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Simulation of Tritium Behavior after Intended Tritium Release in Ventilated Room

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At the Tritium Process Laboratory (TPL) at the Japan Atomic Energy Research Institute (JAERI), Caisson Assembly for Tritium Safety study (CATS) with $12\,\mathrm{m}^3$ of large airtight vessel (Caisson) was fabricated for confirmation and enhancement of fusion reactor safety to estimate tritium behavior in the case where a tritium leak event should happen. One of the principal objectives of the present studies is the establishment of simulation method to predict the tritium behavior after the tritium leak event should happen in a ventilated room. The RNG model was found to be valid for eddy flow calculation in the $50\,\mathrm{m}^3/\mathrm{h}$ ventilated Caisson with acceptable engineering precision. The calculated initial and removal tritium concentration histories after intended tritium release were consistent with the experimental observations in the $50\,\mathrm{m}^3/\mathrm{h}$ ventilated Caisson. It is found that the flow near a wall plays an important role for the tritium transport in the ventilated room. On the other hand, tritium behavior intentionally released in the $3{,}000\,\mathrm{m}^3$ of tritium handling room was investigated experimentally under a US-Japan collaboration. The tritium concentration history calculated with the same method was consistent with the experimental observations, which proves that the present developed method can be applied to the actual scale of tritium handling room.

KEYWORDS: ***tritium, hydrogen, fusion reactor, safety analysis, safety, Caisson, detritiation, FLOW-3D, Renormalization group theory model, perfect mixing flow, simulation, tritium handling***

I. Introduction

For fusion reactors, it is essential to maintain the radioactive safety for workers and the environment when handling of a large amount of tritium. Tritium must be handled in multiple confinements that are cared by the detritiation systems. This concept has been adopted in existing tritium facilities in the world. The detritiation systems are requested to confine and remove tritium efficiently in case a tritium leak event happens. There is much data concerning the secondary confinement systems such as gloveboxes and hoods[(1)-(3)]. On the contrary, only little data is reported about the main confinement systems such as tritium handling rooms[(4)]. For the design of suitable detritiation systems and effective monitor locations in a facility for the main confinement systems, tritium diffusion rate in a ventilated room, tritium removal rate, exchange rate from tritium to tritiated water, adsorption and desorption rate of tritiated water on the wall material must be considered. Tritium diffusion experiments in less than $1\,\mathrm{m}^3$ scale airtight vessel has been carried out to acquire the data of adsorption and desorption rate of tritiated water on the wall material. Furthermore, intended tritium release experiments were carried out to acquire the tritium behavior data in the $3{,}000\,\mathrm{m}^3$ of radiological controlled tritium handling room at Tritium System Test Assembly (TSTA) at Los Alamos National Laboratory (LANL) under the US-Japan collaboration[(5)]. Behavior of tritium in a large room could be grasped by those experiments, however, this data is fragmentary. Therefore, systematic data available for the estimation of tritium behavior in the actual scale of ventilated room of fusion reactors are requested. At present with limited data, the detritiation systems and monitor locations in the facility are designed to maintain a large safety margin in conditions where tritium will be mixed quickly in the room in case a tritium leak event happens. The most suitable design of the detritiation systems is still a further subject for this reason.

At the Tritium Process Laboratory (TPL) at the Japan Atomic Energy Research Institute (JAERI), the Caisson Assembly for Tritium Safety study (CATS) with a large airtight vessel called "Caisson" was installed to acquire the systematic engineering data such as tritium behavior in a ventilated room, exchange rate between tritium and tritiated water, surface adsorption and desorption reactions of tritiated water on the wall material. Especially, it is important to estimate initial and removal tritium behavior in case of a tritium leak event in a ventilated room necessary for fusion safety. For this purpose, intended tritium release experiments in the ventilated Caisson have been carried out since December 1998[(6)]. One of the principal objectives of the present studies is the establishment of a simulation method to predict a

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tritium behavior after a tritium leak event should happen in a ventilated room. The code used in this study is the three-dimensional eddy flow analysis code based on FLOW-3D by Flow Science, Incorporated. The original code of FLOW-3D was partly revised to take a lot of tritium related phenomena into account. Exchange and conversion behaviors between tritium and tritiated water, surface adsorption and desorption reactions of tritiated water on the wall material can be considered in this code. The eddy viscosity model adopted in this study is based on the Renormalization Group Theory Model(7). The main concern to develop the code is to balance the precision of the analysis and the calculating time.

In this paper, the efficiency of turbulent flow estimation is estimated by comparing the local fluid velocity calculation values with the observations measured by hot-wire anemometers. Initial and removal tritium behaviors in the ventilated Caisson are discussed by making a comparison between calculated values and experimental observations. In order to confirm the availability whether this method can be applied to the actual scale of tritium handling room, the calculation values and experimental observations at TSTA are also compared(5).

II. Theory

Density change in a low velocity gaseous flow can be generally ignored. In this study, it is assumed that the fluid is not compressive. The basic equations to estimate the turbulent flow consist of the equations of eddy motions and the continuity equation. Velocities and pressure are unknown quantities in these equations. A temperature is kept constant during the experiment and there is no effective heat source in the experimental room. The energy transport does not need to be taken into account. It is difficult to solve the simultaneous equations of eddy motion and continuity equation directly. This reason is that the continuity equation is not a function of pressure. Instead of continuity equation, the Poisson equation of pressure is generally adopted. This equation is led by the sum of differential equations of the eddy motion and the continuity equation. The staggered plot is adopted for the arrangement of pressure and velocities. The differential method adopted is a SOLA (Numerical Solution Algorithm for Transient Fluid Flow) method(8).

When the time-dependent fluid velocity, density and pressure are ensemble-averaged, that are divided into two elements, that is, mean value and fluctuating value:

$$U_i = \overline{U_i} + u_i, \quad \rho = \bar{\rho} + \gamma, \quad P = \bar{P} + p. \tag{1}$$

The notations of parameters in each equation are summarized in the NOMENCLATURE.

The equations of motion that are the Navier-Stokes equations with some additional terms are solved explicitly to estimate temporary fluid velocity components in the three coordinate directions from the present velocities and pressure. The equations of eddy motion are expressed by ensemble-averaged Navier-Stokes equations:

$$\rho\left(\frac{\partial \overline{U_i}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{U_i U_j})\right) = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(-\nu\rho\frac{\partial \overline{U_i}}{\partial x_j} - \rho\overline{u_i u_j}\right) + \rho g_i. \tag{2}$$

This equation is characterized by the term of Reynolds stress. Reynolds stress formulates as

$$-\rho\overline{u_i u_j} = -\frac{1}{3}\rho\overline{u_k u_k}\delta_{ij} + \nu_T\rho\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right), \tag{3}$$

where ν_T is the coefficient of eddy viscosity.

The continuity equation is

$$\frac{\partial \overline{U_i}}{\partial x_i} = 0. \tag{4}$$

The temporary velocities are not satisfied with Poisson equation. The Poisson equation is solved repeatedly until pressure $\bar{P}$ and fluid velocity components $\overline{U_1}$, $\overline{U_2}$, $\overline{U_3}$, are converged. Converging method adopted is a SOR (Successive Over-Relaxation) method(9).

The diffusive equation is a basic equation to estimate tritium transport. The eddy diffusion contributes greatly to the eddy motion. The diffusive equation is written by

$$\frac{\partial \bar{L}}{\partial t} + \overline{U_j}\frac{\partial \bar{L}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D\frac{\partial \bar{L}}{\partial x_j} - \overline{u_j l}\right) + \bar{R}. \tag{5}$$

This equation is characterized by the term of mass flux tensor. The mass flux tensor can be written by

$$-\overline{u_j l} = (D_t)_{ij}\frac{\partial \bar{L}}{\partial x_i}, \tag{6}$$

where $(D_t)_{ij}$ is the turbulence mass diffusivity and this value was estimated by eddy Schmidt number in this study.

By these three steps above, the tritium behavior of new time-step is evaluated.

The coefficient of eddy viscosity and the turbulence mass diffusivity must be estimated by the experiments beforehand. However, the difficult point is that coefficient of eddy viscosity (or mixing length) depends on the flow pattern and is not constant. To settle this problem, two assistant equations called κ-ε equations are generally adopted. The turbulent kinetic energy and turbulent kinetic energy dissipation rate are defined as

$$\bar{\kappa} = \frac{\overline{u_i u_i}}{2}, \quad \bar{\varepsilon} = \nu\overline{\frac{\partial u_i}{\partial x_k} \cdot \frac{\partial u_i}{\partial x_k}}. \tag{7}$$

From the theory of Prandtl mixing length, the coefficient of eddy viscosity is the product of mixing length by the eddy typical fluid velocity. Moreover, the eddy typical fluid velocity is estimated by the square root of turbulent kinetic energy and the turbulent kinetic energy dissipation rate is estimated by the order of turbulent kinetic energy divided by characterized time in Prandtl's laminar film model. The characterized time is defined by mixing length divided by the square root of turbulent kinetic energy:

$$\nu_T = l\sqrt{\bar{\kappa}}, \quad \bar{\varepsilon} = c_\mu \bar{\kappa} \Big/ \left(\frac{l}{\sqrt{\bar{\kappa}}}\right). \tag{8}$$

The coefficient of eddy viscosity is expressed by

$$\nu_T = c_\mu \frac{\bar{\kappa}^2}{\bar{\varepsilon}}. \tag{9}$$

The turbulent kinetic energy and turbulent kinetic energy dissipation rate are needed to estimate the coefficient of eddy viscosity. In the κ-ε two equations eddy model, the transport equation of ε is estimated by the equation of motion and the continuity equation with some assumptions(10). This equation is written by

$$\frac{\partial \bar{\kappa}}{\partial t} + \overline{U_k}\frac{\partial \bar{\kappa}}{\partial x_k} = \frac{\partial}{\partial x_k}\left\{\left(\nu + \frac{\nu_T}{\sigma_\kappa}\right)\frac{\partial \bar{\kappa}}{\partial x_k}\right\} + \nu_T \bar{E}_p - \bar{\varepsilon}, \tag{10}$$

where

$$\bar{E}_p = \frac{\partial \overline{U_i}}{\partial x_k}\left(\frac{\partial \overline{U_i}}{\partial x_k} + \frac{\partial \overline{U_k}}{\partial x_i}\right). \tag{11}$$

The transport equation of ε is also estimated by the equation of motion and the continuity equation with some assumptions(11)-(16). This equation is written by

$$\frac{\partial \bar{\varepsilon}}{\partial t} + \overline{U_k}\frac{\partial \bar{\varepsilon}}{\partial x_k} = \frac{\partial}{\partial x_k}\left\{\left(\nu + \frac{\nu_T}{\sigma_\varepsilon}\right)\frac{\partial \bar{\varepsilon}}{\partial x_k}\right\} - c_\alpha \frac{\bar{\varepsilon}^2}{\bar{\kappa}} + c_\gamma \frac{\nu_T \bar{\varepsilon}}{\bar{\kappa}} \bar{E}_p. \tag{12}$$

The basic equations for the κ-ε two equations eddy model consist of six equations which are Eqs. (2), (4), (10) and (12). There are six unknown values, which are $\overline{U_1}$, $\overline{U_2}$, $\overline{U_3}$, $\bar{P}$, $\bar{\kappa}$, $\bar{\varepsilon}$, in these equations. However, five empirical constants are included in these equations. These constants must be determined by the calculation compared with the experimental observations. There are a lot of combinations of these constants reported.

The Renormalization Group Theory Model is adopted in this study. This model acts as the standard κ-ε two equations eddy model in the region of the high Reynolds number. The character of this model is that eddy Prandtl numbers; σ_κ, σ_ε, in the κ and ε transport equations equal to $1/\alpha$. The number of α is calculated by

$$\left|\frac{\alpha - 1.3929}{0.3929}\right|^{0.6321} \left|\frac{\alpha + 2.3929}{3.3929}\right|^{0.3679} = \frac{\nu}{\nu_T}. \tag{13}$$

This point is the amendment for the region of the low Reynolds number in this model. **Table 1** shows the combination of these constants adopted. These constants are typical for RNG model.

III. Experiment and Calculation

1. Tritium Intended Release Experiment in the Ventilated Caisson

Figure 1 is a geometrical 3D model of Caisson. The volume of Caisson is about 12.07 m^3 (1.990 m^W, 2.695 m^D and 2.270 m^H). The inside of Caisson is not a complete rectangular parallelepiped. It has a step on the wall called "dent section" which sizes are 1.990 m^W, 0.105 m^D and 0.500 m^H near the roof. Caisson is an airtight vessel and controlled at the negative pressure of 32.1 Pa below atmospheric pressure. The inside of Caisson is nitrogen atmosphere in these experiments. Humidity was controlled not to be detectable. The temperature is kept a constant value during these experiments. Caisson has the ventilation system called air cleanup system (ACS) with an exhaust duct to ACS and a supply duct from ACS. These ducts project at 9 cm below roof. The diameter and area of each duct are 0.0686 m and 3.697×10^{-3} m^2, respectively. The ACS was operated in circulation mode. The tritium in the exhaust flow was entirely removed in the ACS. This flow without tritium returned to Caisson through the supply duct. The ACS is applied to the flow range of 12–300 m^3/h. During each experiment, the fluid flow rate was fixed to 50 m^3/h.

Table 1 Defaults of constants in each model

	Standard κ-ε model	Renormalization group theory model
c_μ	0.09	0.085
c_α	1.44	1.42
c_γ	1.92	Function of the shear rate
σ_κ	1.0	0.72
σ_ε	1.3	0.72

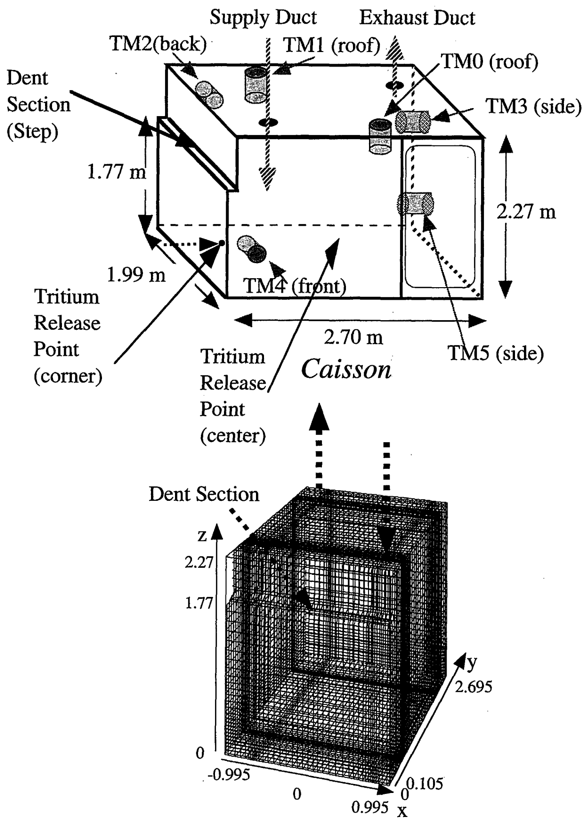

Fig. 1 Geometrical 3D model of Caisson

The fluid velocity of supply duct measured by hot-wire anemometer was 5.2 m/s at its center and 3.5 m/s at its edge. **Table 2** shows the coordinates of center point of supply and exhaust ducts.

Six stationary ion chambers called TM0–TM5 and one temporary ion chamber called TM6 were installed in Caisson for tritium concentration monitoring. About 2.42×10^8–2.79×10^8 Bq of pure tritium diluted with 1.040×10^5 Pa of nitrogen was filled in the stainless container. This container was installed in the release system. Tritium mixed with nitrogen was remotely released and purged by nitrogen for a short time to ensure the tritium was swept from the container for each release experiment. Tritium was previously diluted with nitrogen because tritium behavior is affected by buoyancy. This slight density difference was considered by Boussinesq approximation in each calculation(17). Table 2 shows the coordinates of tritium release points and monitors.

The main objectives of this calculation are as follows. (1) The efficiency of this code is discussed by comparing the local fluid velocity calculation values with experimental observations measured by a hot-wire anemometer. (2) Tritium behavior after release until all monitors became their uniform values (initial tritium behavior) and the behavior when tritium was removed by the ventilation system (removal tritium behavior) are discussed by comparing calculated values with experimental observations. Two release points (corner and center) were chosen to observe the location dependence of tritium behavior. The exchange reaction between tritium and tritiated water and surface adsorption and desorption reactions of tritiated water on the wall material were not taken into account because humidity was controlled to be very low. The geometrical model for initial tritium behavior study was divided to 38 meshes in x-direction, 43 meshes in y-direction and 31 meshes in z-direction. The geometrical model for removal tritium behavior study was divided to 10 meshes in x-direction, 13 meshes in y-direction and 11 meshes in z-direction. The imaginary meshes were not counted in these numbers. The atmospheric density is estimated as 1.157 kg/m^3. The atmospheric viscosity is 1.75×10^{-6} kg/m·s. The diffusion coefficient of tritium against nitrogen is 5.65×10^{-6} m^2/s.

Table 2 Locations of ducts, release points and tritium monitors in Caisson

	x (m)	y (m)	z (m)
Supply duct	0.7695	0.5435	2.1800
Exhaust duct	−0.6490	2.1960	2.1800
Tritium release point (corner)	0.5000	0.0000	0.3900
Tritium release point (center)	−0.0950	1.1900	0.2995
TM 0	0.7450	1.9450	2.2000
TM 1	−0.7450	1.0500	2.2000
TM 2	−0.9250	0.2900	2.0250
TM 3	−0.8000	2.6250	1.5900
TM 4	0.9250	0.2500	0.5900
TM 5	−0.8100	2.6250	0.5900
TM 6-1†1	−0.8040	2.3900	0.5280
TM 6-2†2	−0.8650	1.5700	0.4460

†1 TM 6-1 was the monitor location in the case where tritium is released from corner.

†2 TM 6-2 was the monitor location in the case where tritium is released from center.

The simulation procedure is as follows. The turbulent flow distribution in Caisson was calculated until it became steady. Tritium was set in the volume (0.018 m^W, 0.021 m^D and 0.018 m^H) that was arranged at the tritium release point. The code was restarted to calculate initial tritium behavior (~3 min after release) and removal tritium behavior (~2 h after release). Initial tritium behavior is affected by how the tritium was released into Caisson. The fluid velocity caused by purged nitrogen is one of the keys for initial tritium behavior, therefore, this value was taken into account. The validity of this code was discussed by comparing calculated values with the observed tritium concentration histories of tritium monitors.

2. Tritium Intended Release Experiment in the Ventilated TSTA Main Cell

Figure 2 is a geometrical 3D model of the main tritium handling room called "main cell" of TSTA in the LANL. The volume of main cell is about 3,000 m^3

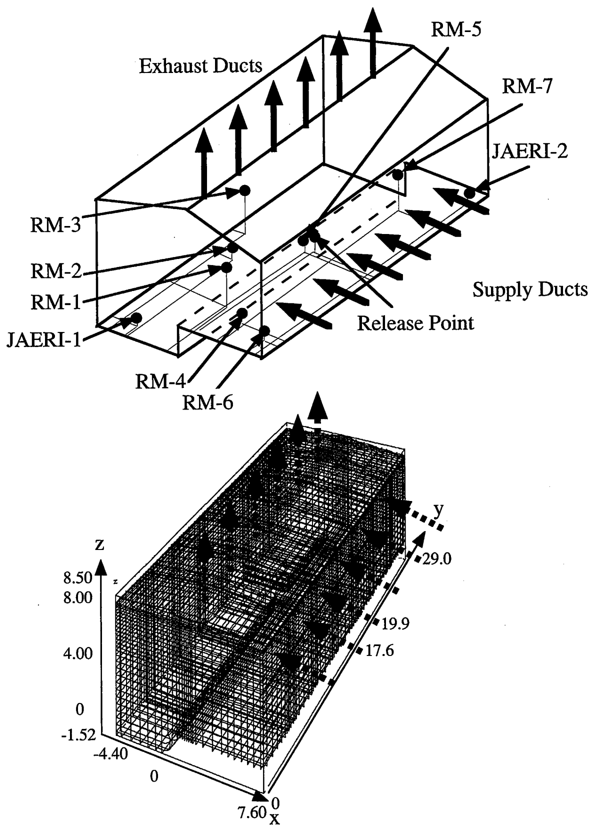

Fig. 2 Geometrical 3D model of "main cell" of TSTA

($12.00\,m^W$, $29.00\,m^D$ and $8.00\,m^H$). The vertical cross section of the main cell roof is an isosceles. The summit of the roof is 8.50 m in height. The main cell locally has pits that are 1.52 m under the ground. The tritium area was normally kept at negative pressure of 32.1 Pa below atmospheric pressure. The atmospheric pressure was 7.80×10^4 Pa when the intended tritium release experiment performed. The humidity was not detectable with humidity monitors and was estimated less than 10% relative humidity. The temperature was 295 K.

There are six supply ducts from the ventilation system and six exhaust ducts to the ventilation system in the main cell. The areas of each supply and exhaust duct are $0.248\,m^2$ ($0.406\,m^W \times 0.610\,m^H$) and $1.000\,m^2$, respectively. The flow rate of each supply and exhaust duct was $0.519\,m^3/s$ and $0.755\,m^3/s$, respectively. **Table 3** shows the coordinates of center point of each supply and exhaust duct. Supplied flow rates and exhausted flow rates were different because of some leaks through the walls. Total $1.416\,m^3/s$ of leaks into the main cell were estimated and it was almost constant because the main cell was always under negative pressure by the ventilation system. These leak locations and leak rates were checked and these were also taken into account in this calculation. Just before the intentional tritium release experiments in the TSTA main cell, the ventilation for this room was isolated by closing all exhaust and supply ventilation valves. **Table 4** shows the ventilation conditions before and after intended tritium release experiments.

Seven stationary ion chambers called RM-1–RM-7 and two temporary ion chambers called JAERI 1 and JAERI 2 were installed in the main cell for tritium concentration monitoring. The 3.70×10^{10} Bq of pure tritium was filled into the stainless container. This container was installed in the release system. Tritium was remotely released and purged by nitrogen for a short period of time to ensure the tritium was swept from the container. **Table 5** shows the coordinates of tritium release point and monitors. Initial tritium behavior was investigated for 5 h. After 5 h of tritium release, normal ventilation system was restored to investigate removal tritium behavior where tritium concentration was gradually decreased.

The main objective of this calculation is whether this method can be applied to the actual scale of tritium handling room. The exchange reaction between tritium and tritiated water and the surface adsorption and desorption reactions of tritiated water on the wall material were not taken into account because humidity was very low. The geometrical model for initial and removal tritium

Table 3 Locations of ducts in the Main Cell of TSTA

	x (m)	y (m)	z (m)
Supply duct 1	7.60	4.53	4.00
Supply duct 2	7.60	8.46	4.00
Supply duct 3	7.60	12.49	4.00
Supply duct 4	7.60	16.51	4.00
Supply duct 5	7.60	20.40	4.00
Supply duct 6	7.60	24.47	4.00
Exhaust duct 1	1.60	4.53	8.50
Exhaust duct 2	1.60	8.46	8.50
Exhaust duct 3	1.60	12.49	8.50
Exhaust duct 4	1.60	16.51	8.50
Exhaust duct 5	1.60	20.40	8.50
Exhaust duct 6	1.60	24.47	8.50

Table 5 Locations of release points and tritium monitors in the Main Cell of TSTA

	x (m)	y (m)	z (m)
Tritium release point	1.95	15.21	0.75
RM 1	−0.50	6.60	3.68
RM 2	−2.30	9.30	−0.62
RM 3	−3.90	12.30	3.48
RM 4	3.70	5.90	0.78
RM 5	1.40	14.40	0.78
RM 6	5.02	5.18	0.66
RM 7	3.90	21.40	3.08
JAERI-1	−2.40	0.50	−1.22
JAERI-2	7.10	25.00	0.28

Table 4 Ventilation conditions before and after intended tritium release experiments (TRE) started in the TSTA

	Before TRE Flow rate (m^3/s) (velocity (m/s))	After TRE started Flow rate (m^3/s) (velocity (m/s))	After ventilation restarted Flow rate (m^3/s) (velocity (m/s))
Supply duct	0.743/each duct (3.000)	0 (0)	0.519/each duct (2.096)
Exhaust duct	1.082/each duct (5.176)	0 (0)	0.755/each duct (3.612)
Leak from joint between roof and walls	1.356	0	0.944
Leak from the hole on the walls	0.678	0	0.472

behavior study was divided to 26 meshes in x-direction, 63 meshes in y-direction and 30 meshes in z-direction. The imaginary meshes were not counted in these numbers. Equipments such as gloveboxes, isotope separation system, fuel cleanup system were not taken into account in this geometrical model. The atmospheric density is estimated as $0.885\,\mathrm{kg/m^3}$ by equation of state. The Chapman and Enskog theory was adopted to estimate viscosity and diffusion coefficients. The atmospheric viscosity is $1.76\times10^{-6}\,\mathrm{kg/m\cdot s}$. The diffusion coefficient of tritium against air is $7.41\times10^{-6}\,\mathrm{m^2/s}$.

The simulation procedure is as follows. The flow distribution in the TSTA main cell was calculated until it became steady. The fluid velocity of each ventilation duct reset to zero. The 3.70×10^{10} Bq of pure tritium was set in the volume ($0.49\,\mathrm{m^W}$, $0.53\,\mathrm{m^D}$ and $0.50\,\mathrm{m^H}$), that was arranged at tritium release point. The code was restarted to calculate initial tritium behavior for 5,400 s. The fluid velocity of purge nitrogen was also taken into account. After checking all tritium concentrations became their uniform values, the code was restarted again to calculate removal tritium behavior for 1,800 s. The validity whether this code can be applied to the actual scale of tritium handling room is discussed by comparing calculated values with observed tritium concentration histories of tritium monitors.

IV. Results and Discussion

1. Fluid Velocity Measurement in the Ventilated Caisson

The consistency of calculated fluid velocities with the experimental observations is essential to estimate the initial tritium behavior and removal one. Local fluid velocity measurements were carried out in the $50\,\mathrm{m^3/h}$ ventilated Caisson. The calculated values are compared with local fluid velocities measured. The hot-wire anemometers with measurable range 0.05–6.00 m/s were used in these experiments.

Figure 3 shows the velocity distribution along z-direction just under the center of supply duct. The calculated values show a tendency to the experimental observations. As the flow spreads horizontally, the velocity of supplied air decreases gradually. To express this tendency by this code is essential for this study because this flow is a key for the whole flow in the ventilated Caisson. This code can express this important flow with acceptable engineering precision. However, there are some discrepancies between experimental observations and calculated values in the velocity distribution just below the supply duct. The main reason is the non-ideal flow supplied from air cleanup system.

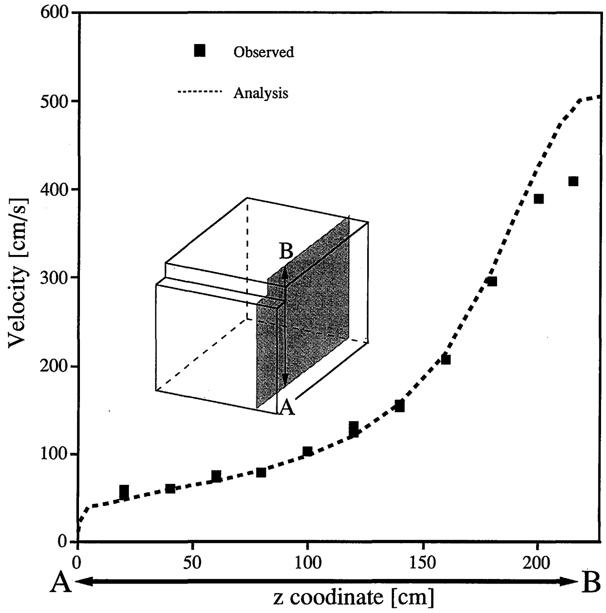

Fig. 3 Velocity distribution along z-direction just under the supply duct

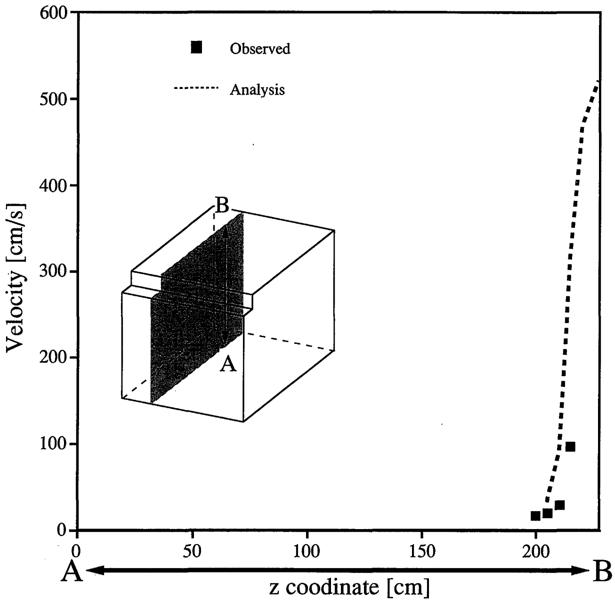

Fig. 4 Velocity distribution along z-direction just under the air exhaust duct

Figure 4 shows the velocity distribution along z-direction just under the center of exhaust duct. The calculated values show a tendency to the experimental observations with acceptable engineering precision. The flow near this duct was not vertically but horizontally exhausted.

Figure 5 shows the typical velocity distribution along y-direction. The calculated values show a tendency to the experimental observations. However, there are some discrepancies between experimental observations and calculated values in the velocity distribution especially near y=0. Many small obstacles on the wall, which are installed for our future investigation, were the reason for those discrepancies and they were not considered in the geometrical model. The tendency toward these discrepancies was applied to all velocity distribution near a wall in Caisson and it had an undesirable effect on the precision of initial tritium behavior.

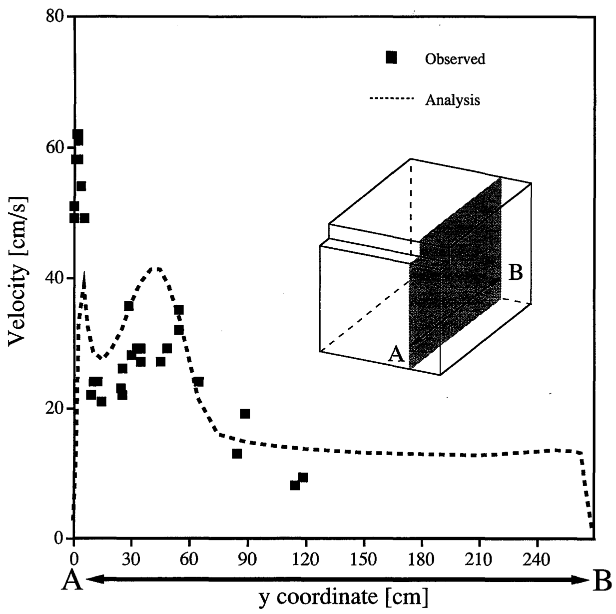

Fig. 5 Typical velocity distribution along y-direction

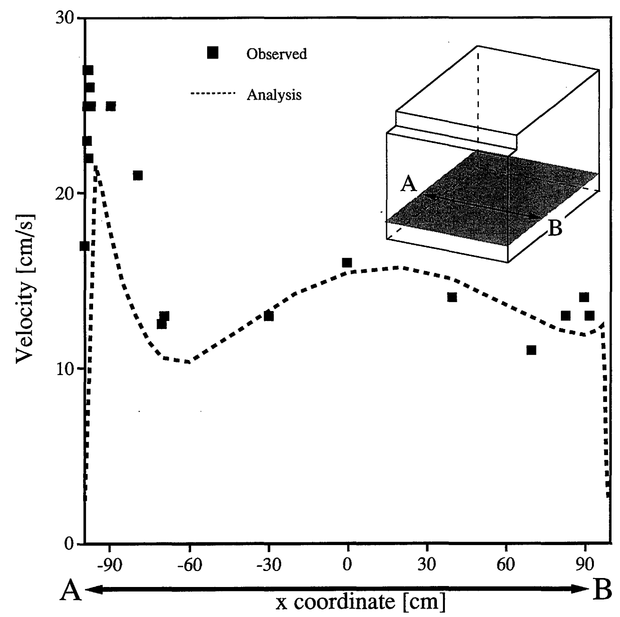

Fig. 7 Typical velocity distribution along x-direction

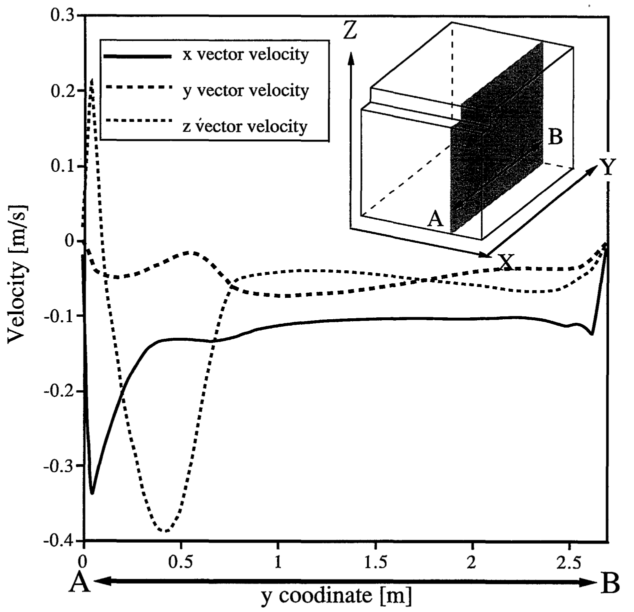

Fig. 6 Velocity components of three coordinate directions

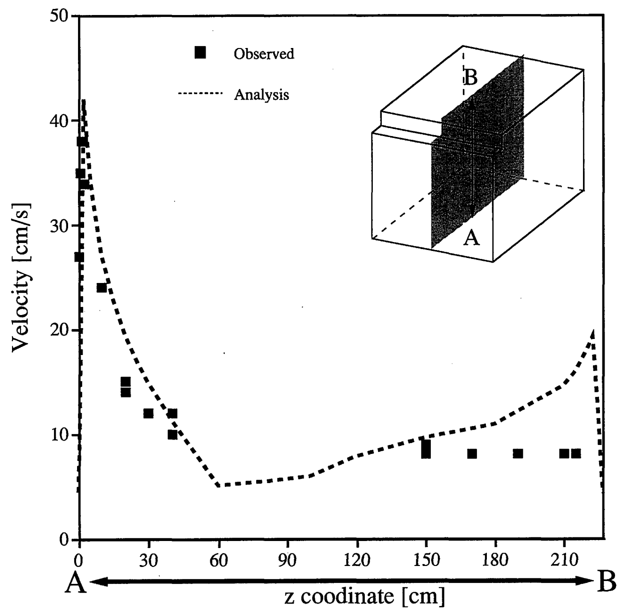

Fig. 8 Typical velocity distribution along z-direction

Figure 6 shows the velocity components of three coordinate directions. The velocity of z-direction at nearby 0.5 m of y coordinate greatly changes under the effect of supplied flow. The velocities of x- and z-directions near the wall (y=0) are particularly strong compared with those of other parts. It is worth notice that the flow near a wall plays an important role to the tritium transport in the ventilated Caisson.

Figures 7 and **8** show the typical velocity distribution along x- and z-directions, respectively. This code can express the velocity distribution in the ventilated Caisson with acceptable engineering precision. There are some discrepancies between experimental observations and calculated values in the velocity distribution near a wall in these figures. The reason is the same mentioned above.

The validity of this simulation method by RNG model was thus proved with acceptable engineering precision.

2. Tritium Intended Release Experiment in the Ventilated Caisson

(1) Initial Tritium Behavior

Figure 9 shows the calculated initial tritium behavior with experimental observations. The atmospheric

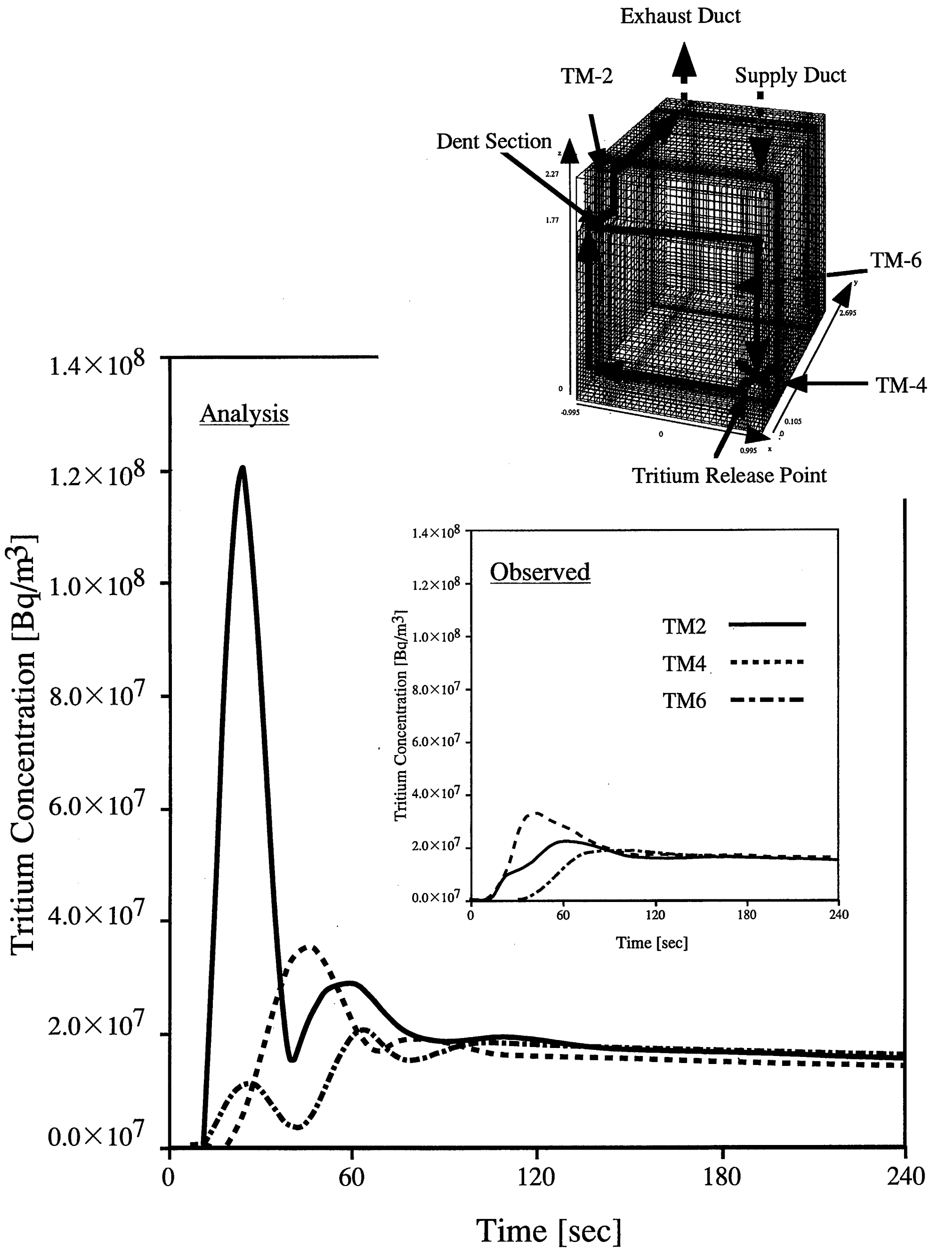

Fig. 9 Initial tritium behavior in ventilated Caisson (Release point: Corner)

pressure is 1.020×10^5 Pa. The typical temperature was 296.1 K during this experiment. The 2.79×10^9 Bq of pure tritium diluted with 1.040×10^5 Pa of nitrogen was released from the corner. In the tritium behavior study by CATS, it is pointed that release behavior from the sample container to the ventilated room is a key for the initial tritium behavior. This effects strongly in the case where tritium is released near a wall because tritium is quickly carried in the strong flow near the wall. The releasing behavior from the release point was estimated by the residence time distribution (RTD) function(18)(19). From the relative correspondence between the calculated estimation and experiment, as shown in Fig. 9, tritium behavior after the intended tritium release can be explained as below. Tritium was carried quickly along the flow and reached to the "dent section" of Caisson. The flow with released tritium was divided into two flows; the flow to the exhaust duct and the flow to the supply duct. The concentration change of TM-2 was mainly caused by the tritium in the flow to the exhaust duct. Most of tritium in this flow was discharged from the exhaust duct. On the other hand, the flow to the supply duct was merged with the strong vertical flow of the supply duct. Tritium reached to the floor was spread on all sides. This caused the concentration change of TM-4. The flow along the floor carried tritium quickly. The concentration change of TM-6 thus resulted.

The time until all monitors became their uniform values was almost the same (~120 s). The calculated stable concentrations (2.0×10^7 Bq/m^3) are also in good agreement with experimental observations. There was a large discrepancy between experimental observation and calculated result concerning the detail concentration behavior of TM-2 near 30 s. One of the reasons is that the complicated flow distribution near TM-2 estimated by this code is slightly different from the actual distribution. This difference is mainly due to obstacles on the wall. The group of released gas was carried out along the complex flow near the wall. Therefore, the slight difference of track of its group near TM-2 between the calculated result and the actual behavior made such a large discrepancy of ionization chamber counting. The waving of the calculated results expressed the actual phenomenon of tritium transport in the ventilated Caisson, however the first waving near 30 s was disappeared in the experimental observations by this reason.

Figure 10 shows the calculated initial tritium behavior and experimental observations, respectively. The atmospheric pressure is 9.940×10^5 Pa. The typical temperature was 295.4 K during this experiment. The 2.42×10^9 Bq of pure tritium diluted with 1.040×10^5 Pa of nitrogen was released from the center. The releasing behavior was also estimated by RTD function. From the comparison of Fig. 10, the following facts were supposed; Tritium was horizontally carried into the direction of the supplied flow from supply duct. Then it reached to the floor with the supplied flow and spread on all sides. This caused the concentration change of TM-4. Tritium was partly carried in the strong flow near the wall to the corner release point mentioned above. The subsequent behavior was the same as explained above.

The important result is that the flow near a wall plays an important role for the tritium transport in a ventilated room. It is worth notice that the initial tritium behavior strongly depends on how the tritium should be released to the ventilated room. For the prediction of initial tritium behavior, it is one of the key subjects to estimate the actual releasing distribution in some assumable cases where a tritium leak accident should happen.

(2) Removal Tritium Behavior

Figure 11 shows the calculated removal tritium behavior and experimental observations, respectively. Calculated values more than $1.48\times10^6\ \mathrm{Bq/m^3}$ of tritium concentration were consistent well with the experimental observations. Tritium concentrations decrease logarithmically to the time. However, experimental removal

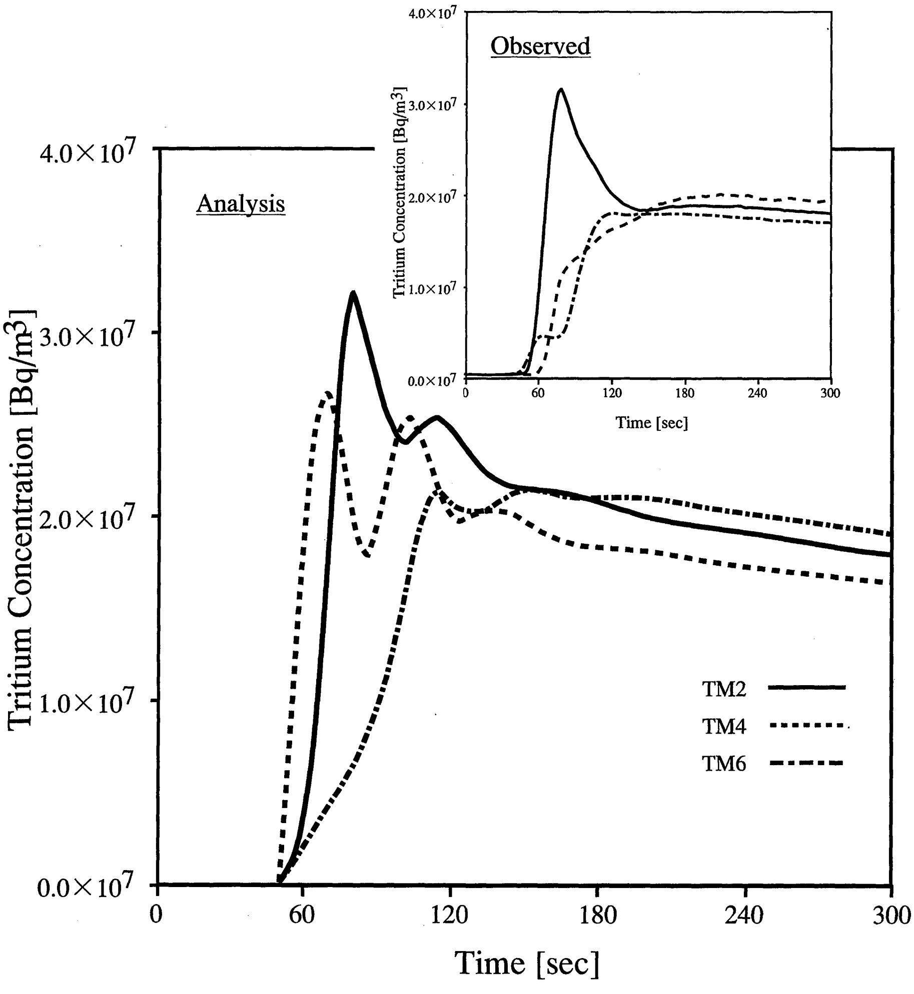

Fig. 10 Initial tritium behavior in ventilated Caisson (Release point: Center)

tritium behavior less than 1.48×10^6 Bq/m^3 of tritium concentration are different from the calculated estimation. This discrepancy can be explained by the memory effect of tritium monitor. This effect is called "tritium soaking effect". This effect is caused by adsorption of tritiated species (mainly tritiated water) on the surface of tritium monitor. The amount of adsorbed tritiated water is many functions of the humidity in atmosphere, the amount of released tritiated vapor, the flow rate of ventilation system, the reaction rates of surface adsorption and desorption of tritiated water, *etc.*

The mixing characteristic strongly affects to the removal behavior. The continuous stirring tank reactors model is adopted to estimate the imperfect mixing characteristic in the Caisson. Tritium soaking effect is not taken into account in this model. **Figure 12** shows this analytical model. It is supposed that the Caisson is regarded as the "closed vessel". The vessel volume is imaginarily divided into some of the perfect mixing vessels with the same volume. The local tritium mass balance of the No. i vessel is written by

$$\frac{V}{N}\cdot\frac{dC_i}{dt}=vC_{i-1}-vC_i, \tag{14}$$

where V is the total volume, N the vessel numbers, C_i the tritium outlet concentration, t the time and v the flow rate. The boundary conditions are that tritium in the flow from air cleanup system (C_0) is 0 and the tritium concentrations in Caisson (C_1–C_N) are about 1.85×10^7 Bq/m^3 at t=0. The vessel numbers give an index of the mixing characteristic. In this model, N=1 corresponds to the perfect mixing and N=∞ corresponds to the plug flow. **Figure 13** shows the calculated removal

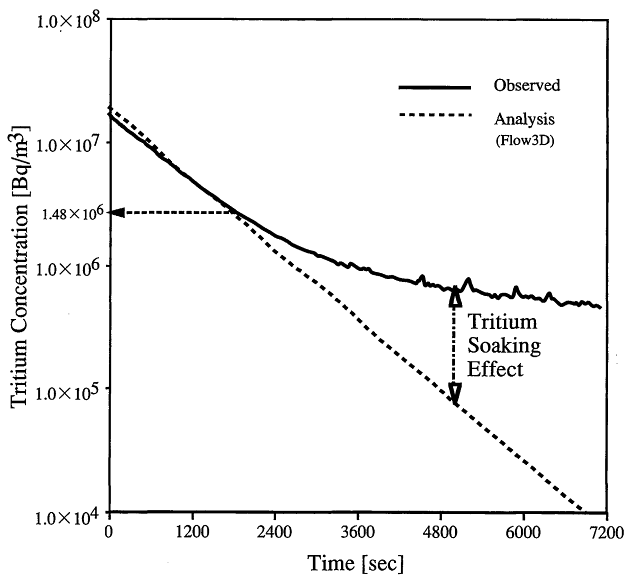

Fig. 11 Removal tritium behavior (TM-1) in ventilated Caisson

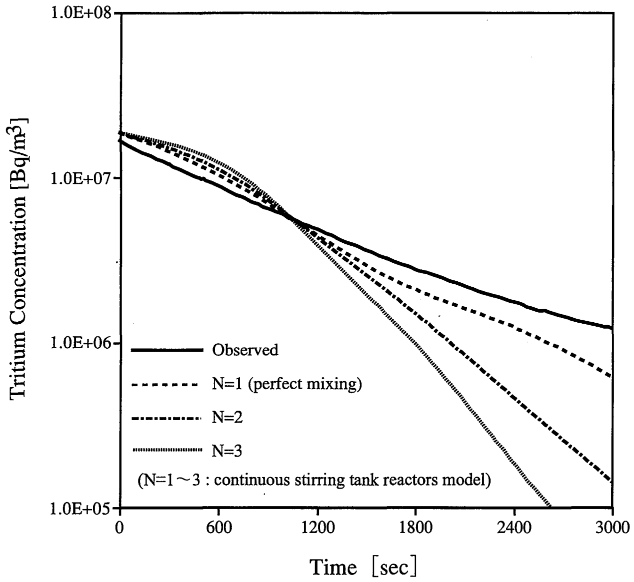

Fig. 13 Calculated removal tritium behavior (TM-1) in ventilated Caisson by continuous stirring tank reactors model

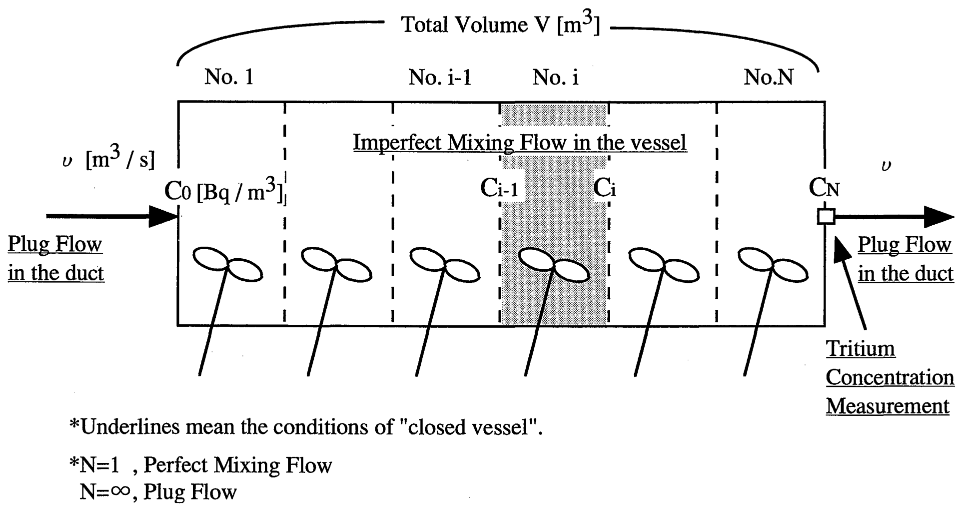

Fig. 12 Continuous stirring tank reactors model

behavior by this model with the experimental observations. The $50\,m^3/h$ ventilated flow in the Caisson can be regarded as the perfect mixing. This model has a possibility to predict the tritium removal behavior for further studies to clear the flow rate dependence, where the mixing characteristic will be changed from a perfect mixing ($N=1$) to imperfect mixing flow ($N>1$) as the flow rate gradually decreases.

3. Tritium Intended Release Experiment in the Ventilated TSTA Main Cell

(1) Initial Tritium Behavior

Figures 14(a) and (b) show the calculated initial tritium behavior and experimental observations, respectively. The flow rate in the main cell decreased quickly after the ventilation was stopped. After the tritium was released, tritium was carried quickly by the residual flow. The concentration of RM-5 located near the release point increased immediately to $1.74\times10^6\,Bq/m^3$ after the intended tritium release. The concentrations of RM-3, RM-1 and RM-4 reached the maximum values in about 300 s after the release. It needed 2,400 s before the concentrations of all monitors became constant.

Calculated initial tritium behavior was consistent well with the experimental observations. Buoyancy effected locally to the tritium transport only near the release point because the tritium ratio in the released N_2–T_2 gas was very low in this experiment. The experimental behavior of each tritium monitor is slightly different from the calculated behavior. The reason is that all equipment in the main cell such as gloveboxes are not taken into account in the geometric model. The actual residual flow would be slightly different from the calculated flow because it is difficult to estimate the residual flow. Despite some assumptions in this calculation, it is worth notice that initial tritium behavior in the $3{,}000\,m^3$ of actual tritium handling room can be wholly estimated.

Formerly, initial tritium behavior was calculated by the three-dimensional flow calculation code based on CFX-F3D(5). Initial tritium behavior could not be predicted in this model. Main reason is that the residual flow could not be reproduced by this code because of larger mesh sizes and less consideration of the flow velocity than those in this study. Initial tritium behavior depends on not the flow rate but its velocity. The velocity distribution of the flow from the supply duct is a key parameter for the initial tritium behavior.

(2) Removal Tritium Behavior

Figure 15(a) shows the calculated removal tritium behavior and the experimental observations, respectively. The ventilation system was restarted after 5 h of the initial tritium behavior study. The tritium concentrations just before the ventilation system was restarted were $4.44\times10^6\,Bq/m^3$. Tritium concentrations decreased logarithmically to the time. About 260 s were needed before the tritium concentration decreased to $2.40\times10^6\,Bq/m^3$. Calculated values more than $2.40\times10^6\,Bq/m^3$ of tritium concentration were consistent well with the experimental

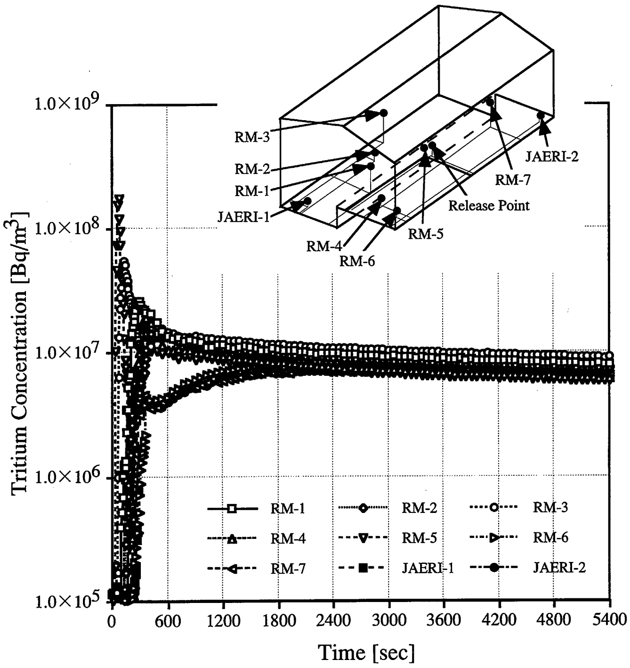

Fig. 14(a) Calculated initial tritium behavior in ventilated TSTA main cell

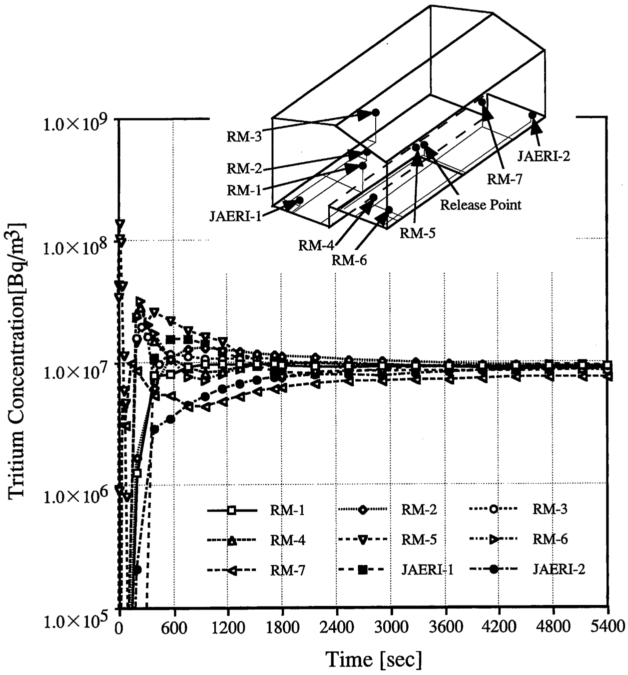

Fig. 14(b) Experimental initial tritium behavior in ventilated TSTA main cell

observations. Tritium concentration decreased quickly to the background level in 90 min. The experimental removal tritium behavior less than $2.40\times10^6\,Bq/m^3$ of tritium concentration is different from the calculated estimation. This is the reason for a tritium soaking effect. The important result of this simulation is that the removal tritium behavior in the $3{,}000\,m^3$ of actual tritium

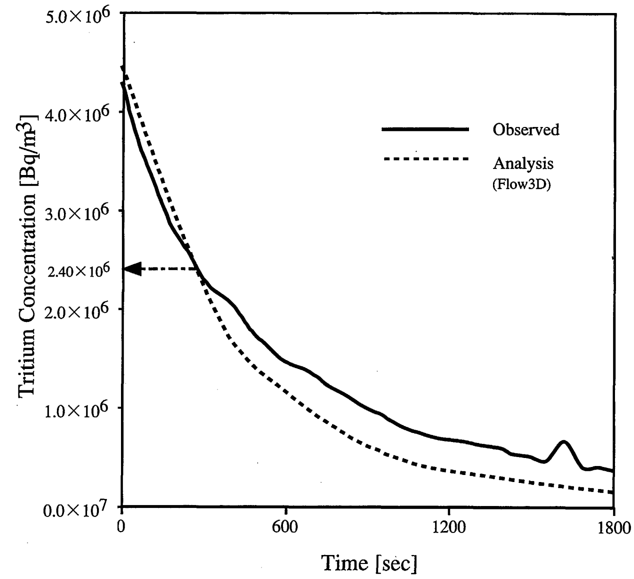

Fig. 15(a) Removal tritium behavior (RM-1) in ventilated TSTA main cell

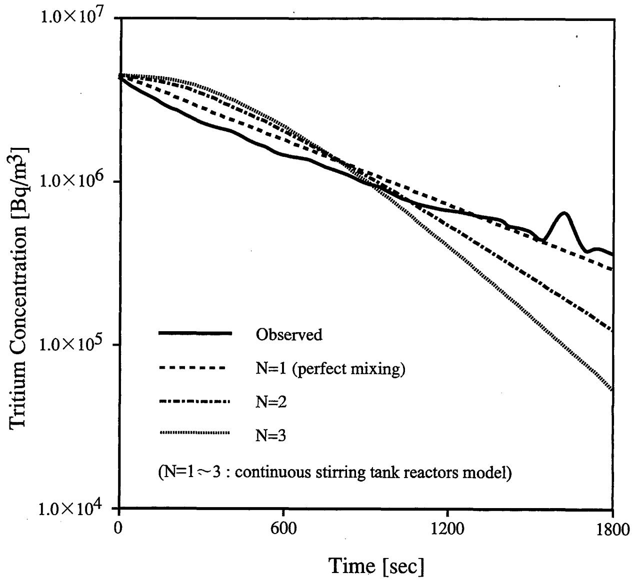

Fig. 15(b) Calculated removal tritium behavior (RM-1) in ventilated TSTA main cell by continuous stirring tank reactors model

handling room can be wholly estimated.

Figure 15(b) shows the calculated removal behavior by the continuous stirring tank reactors model with the experimental observations. The ventilated flow in the actual scale of tritium handling room can also be regarded as a perfect mixing.

V. Conclusion

The summaries of this study are as follows:

(1) The calculated fluid velocities were consistent well with the experimental observations in the $50\,\mathrm{m^3/h}$ ventilated Caisson. The RNG model was found to be valid for eddy flow calculation with acceptable engineering precision.

(2) A simulation method to predict the tritium behavior in a ventilated Caisson were established. The calculated tritium concentration histories after the intended tritium release were consistent well with the experimental observations in the $50\,\mathrm{m^3/h}$ ventilated Caisson. From the relative correspondence between the calculated values and the experimental observations, the initial and removal tritium behavior in the ventilated Caisson is now explicable. It is worth notice that the flow near a wall plays an important role for the tritium transport in the ventilated room.

(3) The intended tritium release experiments were carried out to acquire the tritium behavior data in the $3{,}000\,\mathrm{m^3}$ actual experiment room under a US-Japan collaboration. The calculated tritium concentration histories after intended tritium release by the code optimized for Caisson were consistent well with the experimental observations even in the $3{,}000\,\mathrm{m^3}$ room, which proves that this method can be applied to the actual scale of tritium handling room.

The future stages of this study are as follows:

(1) The flow rate of ventilation system was limited to $50\,\mathrm{m^3/h}$ (4 atmosphere exchanges per hour). The RNG model was found to be valid for eddy flow calculation at this flow rate with acceptable engineering precision. The lower limit of the flow rate to keep the validity of RNG model will be cleared by comparison between the experimental observations and the calculated fluid velocities. As a part of this discussion, one of the subjects considered is whether RNG model is the most suitable to estimate actual velocity distribution in tritium handling room. More investigation on other eddy models will be carried out whether these models also have a possibility to estimate it.

(2) Tritium soaking effect is also an important subject for the prediction of removal tritium behavior and estimation of contaminated amount mainly by adsorption of tritiated water on wall. The humidity in atmosphere, the amount of released tritiated vapor, the flow rate of ventilation system, the reaction rates of surface adsorption and desorption of tritiated water are supposed to be key parameters for tritium soaking effect. The interrelation of these factors on tritium soaking effect will be cleared in the next stage of our study.

[NOMENCLATURE]

C_i: Tritium concentration at the outlet of No.i vessel (Bq/m^3)
c_μ: Eddy viscosity factor
D: Diffusivity (m^2/s)
D_t: Turbulence diffusivity (m^2/s)
g: Body acceleration (m/s^2)
L: ρ_1/ρ

N: Total number of the vessels
P: Pressure (Pa)
p: Instantaneous pressure (Pa)
R: γ_1/ρ
t: Time (s)
u_i: Instantaneous fluid velocity of i coordinate direction (u_1, u_2, u_3) (m/s)
U_i: Fluid velocity of i coordinate direction (U_1, U_2, U_3) (m/s)
V: The total volume of tritium handing room (m^3)
x_i: Coordinate directions (m)
γ: Instantaneous fluid density (kg/m^3)
ε: Turbulent kinetic energy dissipation rate (m^2/s^3)
l: Mixing length (m)
κ: Turbulent kinetic energy (m^2/s^2)
ν: Coefficient of viscosity (m^2/s)
ν_T: Coefficient of eddy viscosity (m^2/s)
ρ: Fluid density (kg/m^3)
v: Flow rate (m/s)

(Subscripts)
i, j, k: Coordinate directions $(1, 2, 3)$
1, 2, 3: Three coordinate directions $(1{=}x, 2{=}y, 3{=}z)$

(Superscripts)
$\bar{\ }$: Mean value

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—REFERENCES—

(1) Los Alamos National Laboratory: Final Safety Analysis Report of Tritium Systems Test Assembly at the Los Alamos National Laboratory, TSTA-SAR, (1996).
(2) Naruse, Y., Matsuda, Y., Tanaka, K.: *Fusion Eng. Des.*, **12**, 293 (1990).
(3) Schira, P., Hutter, E., Jourdan, G., Penzhone, R.: *Fusion Eng. Des.*, **18**, 19 (1991).
(4) Bartlit, J. R., Anderson, J. L., Jalbert, R. A., Carlson, R. V., Okuno, K., Ide, T., Fukui, H., Enoeda, M., Naruse, Y.: *Proc. 13th SOFE*, Knoxville, TN., U.S.A., 798 (1989).
(5) Hayashi, T., Kobayashi, K., Iwai, Y., Yamanishi, T., Nishi, M., Okuno, K., Carlson, R. V., Willms, R. S., Hyatt, D., Roybal, B.: *Fusion Thecnol.*, **34**, 521 (1998).
(6) Hayashi, T., Kobayashi, K., Iwai, Y., Yamada, M., Suzuki, T., O'hira, S., Nakamura, H., Shu, W., Yamanishi, T., Kawamura, Y., Isobe, K., Konishi, S., Nishi, M.: Submitted to *Fusion Eng. Des.* (1999).
(7) Yakhot, V., Orgazag, S. A.: *J. Sci. Comput.*, **1**, 3 (1986).
(8) Hirt, C. W., Cook, J. L.: *J. Comp. Phys.*, **10**, 324 (1972).
(9) Daiguji, H., Miyake, Y., Yoshizawa, A.: "*Computational Fluid Dynamics of Turbulent Flow—Models and Numerical Methods*", Univ. of Tokyo Press, Tokyo, 183 (1998), [in Japanese].
(10) Hinze, J. O.: "*Turbulence*", McGraw-Hill, New York, 227 (1959).
(11) Launder, B. E., Spalding, D. B.: "*Mathematical Models of Turbulence*", Academics, London, (1972).
(12) Jones, W. P., Launder, B. E.: *Int. J. Heat Mass Transfer*, **15**, 301 (1972).
(13) Jones, W. P., Launder, B. E.: *Int. J. Heat Mass Transfer*, **16**, 1119 (1973).
(14) Hanjalic, K., Launder, B. E.: *J. Fluid Mech.*, **52**, 609 (1972).
(15) Harlow, F. W., Nakayama, P. I.: *Phys. Fluids*, **10**, 2303 (1967).
(16) Nakayama, P. I.: *8th Aerospace Science Meeting*, AIAA paper No. 70-3, (1970).
(17) Boussinesq, J.: "*Theorie Analytique de la chaleur*", Ganthier-Villars, Paris, 157 (1903).
(18) Hashimoto, K.: "*Chemical Reaction Engineering*", (1st ed.), Baifuukan, Tokyo, 173 (1979), [in Japanese].
(19) Iwai, Y., Hayashi, T., Kobayashi, K., O'hira, S., Nishi, M.: Submitted to *Fusion Eng. Des.* (2000).