§7. Theoretical Expressions for Removing Tritium from Exhaust Gas

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A tritium cleanup system for application to exhaust gases discharged from a large helical device has been developed. All the hydrogen including the tritium in the system is converted from its various chemical forms into molecules of hydrogen gas before removal. The system essentially consists of five components: a hydrogen separator, a decomposition-processing vessel, a hydrogen-absorbing vessel (Ti), a circular pump, and a buffer tank. The decomposition-processing vessel fulfills a very important role in decomposing various tritiated compounds and extracting tritium in the chemical form of hydrogen molecules.

In the previous study, the system's performance was tested based on computer simulations. In the simulations, the process gas was assumed to be made up of hydrogen and methane, where part of the hydrogen and methane had been tritiated. For expressing the removal of tritium in the simulations, two fundamental Eqs. (1) and (2) were used without any proof.

$$P_{Q2}(t + \Delta t) = P_{Q2}(t) + \frac{dP_{Q2}(t)}{dt} \Delta t - 2 \frac{dP_{CQ4}(t)}{dt} \Delta t \quad (1)$$

$$P_{CQ4}(t + \Delta t) = P_{CQ4}(t) + \frac{dP_{CQ4}(t)}{dt} \Delta t \quad (2)$$

Where, $P_{Q2}(t)$: Partial pressure of hydrogen [Pa] at time t , $P_{CQ4}(t)$: Partial pressure of methane [Pa] at time t , t : Stated time [hr], and Δt : Minimal elapsed time from stated time t [hr]. In this report, it will be shown how practical forms of both the differentiations in Eqs. (1) and (2) can be derived.

(1) Differentiation: $dP_{Q2}(t)/dt$:

The speed of hydrogen separation in a given volume is given by

$$\frac{dV_{Q2}}{dt} = K S [(Pin)^{1/2} - (Pout)^{1/2}] \quad (3)$$

Where, V_{Q2} : Volume of hydrogen in standard state (273 K, 0.1013 MPa) [Nm^3], dV_{Q2}/dt : Speed of hydrogen separation [Nm^3/hr], K : Rate constant [$Nm^3/hr/Pa^{1/2}/cm^2$], S : Area of membrane for hydrogen separation [cm^2], Pin : Absolute partial pressure of hydrogen at separator inlet [Pa], and $Pout$: Absolute pressure of hydrogen at separator outlet [Pa].

The residual volume of hydrogen at stated time t is V_{Q2} when the standard state applies. Then, P_0 is the pressure of the standard state (0.1013 MPa). V_B and P_B are assumed to be the volume of the buffer tank regarded as the whole interior volume of the system and pressure when V_{Q2} has spread in the buffer tank at the stated time. Consequently, we obtain the following Eq. (4)

$$\frac{dP_B}{dt} = (P_0 / V_B) K S [(Pin)^{1/2} - (Pout)^{1/2}]. \quad (4)$$

This is the speed of hydrogen removal as a function of pressure. If we assume that the initial speed of separation is Q_0 , we obtain the following Eq. (5)

$$\frac{dP_B}{dt} = \frac{Q_0 P_0}{V_B} \left[\left(\frac{Pin}{Pin-0} \right)^{1/2} - \left(\frac{Pout}{Pin-0} \right)^{1/2} \right] \quad (5)$$

where, $Pin-0$ and $Pout-0$ are assumed to be initial partial pressures at the inlet and outlet of the separator.

Since $P_{Q2}(0)$ and $P_{Q2}(t)$ are partial pressures of hydrogen in the buffer tank for states at times 0 and t , Eq. (5) becomes

$$\frac{dP_{Q2}(t)}{dt} = - \frac{Q_0 P_0}{V_B} \left[\left(\frac{P_{Q2}(t)}{P_{Q2}(0)} \right)^{1/2} - \left(\frac{P_{Ti}}{P_{Q2}(0)} \right)^{1/2} \right] \quad (6)$$

This gives us the differential $dP_{Q2}(t)/dt$ in Eq. (1). Where P_{Ti} is about 1×10^{-4} Pa that is a practically attainable pressure in actual vacuum system using titanium as hydrogen-absorbing materials.

(2) Differentiation: $dP_{CQ4}(t)/dt$

Suppose that the gas for processing was in the buffer tank at an overall pressure of $P_T(t)$, a part of which was methane at a partial pressure of $P_{CQ4}(t)$. That is, the gas for processing had a volume of V_B at $P_T(t)$ and consisted of methane gas in V_B and at $P_{CQ4}(t)$ and other gas components in V_B at $(P_T(t) - P_{CQ4}(t))$. The three volumes of the entire gas, methane, and other gas components should be same. The only difference is pressure. Therefore, the volume processed after circulation over a time interval of dt is also equal to the volume of methane processed over the same time interval. Assuming that the gas-flow rate is represented by $F(P_T(t))$ [m^3/hr] as a function of the total gas pressure, the volumes themselves processed after circulation over a time interval of dt are $F(P_T(t))dt$ for the entire gas, methane, and the other gas components and decomposed methane is $R_d \times F(P_T(t))dt$ ($= dV$), where R_d is the rate of decomposition. As a result, methane with volume dV disappears, which leads to decrease $dP_{CQ4}(t)$ in the partial pressure of methane in the buffer tank. This change is represented by:

$$P_{CQ4}(t) \times (V_B - dV) = (P_{CQ4}(t) - dP_{CQ4}(t)) \times V_B \quad (7)$$

$$P_{CQ4}(t) \times R_d \times F(P_T(t)) dt = dP_{CQ4}(t) \times V_B \text{ and}$$

$$\frac{dP_{CQ4}(t)}{dt} = - \frac{F(P_T(t))}{V_B} \times R_d \times P_{CQ4}(t) \quad (8)$$

Equation (8) represents the decreased speed that the partial pressure of methane drops to with the decomposition of methane.

Thus, we can estimate the respective partial pressures with Eqs. (1), (2), (6), and (8), if only definite values are assigned to Q_0 , P_0 , V_B , $P_{Q2}(0)$, $P_{CH4}(0)$, P_{Ti} , $F(P_T(t))$ and R_d .