Sulfuric Acid Evaporator Sizing for a Nuclear Hydrogen Production by a SI Process

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1. Introduction

Hydrogen can be an attractive energy if it can be produced cleanly and in a cost effective manner. Nuclear energy can be used as a source of a high temperature process up to 1000℃ for a hydrogen production. The sulfur-iodine (SI) cycle is a baseline candidate thermo-chemical process. It consists of the following three chemical reactions which yield a dissociation of water [1].

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad (1)$$
$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2O_2 \quad (2)$$
$$2HI \rightarrow H_2 + I_2 \quad (3)$$

The vaporization of the sulfuric acid solution is an essential part in the sulfuric acid decomposition section throughout the whole SI process [2].

In this paper, a short tube vertical evaporator is selected and its fluidic characteristics are applied to an overall heat transfer coefficient calculation. As a result of the study, the sulfuric acid evaporators for 300mol/s ($200MW_{th}$) and 60mol/s ($40MW_{th}$) hydrogen production rates are presented and discussed.

2. Sizing Procedure for Sulfuric Acid Evaporator

2.1. Evaporator Type

Fig. 1 shows the Cross-sectional diagram of the short-tube vertical evaporator. Circulation and heat transfer in this type of evaporator are strongly affected by the liquid level. It is customary to operate it with the liquid level appreciably higher than the optimum and usually appreciably above the top tube sheet. Also a circulation in the short-tube vertical evaporator is entirely dependent on a boiling, and when the boiling stops, any solid particles which are generated by equipment corrosion sediment to the bottom of the evaporator and then can be easily removed as a slurry form through a drain valve[3].

2.2. Overall Heat Transfer Coefficient Calculation

Fluidic characteristics of a process stream are applied to calculate the overall heat transfer coefficient, which are as follows [4].

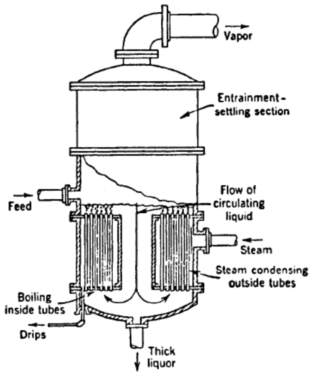

Fig. 1. Cross-sectional diagram of the short-tube vertical evaporator.

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_i(D_i/D_o)} + \frac{1}{h_w} + \frac{1}{h_s} \quad (4)$$

$$hi = \frac{0.023c_{p,i}G_i}{(c_{p,i}\mu_i/k_i)^{2/3}(D_iG_i/\mu_i)^{0.2}} \quad (5)$$

$$h_o = \frac{0.273c_{p,o}G_o}{(c_{p,o}\mu_o/k_o)^{2/3}(D_oG_o/\mu_o)^{0.365}} \quad (6)$$

$$h_w = \frac{2k_t}{(D_o - D_i)} \quad (7)$$

where,

U: Overall heat transfer coefficient [W/(m^2 K)]
h_o: Outside heat transfer coefficient [W/(m^2 K)]
h_i: Inside heat transfer coefficient [W/(m^2 K)]
D_i: Inside diameter of tube [m]
D_o: outside diameter of tube [m]
h_w: heat transfer coefficient across the tube wall [W/(m^2 K)]
h_s: fouling heat transfer coefficient [W/(m^2 K)]
G : superficial mass flow rate per unit area [kg/(s m^2)]
k: thermal conductivity [W/(m^2 K)]
c_p: heat capacity [kJ/(kg K)]

Subscripts *i* and *o* mean the inside and outside respectively and subscript *t* means the tube itself. Equations (5) and (6) are tube and shell side heat transfer coefficient equations and equation (7) is the coefficient for the tube material. 5670 W/(m^2 K) for the fouling factor(h_s) is applied from literature [4].

Thermal conductivity and viscosity are calculated by an equation for a highly pressurized gas phase [3] and heat capacity is obtained from HSC 5.1 [5]. These properties are calculated at an operating temperature and are assumed to be constant throughout the temperature range.

The thermal conductivity of tube is 16.27 J/(s m K).

Inside and outside diameter of tube is fixed at 1/2" and 5/8".

2.3. Sulfuric Acid Evaporator Sizing

Process gas condition for a sulfuric acid evaporator is represented in Table 1 based on a 300mole/s hydrogen production rate (200MW$_{th}$ VHTR 40% thermal efficiency). Heat duty is 75300kJ/s. For the condition based on 40MW$_{th}$, each of the flow rates and heat duty is multiplied by 1/5 times.

Table 1. Input/output conditions of the sulfuric acid evaporator

		H_2O	H_2SO_4	He(g)
Input (Liquid)	Mole Flow Rate [mol/s]	52.49	481.19 (90mol%)	17800
	Temperature [℃]	240		689
Output (Gas)	Mole Flow Rate [mol/s]	52.49	481.19 (90mol%)	17800
	Temperature [℃]	414		445

Then, the heat transfer area and tube length should be calculated by the following equations.

$$A = \frac{Q}{U\Delta T_{lmtd}} \quad (8)$$

$$L_t = \frac{A}{\pi n_t D_i} \quad (9)$$

where,

Q : heat duty [kJ/s]
A: heat transfer area [m^2]
ΔT_{lmtd} : log-mean temperature difference [K]
L_t : tube length [m]
n_t : tube number [ea]

Shell diameter and height are calculated by the following equation. Tubes are arranged at a triangular pitch and the tube pitch is 1.25 times that of the tube inside diameter. The gap between the tube bundle and shell is 10cm.

$$D_s = p_T \frac{n_t}{18} + D_t + 0.01 \quad (10)$$

$$H_s = 1.25 L_t \quad (11)$$

where,

D_s: shell diameter [m]
H_s: shell height [m]
p_T : tube pitch [m]

3. Conclusion

The sulfuric acid evaporator sizing was accomplished and the results are as follows;

Table 3 shows the calculation results for 200MW$_{th}$ and 40MW$_{th}$. When its scale is the 40MW$_{th}$, the superficial mass flow velocity is lowered and the overall heat transfer coefficient is also decreased. Then, the heat transfer area does not decrease linearly.

Fig. 2. represents the sizing results for the sulfuric acid evaporator for 200MW$_{th}$ and 40MW$_{th}$.

Table 3. Calculation results for the overall heat transfer coefficient, heat transfer area and tube number

H_2SO_4 Evaporator	U [kJ/(℃ m^2 s)]	Heat Transfer Area [m^2]	Tube Number [ea]
200MW$_{th}$	0.3979	752.53	7560
40MW$_{th}$	0.1665	373.10	6050

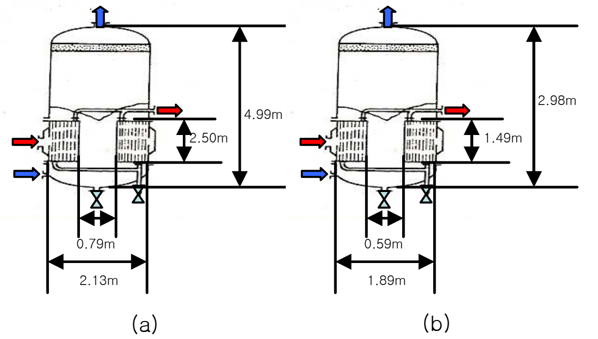

Fig. 2. Sulfuric acid evaporator sizing for (a) 200MW$_{th}$ and (b) 40MW$_{th}$.

Acknowledgments

(12)

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