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Development of Two-Dimensional Hydrogen Mixing Model in Containment Subcompartment Under the Severe Accident Conditions

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Abstract

A two-dimensional continuum model for the prediction of the hydrogen mixing phenomena in the containment compartment under the severe accident conditions is developed. The model could predict well the distribution of time-dependent hydrogen concentration for selected HEDL Experiment. For a simulation of these experiments, the hydrogen is mixed uniform over the test compartment. To predict the extent of non-uniform distribution, the dominant factors such as the geometrical shape of obstacle and velocity of source injection in mixing phenomena are investigated. If the obstacle disturbing the flow of gas mixture exists in the compartment, the uniform distribution of hydrogen may be not guaranteed. The convective circulation of gas flow is separately formed up and down of the obstacle position, which makes a difference of hydrogen concentration between the upper and lower region of the compartment. The recirculation flow must have a considerable mass flow rate relative to velocity of the source injection to sustain the well-mixed conditions of hydrogen.

1. Introduction

The mixing transient of hydrogen within the containment under the severe accident conditions can be affected by numerous mixing mechanism, including source momentum, forced convection, inter-compartmental pressure gradient driven flow, natural convection and diffusion(see Table 1). These physical intuitions must be translated into mathematical expressions for problems to be addressed in a tractable form. Most analytical models[1-7] can be broadly grouped into two categories - lumped-parameter models and continuum models. In general, the computer code CONTAIN or MARCH has been used to calculate the hydrogen distribution, where the codes are a lumped parameter model based on control volume or nodal balances of pasive entities such as component mass and energy. These model provides accurate descriptions of large uniformly mixed volumes. However, the underlying assumption is that of well-mixed volumes because no spatial detail within a compartment can be discerned. The post-TMI investigation, which had determined the installation of new mitigative systems in the smaller volume or more compartmentalized spaces, demonstrated ans emphasized that if the obstacle disturbing the flow of gas mixture exists in subcompartment, the uniform mixing of the hydrogen distribution can be not guaranteed. Therefore, to reduce the possibility of hydrogen burn and to control the time-dependent hydrogen concentration, a more accurate model to predict the hydrogen transport in subcompartment is needed. And a more simple model to take the place of the existant expensive continuum model is needed.

In this study, a two-dimensional axi-symmetric continuum model will be presented. Also, after showing the appropriate verification of a new analytical model, the effects of the dominant physical factors affecting the hydrogen distribution in test compartment will be investigated focused on the establishment of the hydrogen control strategies.

2. The Development of Analytical Model

A two-dimensional incompressible continuum model is established to treat one velocity field and one mixture of multi-fluid such as hydrogen(or helium), steam, and air. The velocity of mixture is defined by the relationship

$$\mathrm{v} = \frac{\sum_{i=1}^{N} \rho_i \mathrm{v}_i}{\sum_{i=1}^{N} \rho_i} \qquad (1)$$

for a mixture of N species. The independent behavior of gas species is treated by the equation of species continuity. In deriving the governing equations of the species, the continuity equation is generally given by

$$\rho \frac{\partial Y_i}{\partial t} + \rho \vec{v} \cdot \nabla Y_i + \nabla \cdot \rho Y_i V_i = 0 \qquad (2)$$

In Eq. (2), the diffusion velocities V_i which is defined by the velocity of the species with respect to stationary coordinate axis, v_i and mass-averaged velocity, v, must be determined. This could be solved by one of the two methods: by Fick's law of mass diffusion with mass diffusivity and by transport equation for the collection of species. In this study, in order to maintain the consistency of our aim, Fick's law is used, as which applies on the analysis of the hydrogen combustion problems.

The calculations of the mixture transport properties are carried out by approximate averaging formula recommended by Perry's Chemical Engineering Handbook[8], where the values of the properties depend on the mole fraction of each species. The turbulance of mixing is treated by Prandtl's mixing length model[9] which the eddy viscosity is expressed by the gradient of local average velocity.

3. Results and Their Verification

To evaluate the ability of the model to predict hydrogen mixing phenomena, selected experiment from Hanford Engineering Development Laboratory (HEDL) test programs has been simulated. The hydrogen mixing tests performed at HEDL[10] are representative of events in which hydrogen is injected at higher rates than typical of slowly degrading core event. The test includes the presence of steam, complex geometrical arrangements, and containment air recirculation systems. The facility and associated features are depicted in Fig. 1. Besides, Fig. 1 shows the test geometry non-uniformly nodalized, where the optimal number of nodes are investigated in 22 x 22 by preliminary runs. By this nodalization, we obtain the helium concentration compared with experimental results as shown Fig. 2. The predicted peak concentration of helium shows a good agreement to experimental result over span of the calculation. But, a little difference on predictions of the concentration reveals; at the timing of source injection and at the final saturated stage, the higher increasing rate and the higher concentration. These differences result from the modelling of two-dimensionalization of experiments and, therefore, it is acceptable for this calculation to simulate. The helium distribution is predicted to mix well uniformly within the compartment after the injection of sources as observed in HEDL experiments. Fig. 3 shows the degree of mixing in the compartment where the ordinate represents the maximum-to-average ratio. The ratio are rapidly approaching to unity when the source injection has finished due to recirculation flows. The position of maximum helium concentration is near a source. The typical of flow patterns being influenced by the recirculation flow are shown in Fig. 4.

On the other hand, this study simulated the hydrogen mixing under the same experimental conditions, which analyzed the similar behavior like the helium mixing.

4. The Analyses of the Factors Influencing the Hydrogen Mixing

4.1 Recirculation Flow

Fig. 5 shows the averaged hydrogen concentrations with a obstacle of circular disk at 2.35-2.55 m in height and 1.00 m in size. Here, the term, "size" means the length from the outer compartment wall, where the size of 1.00 m correspnds to about 56 % hindrance of flow area. The case (a), which simulates the simple hydrogen mixing in case of no recirculation flow, shows the concentration difference between the upper and lower region is about 2 %. This result explains that the obstacle is dominant factor to determine the hydrogen mixing phenomena. The result of case (b), which is allowed to operate the fan of 1.0 m/sec, is similar to that of case (a) except for the influence area of the recirculation flow. Because the flows of source injection and recurculation go just to the opposite direction and the mass flow rate of source is larger than that of allowed recirculation, there is no difference between (a) and (b) cases. As seen in case (c), however, the larger the velocity of recirculation flow is the less the difference of averaged concentration between the upper and lower region is. The recirculation flow can make a well-mixed situation in the upper region of the compartment and make the momentum toward the outer radius increased. Therefore, the averaged concentration in the upper region is reduced.

The typical velocity profiles with and without recirculation flow are shown in Fig. 6. For no recirculation flow, a single circulation flow pattern is formed from top inside to bottom outside, but partially developed. Near upper surface of obstacle, the flow is very slow. With a recirculation flow, the obstacle is a border of separated circulation patterns and the flow proceeds over all region of test compartment.

4.2 Obstacle Size

In case of no recirculation flow, the result with the obstacles installed at 2.35 m - 2.55 m in height with a size variation of 0.15(case a), 1.00(case b), and 1.50(case c) m respectively, are shown in Fig. 7. Case (a), having a short obstacle, shows the hydrogen distribution is nearly uniform(the difference is about 0.7 %) and is close to the mixing of free volume. Case (b) shows the larger difference of 2 %. It is stated, therefore, that the longer the size of obstacle is, the larger the difference between the upper and lower region is. But, case (c), which simulates the very small flow area from lower to upper region , shows the difference is reduced on the contrary. This unpredicted result could be explained by the fact that very severe hindrance of flow do make a circulation of lower region only and the gases penetrating the obstacle go through the upper region and exit the compartment. Hence, the hydrogen concentration of upper region is reduced and so does the difference. This is illustrated in Fig. 8.

4.3 Source Injection Velocity

The source gases are injected near center of compartment bottom with a variation of 1.0(case a), 3.0(case b), and 5.0(case c) m/sec respectively. For this calculation, the obstacle is installed 2.45 m in height, 0.2 m in thickness, and 1.00 m in size. Fig. 9 shows the hydrogen concentration without a recirculation flow. Because fast injection of source makes the mass flow rate increased, the averaged hydrogen concentration is increased from case (a) to case (c). The difference between regions of hydrogen concentration is increased, too. This is because of separated circulation flow in upper and lower region. Fig. If the recirculation flow is allowed for the hydrogen mixing, the effects of source injection are determined by the relative velocities of both. The concentration difference between regions could be decreased as seen in Fig. 10, which simulates the recirculation flow as 3.0 m/sec. Since the flow into the lower region is formed, the concentration is decreased in the upper region. Also, since the gases entering from the upper region and gase injected from the source are mixed, the concentration of the lower region is increased. Therefore, it can be stated that the uniform distribution of hydrogen may be conformed by the competitive recirculation flow compared with source injection velocity.

5. Conclusions

In this study, the hydrogen mixing model is developed to analyze the transport phenomena and predict distributions of the hydrogen concentration. Also, this study has been aimed to obtain the understanding of the qualitative mixing conditions under different geometrical and physical factors and then a basis to establish "well-mixing" factor in subcompartment as a complement of lumped parameter models. This model is successfully verified by comparing with selected experiments. And the dominant factors to determine the hydrogen mixing are investigated to predict the possibility of the local stratification in subcompartment. Thus, it is concluded that

(1) If the compartment has only a free volume, the hydrogen shows a well-mixed distribution. And the flow is governed by the convective circulation over all compartment.

(2) If the obstacle disturbing the flow of gas mixture exists in the compartment, the uniform distribution of hydrogen may be not guaranteed.

(3) The recirculation flow must have a considerable mass flow rate relative to velocity of the source injection to sustain

the well-mixed conditions of hydrogen.

For this study, we will go on investigating geometrical effects for the distribution of hydrogen and present the correction factor of well-mixing in sub-compartment.

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Mechanism	Description
Source momentum	Especially entrainment caused by strong jets
Intercompartmental flow	Driven by pressure gradients produced by heterogeneous sources and localized heat mass transfer
Forced convection	Produced by mechanical devices, such as recirculation fans and fan coolers, and by momentum transfer from sprays.
Natural convection	Buoyant flows induced by source gases, temperature differences, heat transfer to cold sinks, and condensation ; affected by initial compartment conditions.
Diffusion	Both molecular and turbulent

Table 1 Important Hydrogen Mixing Mechanisims

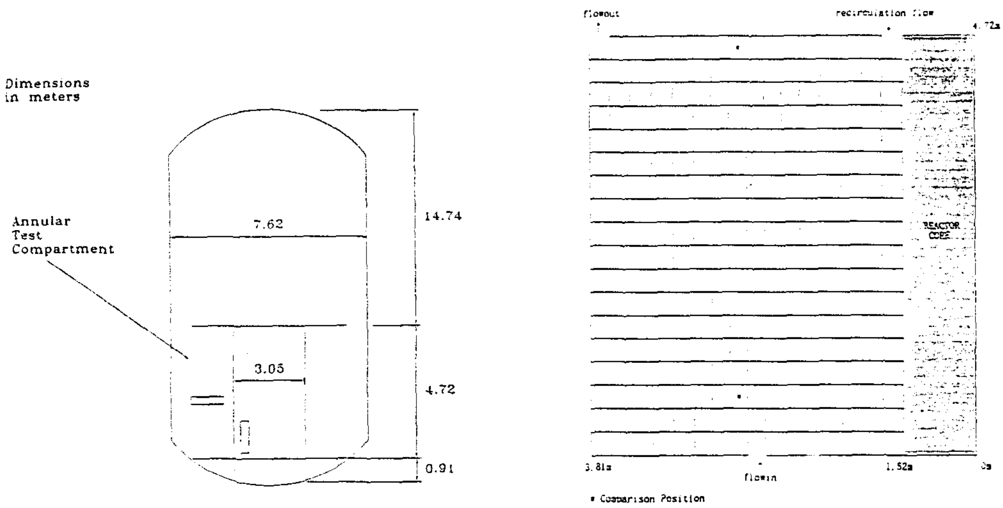


Fig. 1 HEDL Facility and Calculation Discretization

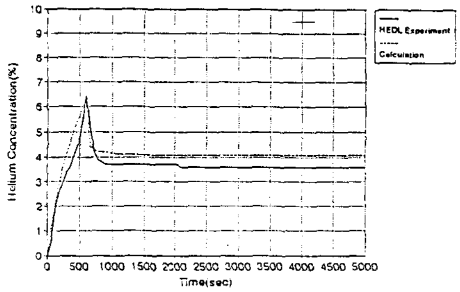


Fig. 2 Comparison of Calculation with Experimental Result (Mixture : He-H_2O-Air)

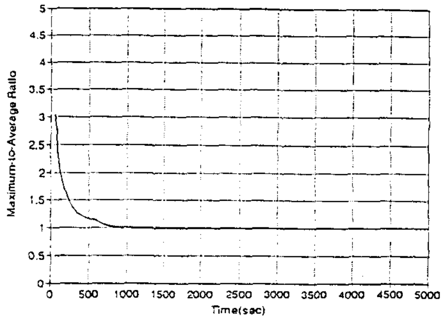


Fig. 3 Maximum-to-Average Ratio of Helium Concentration

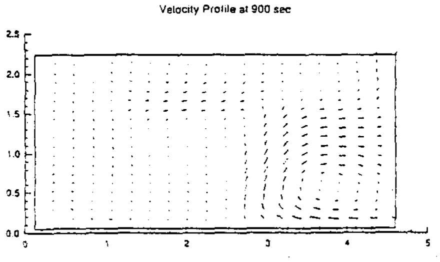
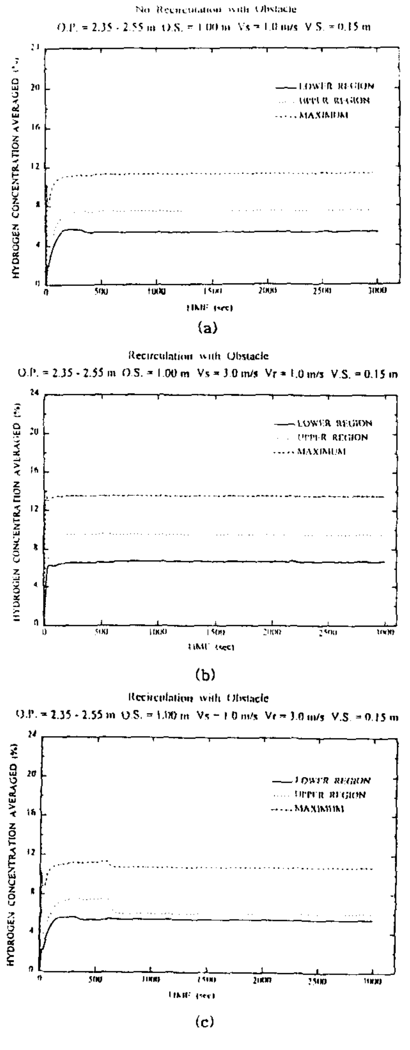


Fig. 4 Velocity Profile of Helium at 900 sec



(a)

(b)

(c)

Fig. 5 Hydrogen Concentration with Recirculation Flow

(a) Without Recirculation Flow　　(b) With Recirculation Flow

Fig. 6 Velocity Profile of Hydrogen Concentration

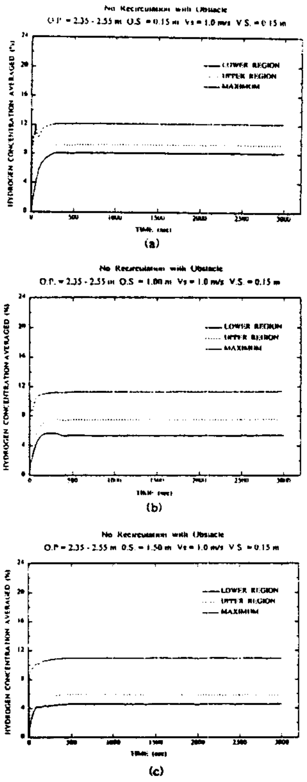


Fig. 7 Hydrogen Concentration with Variation of Obstacle Size in No Recirculation Flow

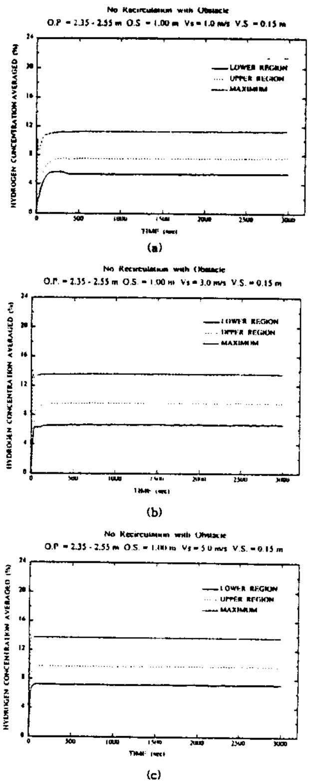


Fig. 9 Hydrogen Concentration with Variation of Source Injection Velocity in No Recirculation Flow

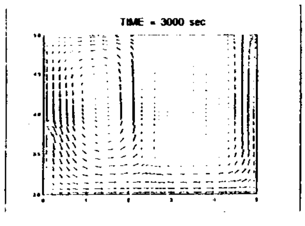


Fig. 8 Hydrogen Velocity Profile with Long Obstacle in No Recirculation Flow

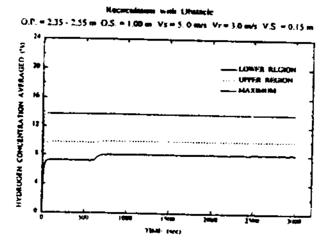


Fig. 10 Hydrogen Concentration with High Source Injection Velocity in Recirculation Flow