shell I.D.	0.74	Surface area m^2	1881

5. Conclusion

Through this study, an optimal design for Na-CO_2 heat exchanger with IHTS condition has been carried out. As a result, it has been found that the baffle spacing has noticeable effects on the thermal-hydraulic characteristics for Na-CO_2 heat exchanger. In the current design, the case of eight baffles is the most reasonable design to meet the requirements mentioned above.

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