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Analytical Study for Development of Cold Trap Design Technology

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1. Introduction

In a Sodium-cooled Fast Reactor (SFR), liquid sodium is subject to the formation of impurities by its high chemical reactivity with so many elements and common compounds used in nuclear reactor construction materials. The impurities are mainly in the form of hydrides, oxides, metallic compounds, metallic and carbon particles, which originate primarily from steam generator corrosion, moisture from system component surface, and leakage of air into the system. These are finally deposited in the form of the crystallization of sodium hydride (NaH) or sodium oxide (Na_2O) at the cold points of the circuit, which may lead to the clogging of the narrowed sections or may damage the pump. Therefore, it is important to research purifying performance of a cold trap.

Up to now, many studies for cold traps have been accomplished but the studies for their performance are still under execution [1~4].

2. Analysis and Results

The primary function of a cold trap is to remove oxygen from sodium, so this study has been oriented toward the behavior of oxygen. Figure 1 shows the schematic diagram of sodium purification loop. The cold trap which is chosen as the subjects to the analysis is as shown in Figure 2. It consists of an outer coolant channel, annulus and center region filled with wire mesh packing. Liquid sodium is cooled below the saturation temperature of oxygen in the cooling region. A part of supersaturated oxygen precipitates as crystals of sodium oxide (Na_2O) on the annular walls and at the bottom of the trap. Most of the rest precipitates on the surface of the mesh packing. Liquid sodium flows through mesh in the axial direction.

The analysis takes into account all aspects of the system including their structures, the shape of the mesh packing, and the precipitation and dissolution characteristics of the cold trap. Three surfaces are the inner and outer surfaces of the annular space which the sodium contacts as it moves down the cold trap and the cylindrical surface that it contacts as it moves upward out of the cold trap.

Because the impurity concentration at which precipitation occurs is a function of the cold trap surface temperature, a complete temperature calculation is required in the cold trap. The rest of the system is considered to be isothermal. The outer air-cooling channel, the incoming sodium annulus, and the outgoing mesh packing are designated, respectively, as regions a, b, and c.

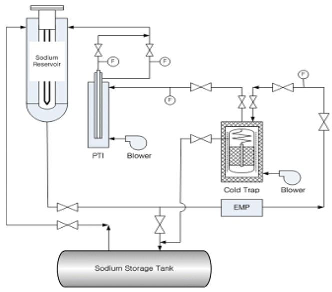

Fig. 1. Schematic diagram of sodium purification loop.

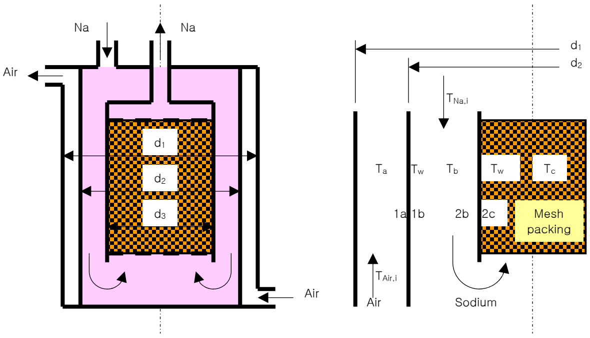

Fig. 2. Section-cut and calculation regions of the cold trap.

The law of conservation of energy in each region of a cold trap provides three differential equations, Equations (1) through (3), and Equation (3) is also the case for heat transfer throughout the economizer [2].

$$\frac{dT_a}{dx} = \frac{h_{1a} h_{1b} \pi d_1}{(h_{1a} + h_{1b})(mc_p)} (T_b - T_a) \qquad (1)$$

$$\frac{dT_b}{dx} = \frac{h_{1a} h_{1b} \pi d_1}{(h_{1a} + h_{1b})(mc_p)} (T_a - T_b) + \frac{h_{2b} h_{2c} \pi d_2}{(h_{2b} + h_{2c})(mc_p)} (T_c - T_b) \qquad (2)$$

$$\frac{dT_c}{dx} = \frac{h_{2b} h_{2c} \pi d_2}{(h_{2b} + h_{2c})(mc_p)} (T_b - T_c) \qquad (3)$$

The optimal crystallization temperature for sodium oxide is known between 110 and 130℃. Hence, the key problem is to control air outside channel of the cold trap so as to drop sodium temperature in the packing area and make it be held in the optimal crystallization temperature of 120℃. The following solution for the bulk temperature in each region, the wall temperature for the surfaces of precipitation may be calculated directly. Oxygen solubility data is expressed as following formula:

$$\text{Log } C_e\,[O_2,\text{ ppm}] = 6.250 - \frac{2444.5K}{T} \qquad (4)$$

Insertion of the sodium temperature distribution in each region into this Equation (4) produces the equilibrium oxygen impurity concentration distribution in the cold trap.

Nucleation of impurities occurs on the packing surfaces and is quickly supersede by crystal growth, ensuring sodium purification thereafter. The crystal growth is thus a major controlling step for the impurity precipitation rate and seems to be limited by the diffusion kinetics. The differential mass transfer of the impurities to and from the precipitation surface in the cold trap is of the first order [4] and can be expressed as:

$$\frac{dM}{dt} = k_a A_m (C - C_e) = W(C_{in} - C) \qquad (5)$$

where dM/dt is the rate of mass precipitation, k_a is the mass transfer coefficient, A_m is the precipitation surface area, W is the sodium flow rate, C is the bulk impurity concentration, C_{in} is the inlet impurity concentration, and C_e is the equilibrium concentration at the temperature as determined by a solubility curve for the impurity precipitating in a sodium system.

The trapping efficiency η and capacity M_t can be defined by [5]

$$\eta = \frac{C_{in} - C_{out}}{C_{in} - C_e} \qquad (6)$$

$$M_t = \int_0^{t_e} (C_{inlet} - C_{outlet})\, W dt \qquad (7)$$

Moreover, dimensionless capacity m_t, which provides the volume ratio of the precipitated sodium oxide to the mesh packing was defined.

$$m_t = \frac{M_t}{\gamma_{ox} V_M} \qquad (8)$$

Figure 3 shows the relation between dimensionless trapping capacity and initial trapping efficiency of the axial flowing type cold trap in case with the following conditions: mesh packing volume of 1.0 ㎥, inner diameter of 5.0 cm, space ratio of 0.987, wire diameter of 0.254 mm, pitch of mesh wire of 3.36 mm, sodium flow rate of 170 kg/min, and temperature of 120℃. The initial efficiency is very high but the dimensionless capacity is small. Its small capacity is due to the small entrance area to the mesh packing.

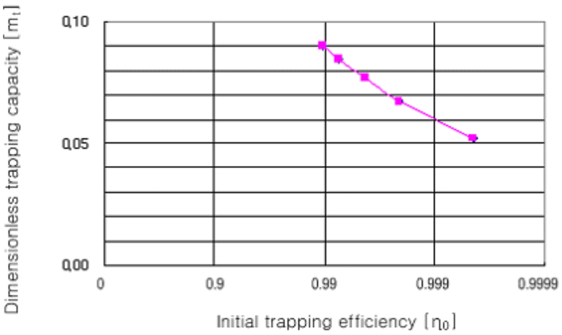

Fig. 3. Relation between dimensionless trapping capacity and initial trapping efficiency.

3. Conclusions

Analytical study has been performed to design a proper cold trap. It was observed that an increased purification performance could be achieved using a mesh packing with higher mass transfer coefficients at the given sodium stream and cooling conditions.

The initial trapping efficiency and the dimensionless trapping capacity of the cold trap were analyzed. Liquid sodium flow through in the axial direction. The performance of the cold trap is greatly affected by the ratio of the inlet area to the precipitation surface area. The dimensionless capacity increases but the initial efficiency decreases with the increase in the ratio.

This study is not enough to improve the cold traps, so further analytical and experimental studies on several mesh packing types of cold traps will be performed.

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