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# MODELING AND QUANTIFICATION OF NUCLEATION, DISSOLUTION AND TRANSPORTATION OF BUBBLES IN PRIMARY COOLANT SYSTEM OF SODIUM FAST REACTOR

**Eisaku TATSUMI**
*Graduate School of Engineering,*
*Osaka University*
*2-1, Yamada, Suita, Osaka,*
*565-0871, Japan*
*Phone: +81-6-6879-7895*
*Fax: +81-6-6879-7891*
*Email: tatsumi_e@ge.see.eng.osaka-u.ac.jp*

**Takashi TAKATA**
*Graduate School of Engineering,*
*Osaka University*
*2-1, Yamada, Suita, Osaka,*
*565-0871, Japan*
*Phone: +81-6-6879-7895*
*Fax: +81-6-6879-7891*
*Email: takata_t@see.eng.osaka-u.ac.jp*

**Akira YAMAGUCHI**
*Graduate School of Engineering, Osaka University*
*2-1, Yamada, Suita, Osaka, 565-0871, Japan*
*Phone: +81-6-6879-7890*
*Fax: +81-6-6879-7891*
*Email: yamaguchi@see.eng.osaka-u.ac.jp*

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## ABSTRACT

In order to estimate inert gas behavior in a circulating system of a sodium-cooled fast reactor (SFR), it is necessary to develop a computational code for a dynamics of the gas in the primary system. In the present study, multi-dimensional analysis in the upper plenum of the SFR is performed using a numerical method for gas bubble transportation developed based on one-way-coupling method. As a result of the analyses, non-dimensional correlation model for gas behavior has been derived. The model is employed in the VIBUL code that is a plant dynamics code based on one point approximation. In order to investigate the usefulness of the present model in the plant dynamics, analyses in the rated condition are carried out. We discuss the difference of the two models in predicting the bubble number density in the upper plenum.

## 1. INTRODUCTION

In a sodium-cooled fast reactor (SFR), inert gases exist in the primary coolant system either in a state of dissolved gas or free gas bubbles. There are several sources of the inert gas in the system.

One is argon gas used as a reactor vessel cover gas. The primary coolant system has free surfaces which are covered with the argon gas. The usage of the free surface is unavoidable because reservoir function is needed to absorb the thermal expansion of the liquid sodium. The reactor cover gas is slightly pressurized above the atmospheric pressure. Therefore, the argon gas dissolves in the liquid sodium and is dispersed in the primary coolant system by advection and diffusion. In addition, the free surface is disturbed by the large sodium flow velocity and the sodium flow entrains the argon cover gas. Consequently, free gas bubbles can be included in the liquid sodium by the gas entrainment at the free surface. Another source is helium gas that is produced as a result of disintegration of $B_4C$ control rod material and is emitted as small bubbles in the reactor core.

These free gas bubbles are transported according to the coolant flow in the primary system and may cause disturbance in reactivity in the core, a nucleation site for boiling and cavitation, flow instability, and an influence on heat transfer. Therefore the investigation of inert gas behavior is of importance from the viewpoint of design and safety of the SFR. At the same time, it is necessary to define the acceptance level of the gas content in the primary system because the existence of the gas in the system is unavoidable.

A computational code VIBUL for a dynamics of the gas in the primary system had been originally developed for French fast reactor (Berton, 1991) and modified for Japanese SFR design (Yamaguchi and Hashimoto, 2005). The amounts of free bubbles and dissolved gas in primary systems can be quantified with this code. However, simple models for bubble transport in a plenum are implemented and one point approximation is assumed in the code. The simplification may not be sufficiently accurate to describe the gas behavior especially in the components such as an upper plenum of the reactor vessel (R/V) and the intermediate heat exchanger (IHX) where multi-dimensional effect is not negligible. It is essential to simulate gas behavior in the complicated geometry and to estimate the amount of the gas bubbles and dissolved gas. Based on the computation, dominant phenomena to the gas behavior are identified and the non-dimensional correlations for the bubble transportation are developed. The gas behavior model currently implemented in the VIBUL code is refined if the new correlations are included to account for the multi-dimensional flow and bubble dynamics.

In this paper, a computational method for bubble transport has been developed based on multi-dimensional thermal-hydraulics. The computational method is applied to the reactor upper plenum configuration because the flow field in upper plenum is complicated due to the internal structure including free surface and the multi-dimensional effect is important. As a result of the computation, a model for the gas behavior in the upper plenum has been developed based on non-dimensional correlation. The gas behaviors are: dissolution into liquid sodium; outflow to hot-leg (H/L) nozzle; release into the reactor cover gas.

The present model is implemented into VIBUL code. We estimate the influence of the present model on gas behavior and compare the result used the present model with the VIBUL model. And then we describe the multi-dimensional effect of the present model on the gas behavior in the reactor upper plenum.

## 2. NUMERICAL METHODS

### 2.1. VIBUL Code

A computational code VIBUL has been developed for a dynamics of gas behavior in a primary coolant system (Yamaguchi and Hashimoto, 2005). In the code, the size distribution of gas bubbles and amounts of the dissolved gas are estimated in components of the system. The bubble radius range is discretized in logarithmic scale into groups between the minimum and the maximum radius. Conservation equations of gas bubbles are solved for each of bubble size group. Figure 1 shows the conservation in a plenum.

In a component of the primary system, mass conservation of free gas bubbles must be satisfied for each size group of free gas bubbles. The conservation for i-th bubble number is written as:

$$V_{Na}\frac{d}{dt}N_{bi} = -\alpha_i V_{Na} N_{bi} - QN_{bi} + Q\tilde{N}_{bi} + S_i\,, \qquad (1)$$

where $V_{Na}$ is the volume of a plenum, $Q$ is the volumetric flow rate of sodium, $N_{bi}$ is the number of bubbles per unit volume with $i$-th radius, $\tilde{N}_{bi}$ is the one in the upstream control volume, $S_i$ is the source term of $i$-th radius and $\alpha_i$ is a degassing constant. Each terms of the right hand side of Eq. (1) represents the bubble emission at the free surface, the outflow advection, the inflow advection and the source terms.

In addition, the conservation of total mass of the gas is solved in a component of the system and is represented as:

$$V_{Na}\sum_{i=1}^{N} N_{bi}\frac{d}{dt}N_{mi} + V_{Na}\frac{d}{dt}N_d = -2\sqrt{\frac{Dv_hL}{\pi}}(N_d - H_cP_{FS}) - QN_d + Q\tilde{N}_d\,, \qquad (2)$$

where $N_m$ is the molar amount of gas included in a bubble, $N_d$ is the molar amount of dissolved gas in a unit volume of sodium. $D$, $v_h$, $L$, $H$ and $P_{FS}$ are the diffusion coefficient of the gas in sodium, the horizontal velocity at the free surface, Henry's constant and the pressure of the cover gas. The first term in the right hand of Eq. (2) expresses the diffusion terms evaluated based on the analogy of one-dimensional thermal conduction problem.

In addition, the following phenomena are taken into consideration based on basic physical modeling: mass transfer at bubble-liquid interface of a single bubble; bubble nucleation at IHX; bubble detachment from the wall according the balance of drag, surface tension and buoyancy forces; bubble break up at the primary pump or fuel subassemblies in which sodium flows at high velocity and turbulence is significant, and so on.

However, the VIBUL code employs simple models especially for bubble release at free surface in a plenum. In the present study, multi-dimensional analysis is carried out to investigate gas behavior in the reactor upper plenum including free surface and a model of gas behavior is derived from the computational experiments. And then we implement the model into VIBUL code.

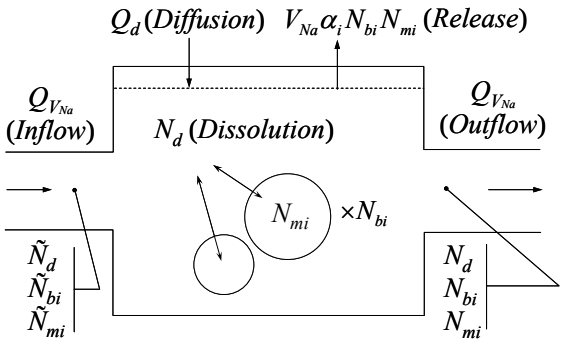


*Fig.1 Conservation of gas bubbles in a plenum*

### 2.2. VIBUL Model of Gas Behavior in Upper Plenum in VIBUL

In an upper plenum of SFR, gas bubbles dissolve into liquid sodium, flow out to H/L nozzle or are released at free surface. The model of bubbles released at the free surface is represented as a degassing constant $\alpha_i$ described in Eq. (1). The degassing constant $\alpha_i$ is estimated by the following equation:

$$\alpha_i = \frac{S_{Na}\,v_{ti}}{V_{Na}}\,, \qquad (3)$$

where $S_{Na}$ is an area of the free surface, $V_{Na}$ is a volume of the sodium in the plenum and $v_t$ is the terminal rising

velocity of a bubble. The degassing constant expresses the release fraction per unit time of a bubble. This model is assumed that gas bubbles in a plenum are mixed uniformly in no time and are released at free surface by the fraction shown in Eq. (3).

In the upper plenum, the flow field is complicated due to the internal structure and the free surface. Hence, the simplification is not sufficiently accurate to describe the gas behavior in the plenum where the multi-dimensional effect is important.

### 2.3. Physical Model of Gas Behavior in Flow Field

Flow field is computed by solving mass conservation equation and Navier-Stokes equation in Eulerian coordinate.

A bubble is transported by drag force and buoyancy force with shrinking or growing according to the mass transfer between bubble and liquid. Equations of mass and momentum conservation for a bubble are solved with the Lagrangian scheme.

The mass conservation equation for a single bubble is given by:

$$\frac{dN_{mi}}{dt} = -4k_i\pi r_i^2\left[H_c(P+\frac{2\sigma}{r_i}) - N_d\right], \qquad (4)$$

where $r$ is the radius of a bubble, $P$ is the pressure in the liquid sodium, and $\sigma$ is the surface tension. $k_i$ is a mass transfer coefficient (Clift et al., 1978) which is given by:

$$k_i = \frac{Sh\,D}{2r_i}, \qquad (5)$$

where $Sh$ is the Sherwood number and $D$ is the diffusion coefficient of the gas in sodium. $H_c$ in Eq. (4) is the Henry's constant and is defined as:

$$H_c = \frac{S\rho_{Na}}{M_{Na}}, \qquad (6)$$

where $S$ is the solubility, $\rho_{Na}$ is the density of sodium and $M_{Na}$ is the molar mass of sodium. The solubility for noble gases such as argon and helium are given by Reed and Dropher (1970). Eq. (4) is solved with the Eulerian explicit method.

The momentum conservation equation with regard to a bubble in a flow field is written as:

$$\frac{d\mathbf{V}_G}{dt} = \boldsymbol{g}(\frac{\rho_L-\rho_G}{\rho_G}) + \frac{3}{8r}C_D\frac{\rho_L}{\rho_G}|\mathbf{V}_L-\mathbf{V}_G|(\mathbf{V}_L-\mathbf{V}_G), \qquad (7)$$

where $\boldsymbol{V}$, $\boldsymbol{g}$ and $C_D$ are velocity vector, the acceleration vector due to gravity and the drag coefficient. Subscripts $G$ and $L$ indicate gas phase and liquid phase, respectively. The first and the second terms of the right hand side of Eq. (7) are the buoyancy force and the drag force, respectively. The drag coefficient is calculated assuming that a bubble is sphere-shaped because the size of the bubble to be considered is low enough and the bubble can be approximated spherical due to high surface tension. Eq. (7) is integrated with the fourth-order Runge-Kutta method.

It is assumed that the influence of a bubble motion on the liquid phase is negligible because the bubble volume fraction is low enough. Hence, one-way-coupling method is used, in which the liquid phase only affects the bubble motion but the influence of the bubble motion on the flow field is ignored. In the present model, the fluid flow and the bubble tracking calculations are performed in a segregated manner; that is, the steady state continuous phase flow field is computed first, then the bubble motion is obtained based on the postulated velocity field.

## 3. MODELING OF GAS BEHAVIOR IN UPPER PLENUM

### 3.1 Reactor Upper Plenum Modeling

In the previous works, the gas behavior analysis has been numerically carried out in the 1/10th scaled model of the reactor upper plenum by the authors (Tatsumi et al., 2006). The numerical analysis has referred to the 1/10th water experiment study (Kimura et al., 2003) in order to estimate the flow patter in upper plenum. The computational region is shown in Fig. 2. In the region, it is assumed that gas bubbles are released into cover gas when the gas bubbles go beyond the upper end of the region. In the previous study, parametric analyses have been performed and a model of the gas behavior has been developed based on dimensionless numbers; Froude number, Eötvös number and Froude number based on a bubble dynamics.

In the present study, a model of gas behavior in the upper plenum is implemented into VIBUL code for a dynamics of the gas in the primary system. Hence, we develop a model for gas behavior in the actual upper plenum based on the previous study and model.

The computational geometry and mesh are based on two-dimensional Cartesian coordinates as shown in Fig. 3. The configuration data are on the basis of the actual data: the height between the core exit and the H/L nozzle ($H$), H/L inner diameter ($D_{out}$), core exit inner radius ($R_{in}$), the radius of the reactor vessel ($L1$) and the radial position of the H/L pipe ($L2$) are 2.8m, 1.25m, 3.25m, 5.0m and 3.5m, respectively, as shown in Fig. 3. Equally-spaced mesh divided into 80 (I) × 40 (J) is arranged to the computational region as shown in Fig. 3. Mesh size is $6.25\times10^{-2}$ m and $7.0\times10^{-2}$ m as $\Delta x$ and $\Delta y$, respectively. This condition is defined as the reference case.

Initial temperature in the upper plenum is the same as the design temperature of the SFR, i.e. 823K. Although the dissolution of the bubbles is related to the system pressure and initial molar concentration of the dissolved gas, atmosphere pressure and no initial dissolution are assumed for simplicity. Also, since the argon gas is the most significant source, the helium gas is not considered.

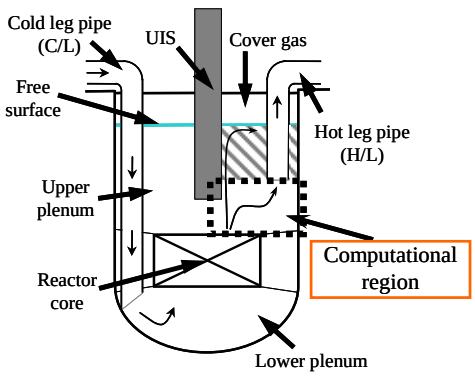


*Fig.2 Cross section of reactor vessel*

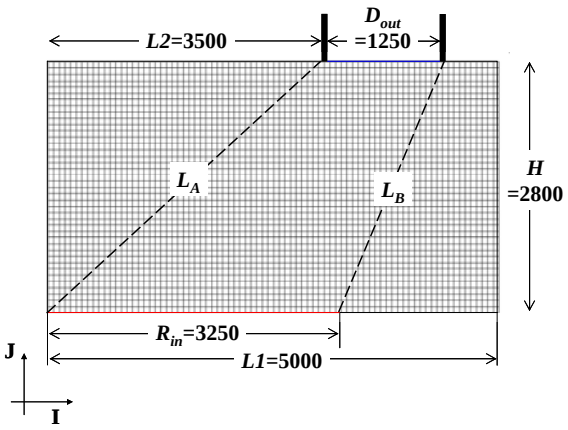


*Fig.3 Computational geometry and mesh arrangement*

### 3.2 Initial Conditions of Bubbles

The maximum and minimum radii of bubbles are defined as follows. A large size of bubble breaks up through the primary pump or the fuel assemblies. The break-up phenomena depends on the shear force related with the differential velocity at a distance of bubble diameter.

It is known that the bubble breaks up when the Weber number (*We*) is greater than the critical Weber number ($We_c$) of 4.7 (Lewis and Davidson, 1982). *We* is expressed as:

$$We = \frac{2r\rho\overline{u'^2}}{\sigma}, \tag{8}$$

where $\overline{u'^2}$ is the mean square of the flow velocity fluctuation within the geometrical scale of the bubble diameter. The maximum stable radius is calculated using the *We* number. Regarding the primary pump, the maximum radius is given to be 297μm, in the Super Phenix design condition. Since a bubble density is low in the primary cooling system, bubble coalescence is negligible. Therefore, a bubble larger than 297μm of radius does not exist in the system.

The inner pressure of a bubble increases significantly due to surface tension in accordance with the decrease of bubble radius. Consequently, a tiny bubble dissolves immediately.

In the previous study of the gas dynamics analysis (Yamaguchi and Hashimoto, 2005), it was found that most of the bubbles existed in the range of 10 - 80μm. From these viewpoints, we select 1μm and 300μm as the minimum and the maximum radii, respectively.

Bubbles in the upper plenum either dissolve into liquid sodium, flowed out to H/L pipe or released into cover gas. Therefore the mass fractions of the bubbles released at the free surface ($f_{rel}$), dissolved in liquid sodium ($f_{dis}$) and flowing out of the upper plenum ($f_{out}$) are calculated. The three quantities sum up to unity.

### 3.3 Parametric Study

A parametric study is carried out to estimate the influence of the plenum geometry and the flow field on gas behavior. The parameters are the height of the plenum, the radial position of H/L pipe, the H/L inner diameter, and the core exit velocity. These parameters are varied as summarized in Table. 1. We propose the non-dimensional correlation for gas behavior in full scaled upper plenum from the result of the parametric study.

*Table.1 Selection parameters value for sensitivity analysis*

| Parameter | | | Reference Case | | |
|---|---|---|---|---|---|
| *H* [m] | 2.10 | 2.45 | 2.80 | 3.15 | 3.50 |
| *L2* [m] | | 2.50 | 3.00 | 3.50 | |
| $D_{out}$ [m] | | 0.75 | 1.25 | 1.75 | |
| $V_{in}$ [m/s] | 2.0 | 3.0 | 3.3 | 4.0 | |

### 3.4 Derivation of Non-dimensional Correlation for Gas Behavior Model

In the previous study, non-dimensional correlations have been derived for the gas behavior model based on 1/10th scaled upper plenum test and analysis (Tatsumi et al., 2006). It has been found that the gas behavior model is expressed by non-dimensional correlations as a function of $Fr\ Fr'^{1.5}\ Eo^{-0.5}$. Here, Froude number based on the flow velocity (*Fr*), Froude number based on the bubble terminal velocity (*Fr'*) and Eötvös number (*Eo*) are expressed as:

$$Fr = \frac{V_{in}}{\sqrt{gH}}, \tag{9}$$

$$Fr' = \frac{v_t}{\sqrt{gL'}}, \tag{10}$$

and $$Eo = \frac{g(\rho_L - \rho_G)d^2}{\sigma}, \tag{11}$$

where *H*, $V_{in}$ and $v_t$ denote the differential elevation of the core exit and the H/L nozzle, the core exit velocity and the terminal velocity of a bubble, respectively. *L'* is the distance between the core exit and the H/L nozzle and is defined as the arithmetic average of $L_A$ and $L_B$ (see Fig. 3).

Figures 4 and 5 show $f_{dis}$ and $f_{out}$ from the parametric study. It is seen that the results are scattered. The previous correlation for 1/10th scale model has been extended to the bubble behavior model in the full scaled upper plenum.

It is assumed that $f_{dis}$ and $f_{out}$ are expressed as $f$ (*Fr*, *Fr'*, *Eo*, $D_{out}/H$ ) as in the scale model correlation (Tatsumi et al., 2006). Thus, the non-dimensional correlation for $f_{dis}$ and $f_{out}$ are derived in terms of $Fr\ Fr'^{1.5}\ Eo^{-0.5}$ as shown in Figs. 6 and 7.

The function of the correlation for $f_{dis}$ shown in Fig. 6 is written as:

$$f_{dis} = 3.261\times10^{-5}(Fr\ Fr'^{1.5}\ Eo^{-0.5})^{-0.8489}, \quad R^2 = 0.9933. \tag{12}$$

where $R^2$ is the correlation coefficient.

The non-dimensional correlation for $f_{out}$ is also derived in a similar way to $f_{dis}$. A function as $(H / D_{out})^{0.2}$ is multiplied $f_{out}$ in all case computed in parametric analysis because $f_{out}$ is to be dependent on $D_{out}$ and *H* which shows the probability of bubbles flowed out to the nozzle and the fraction of bubbles dissolved into liquid before arrival at free surface, respectively. The function of the approximated curve is described as:

$$f_{out} = (D_{out} / H)^{0.2} \left\{1-\exp(-0.1682X^2 - 4.661X - 31.92)\right\}, \tag{13}$$

$$R^2 = 0.9929,$$

$$X = \log(Fr\ Fr'^{1.5}\ Eo^{-0.5}). \tag{14}$$

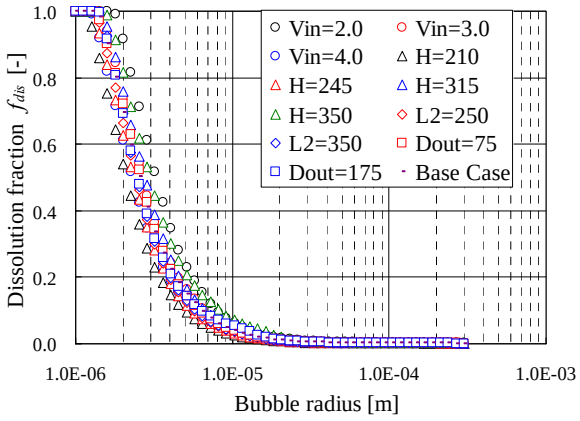


*Fig.4 Dissolution fraction in parametric study*

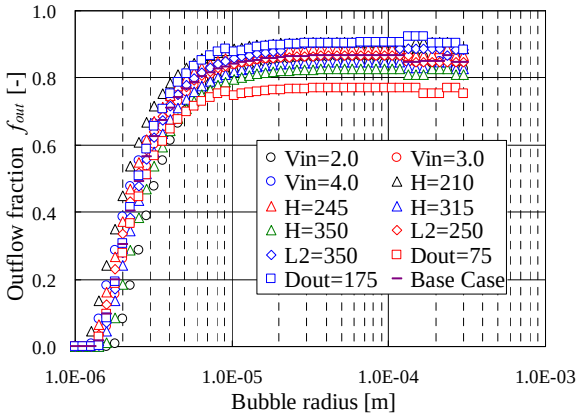


*Fig.5 Outflow fraction in parametric study*

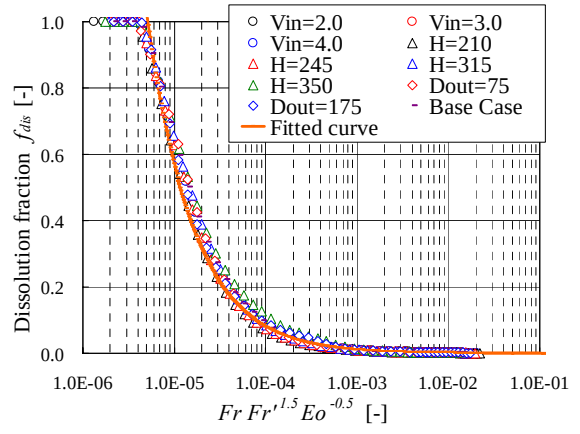


*Fig.6 Non-dimensional correlation for dissolution fraction*

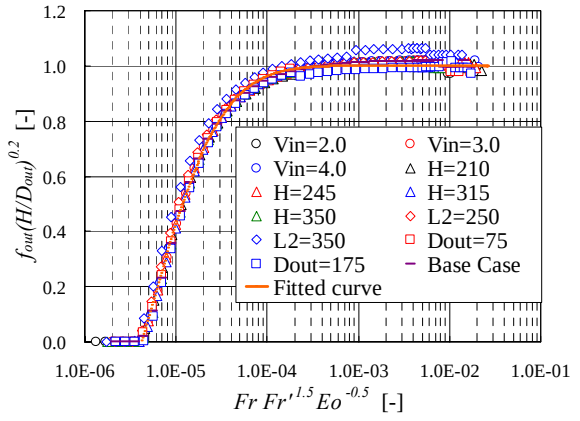


*Fig.7 Non-dimensional correlation for outflow fraction*

For numerical consistency, the values of $f_{dis}$, $f_{\text{out}}$, and their summation are limited so that they lie between 0 and 1. In addition, $f_{rel}$ is calculated from the others ($f_{dis}$ and $f_{out}$).

From Eqs. (12) and (13), it is seen that the fractions are dependent on $Fr\,Fr'^{1.5}$. Substituting the expression of the terminal velocity $v_t = \left(\frac{4dg}{3C_D}\right)^{1/2}$, $Fr\,Fr'^{1.5}$ can be rewritten as:

$$Fr\,Fr'^{1.5} = \left(\frac{4}{3C_D}\right)^{1/2}\left(\frac{d}{L'}\right)^{5/4}\frac{Fr}{Fr'}, \qquad (15)$$

where $C_D$ is the drag coefficient of a bubble. From Eq. (15), it is noted that relative importance of the two Froude numbers representing the flow velocity and the bubble terminal velocity is the governing non-dimensional quantity. From the geometrical point of view, the ratio of the bubble diameter and the bubble migratory distance ($L'$) is another dominant quantity. In addition to those, the drag coefficient appears in Eq. (15), which suggests the terminal velocity is to be multiplied by the drag coefficient.

So far, the gas behavior model in the full scaled reactor upper plenum has been developed based on the phenomenologically governing dimensionless quantities that take multi-dimensional effect into consideration. As a next step, the proposed model is to be implemented into the VIBUL code for a dynamics of gas behavior in the primary system of the SFR.

### 3.5 Discussion on Three Dimensional Effects

It is noted the correlation equations given by Eqs. (12) and (13) are on the basis of two-dimensional analysis of the reactor upper plenum flow. The three-dimensional analysis is needed to estimate actually the gas behavior in the coolant system of SFR. The issues of the two-dimensional analysis are shown as follows;

(1) Region above the H/L nozzle elevation is no included in the model:
(2) The flow velocity at the outlet nozzle coincides with the actual equipment, but the core exit velocity is adjusted to conserve the mass flow rate:
(3) The volume of the reactor upper plenum is inconsistent due to Cartesian coordinates:
(4) The circulation flow in circumferential direction in the upper plenum is neglected.

Thus bubbles tend to stay in the plenum for longer time period.

As a future work, we will quantitatively estimate the three-dimensional effects on the gas behavior in the plenum.

## 4. APPLICATION OF GAS BEHAVIOR MODEL TO VIBUL CODE

### 4.1 VIBUL and Present Model of Released Gas Bubbles

The computational code VIBUL uses a simple model for gas transportation in an upper plenum as mentioned in section 2.2.

In the previous section, the gas behavior model in the upper plenum is developed and the correlation functions are given by Eqs. (12) – (14). The function of bubbles released to the reactor cover gas region at the free surface is simply calculated by

$$f_{rel} = 1 - f_{dis} - f_{out}\,. \qquad (16)$$

Figure 8 shows the bubble release fractions, which are obtained from the VIBUL model and the present model, at the free surface as a function of a bubble radius. In the VIBUL model, $f_{rel}$ is defined as the ratio of the first and fourth terms in the right side of Eq. (1).

In the VIBUL model, it is predicted that the release fraction increases gradually as the bubble radius becomes larger because the release fraction is estimated using the terminal velocity of bubble as in Eq. (3). Furthermore, it is assumed that the bubbles are instantaneously mixed in the plenum due to one point approximation used in the code. Apparently the release fraction is overestimated regardless of the flow velocity if the instantaneous mixing is assumed.

In the present model, the release fraction is almost constant regarding the large bubbles. The terminal velocity of 300μm bubble is calculated to be $1.43\times10^{-1}$m/s and is much smaller than the core exit velocity. Consequently, it might be said that the buoyancy force is not influential on the gas behavior compared with the inertia force. As a result, almost the constant value is obtained regardless of the radius. However, in the region of small radius of bubbles, a dissolution phenomenon is dominant on the gas behavior due to the higher surface tension. The smaller bubbles dissolve into liquid sodium and do not reach the free surface. Therefore, the release fraction of the smaller bubbles decreases as the radius becomes smaller.

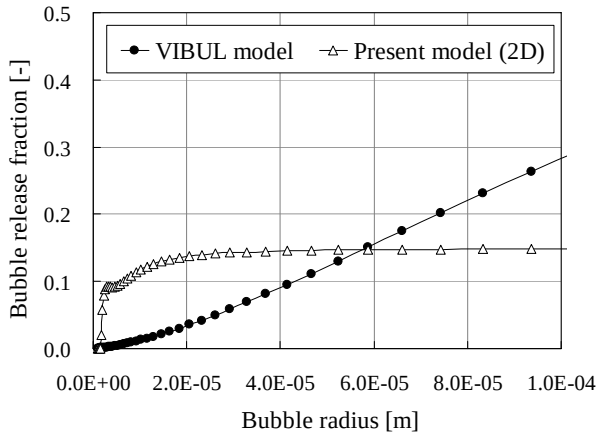


*Fig.8 Bubble release fraction in rated condition*

## 4.2 Implementation of Present Model into VIBUL Code

Figure 9 shows the nodalization of the primary coolant system in the VIBUL code. The present model is applied to the upper plenum shown in Fig.9. The mass fractions of the bubble released at free surface and the bubble dissolved into liquid sodium can be given from the non-dimensional correlation of the model. In the present analysis, we compare the distribution of the gas bubbles at the evaluation point No.1 (upper plenum (U/P) inlet) and No.2 (U/P outlet) applying both the VIBUL model and the present model. The analyses are performed in the condition of the rated operation.

In the VIBUL code, the total mass balance of the gas in a plenum is obtained after the calculation of the amount of bubbles released at the free surface and dissolved into the liquid sodium.

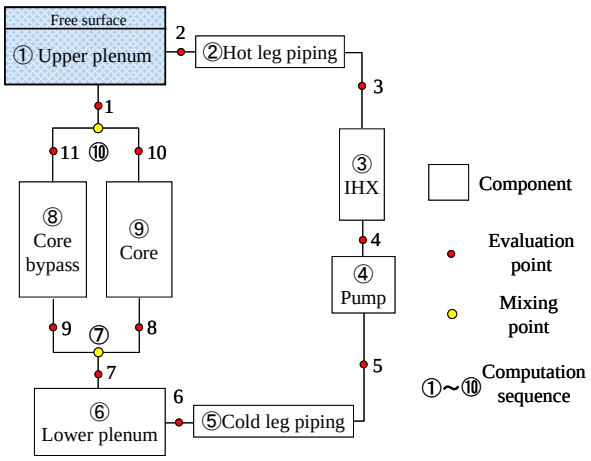


*Fig.9 Nodalization of coolant system in VIBUL code*

## 4.3 Results and Discussions

Number densities of argon bubbles at the inlet and the outlet of the upper plenum in the rated condition are shown in Fig. 10. It is found that the present model gives smaller number density than the VIBUL model at the region of the smaller bubble radii less than $4.0\times10^{-5}$ m. On the contrary, the number density with the present model is larger than that with the VIBUL model in the bubble radii approximately ranging from $4.0\times10^{-5}$ m to $6.0\times10^{-5}$ m.

To investigate the difference of the two models, two additional computations are performed. One uses the present release model and one point model for bubble dissolution. The other assumes the present dissolution model and the release fraction is evaluated based on the one point model. Comparing the two computations with Fig. 10, the cause of the difference appearing in Fig. 10 can be identified.

Figure 11 shows the former result. It is shown that the bubble number density with present release model becomes smaller in all bubble radii than the VIBUL model. That is because the release fraction in the present model is larger than that of the VIBUL model at the region of the smaller radii less than $6.0\times10^{-5}$ m (see Fig.8). In addition, the release fraction is comparatively low (< 0.2) and hence the present release model has a little influence on the number density.

Result of the latter computation is given in Fig. 12. It is noted that the number density with the present dissolution model is larger than that with the VIBUL model between $4.0\times10^{-5}$ m and $6.0\times10^{-5}$ m of the bubble size. In the one point approximation model, the bubbles are assumed to be mixed instantaneously and distributed uniformly in the plenum. On the other hands, the bubbles stay in the plenum for shorter time because most of the bubbles are transported directly according to the flow from the core exit to H/L nozzle in case of the present model. Consequently, it seems that the bubbles do not dissolve into the liquid due to the short staying time of the bubbles in the plenum.

In the present study, the model based on the two-dimensional analysis refines the VIBUL model using the one point approximation. In case of the two-dimensional analysis, most of the bubbles in the plenum are conveyed according to the main flow from the core exit to H/L nozzle. From the present study, it is shown that the multi-dimensional effect on gas behavior can be estimated in a plant dynamics code by the empirical model based on non-dimensional correlation.

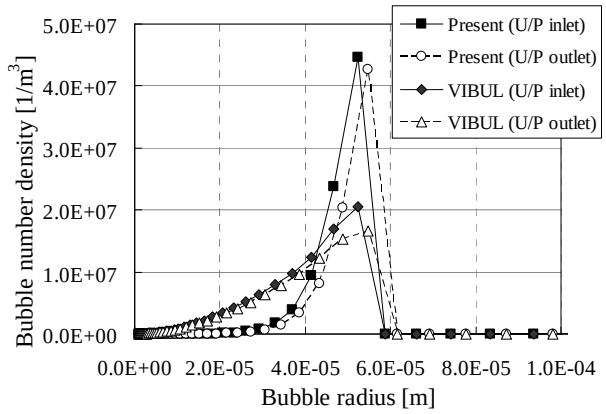


*Fig.10 Number density of gas bubbles with present model and VIBUL model*

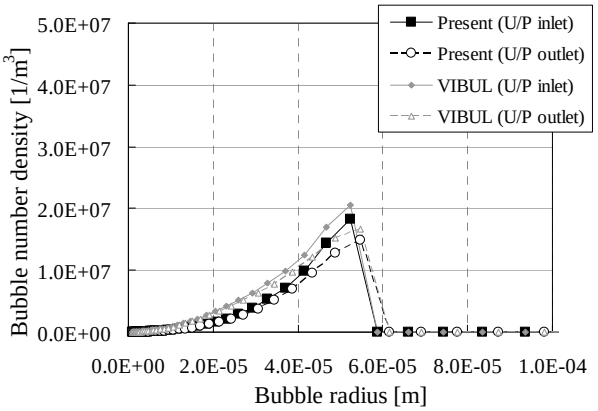


*Fig.11 Number density of gas bubbles with present release model*

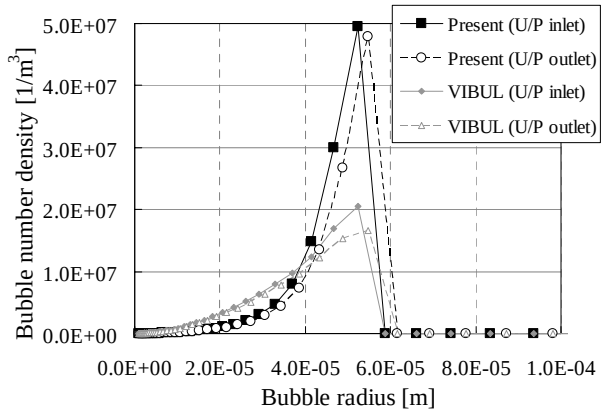


*Fig.12 Number density of gas bubbles with present dissolution model*

## 5. CONCLUSIONS

We have carried out the multi-dimensional analysis of gas behavior in upper plenum of sodium-cooled fast reactor. From the analyses, the gas behavior model has been developed based on non-dimensional correlation. And then, the gas model has been implemented into VIBUL code, which can estimate a plant dynamics and gas transport. The bubble number density has been computed with the present model at the inlet and the outlet of the upper plenum in the primary coolant system.

In conclusion, the present model can evaluate the multi-dimensional effect on gas behavior in the primary coolant system. It is found that the number density becomes larger than the one point model at 40-60 μm by a factor of two because of the multi-dimensional flow effect.

In the future, we will quantitatively estimate three-dimensional effects on the gas behavior and perform the validation of the gas behavior model by experiment. Furthermore, the acceptance level of the gas content in the primary system is to be determined using the VIBUL code.

## NOMENCLATURE

| | |
|---|---|
| $C_D$ | Drag coefficient [-] |
| $d$ | Bubble diameter [m] |
| $D$ | Diffusion coefficient [-] |
| $D_{out}$ | H/L inner diameter [m] |
| $Eo$ | Eötvös number [-] |
| $Fr$ | Froude number based on flow velocity [-] |
| $Fr'$ | Froude number based on terminal velocity of a bubble [-] |
| $g$ | Acceleration due to gravity [m/s$^2$] |
| $H_c$ | Henry's constant [-] |
| $k$ | Mass transfer coefficient [-] |
| $M_{Na}$ | Molar mass of sodium [kg] |
| $N_b$ | Number of bubble per unit volume [1/m$^3$] |
| $N_d$ | Molar amount of dissolved gas in a unit volume [mol/m$^3$] |
| $N_m$ | Molar amount of gas in a bubble [mol] |
| $P_{FS}$ | Pressure of cover gas [Pa] |
| $Q$ | Volumetric flow rate of sodium [m$^3$/s] |
| $r$ | Bubble radius [m] |
| $Sh$ | Sherwood number [-] |
| $S_i$ | Source term [1/s] |
| $S_{Na}$ | Area of free surface [m$^2$] |
| $v$ | Velocity [m/s] |
| $v_h$ | Horizontal velocity at free surface [m/s] |
| $v_t$ | Terminal velocity of a bubble [m/s] |
| $V_{Na}$ | Control volume [m$^3$] |
| $We$ | Weber number [-] |
| $\alpha$ | Degassing constant [-] |
| $\sigma$ | Surface tension [N/m] |
| $\rho$ | Density [kg/m$^3$] |

### Subscripts

| | |
|---|---|
| G | Gas phase |
| L | Liquid phase |

## REFERENCES

Berton, J. L., VIBUL, 1991, "Un modèle de calcul de la vie des bulles en réacteur", NTCEA, SSAE, LSMI91, 023.

Clift, R., Grace, J. R. and Weber, M. E., 1978, "Bubbles, drops, and particles", Academic Press.

Kimura, N., Hayashi, K., et al., 2003, "Hydraulic Experiment for Compact Reactor Vessel –Measurement of Flow Field Optimization in Upper Plenum", JNC TN9400 2003-032 (in Japanese).

Lewis, D. A. and Davidson, J.F., 1982, "Bubble splitting in Shear flow", Trans. IChemE, Vol. 60, pp. 283-291.

Reed, E. L. and Dropher, J. J., 1970, "Solubility and Diffusivity of inert gases in liquid sodium, potassium and NaK", Liquid Metal Engineering Center Report LMEC-69-36.

Tatsumi, E., Yamaguchi, A., et al., 2006, "Numerical study on dissolved gas and bubble behavior in fluid", Fifth Korea – Japan Symposium on Nuclear Thermal Hydraulics and Safety, Korea, November, 2006, F005.

Yamaguchi, A. and Hashimoto, A., 2005, "A Computational Model for Dissolved Gas and Bubble Behavior in the Primary Coolant System of Sodium-Cooled Fast Reactor", 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, France, October, 2005, 477