Development of a Non-condensable Gas Transport Model in the SPACE Code

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1. Introduction

A general purpose multi-dimensional two phase thermal hydraulic analysis code, SPACE has been developed utilizing two-fluid three-field governing equations [1-4]. Various mesh systems have been developed to allow users to model the wide variety of geometries encountered in nuclear reactor system. Several numerical schemes, such as collocated, staggered, semi-implicit, and implicit schemes, also afford users the considerable flexibility in meeting particular analysis objectives. In this study, non-condensable gas transport model is incorporated into the SPACE code. In the following sections, the main feature of the non-condensable gas transport model and its application results will be presented.

2. Non-condensable Gas Transport Model

2.1 General description

To consider non-condensable gas species as a component of the gaseous phase, the gas field in the SPACE code is assumed to be a homogeneous equilibrium mixture of vapor and non-condensable gases. Conservation equation of the non-condensable gas mixture, which is comprised of the non-condensable gas species, is involved in the SPACE three-field governing equations, whereas species transport equations are decoupled from the major governing equations. Therefore, the non-condensable gas species transport equations are solved separately, after ten major governing equations are solved.

2.2 Non-condensable gas mass conservation equations

The mass conservation equation for the non-condensable gas mixture is as follows.

$$\frac{\varepsilon V}{\Delta t}\left(\alpha_g^n \rho_n^n - \alpha_g \rho_n\right) + \sum_{E \in P} \varepsilon^E \, {}^d\alpha_g^E \, {}^d\rho_n^E \left(\iota_P^E U_{gn}^n A^E\right) = 0$$

The following is the mass equation for i-th non-condensable gas species.

$$\frac{\varepsilon V}{\Delta t}\left(\alpha_g^n \rho_{ni}^n - \alpha_g \rho_{ni}\right) + \sum_{E \in P} \varepsilon^E \, {}^d\alpha_g^E \, {}^d\rho_{ni}^E \left(\iota_P^E U_{gn}^n A^E\right) = 0$$

In the above equations, α_g^n and U_{gn}^n is a new time void fraction and a new time velocity, respectively. ρ_{ni} is the density of the i-th non-condensable gas species. ρ_n is the density of non-condensable gas mixture. Once α_g^n and U_{gn}^n are known, the density of individual non-condensable gas species can be easily obtained from the second equation. Only N-1 of the non-condensable gas species equations need to be solved, since the mass of the N-th species can be obtained from the difference between those of the non-condensable gas mixture and the sum of the N-1 non-condensable gas species.

2.3 Non-condensable gas properties

An important step in the setup of the non-condensable gas transport model is to define the material properties. To calculate the mixture properties including more than one species, each non-condensable gas species is considered as an ideal gas. A mixture of several species of perfect gases is still a perfect gas and the composition of a gas mixture can be defined by the mass fraction. To determine the properties of a mixture, we need to know the composition of the mixture as well as the properties of the individual components. The properties of individual non-condensable gas species are first calculated to obtain the properties of the total non-condensable gas as well as the mixture of steam/non-condensable gas.

Thermal properties of the non-condensable gas mixture are evaluated from the functional form of state equations with the mass-fraction weighted coefficients. Perfect gas equation of state is applied to determine the density. Internal energy is evaluated with the gas temperature and the properties of individual gas species at the reference temperature.

The transport properties, such as viscosity and thermal conductivity, are obtained for individual non-condensable gas species. Sutherland's formula computes the viscosity for a perfect gas with fixed composition as a function of temperature. The thermal conductivity is also defined as a function of temperature. The transport properties for the mixture of steam/non-condensable gas are determined based on kinetic theory as

$$\mu_g = \sum_{i=1}^{N} \frac{x_i \mu_i}{\sum_{j=1}^{N} x_i \phi_{ij}}$$

$$\text{Where, } \phi_{ij} = \frac{1}{\sqrt{8}}\left(1+\frac{M_i}{M_j}\right)^{-0.5}\left[1+\left(\frac{\mu_i}{\mu_j}\right)^{0.5}\left(\frac{M_i}{M_j}\right)^{0.25}\right]^2$$

x_i is the mole fraction of species i.

3. Application Results

3.1 Test problem

The 15 cell pipe network test problem designed to check validation of non-condensable gas transport model is shown in Figure 1. Initially, the pipe is filled with pure hydrogen gas. The helium gas, the molecular weight of which is 4, is injected through bottom face and the nitrogen gas, the molecular weight of which is 28, is injected through the right end of the branch pipe. Since the molecular weights of the non-condensable gases are very different, we can check easily if they are mixing properly. The outlet boundary condition is given at top face.

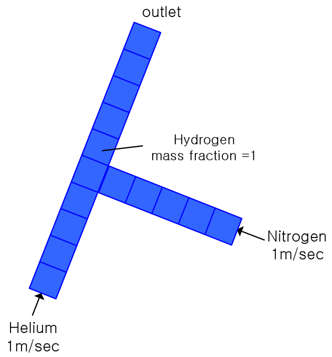

Figure 1. Geometry of the test problem

3.2 Results

Figure 2 and Figure 3 show mass fractions of the helium gas and the nitrogen gas, respectively.

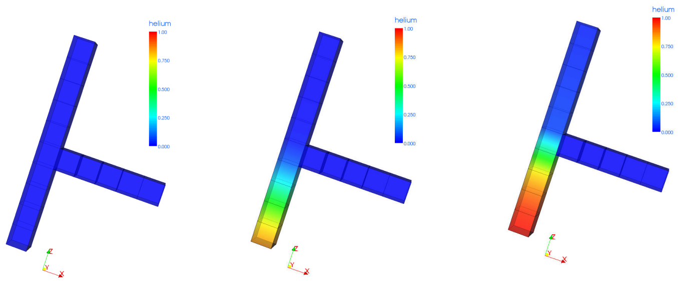

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Figure 2. Helium mass fraction

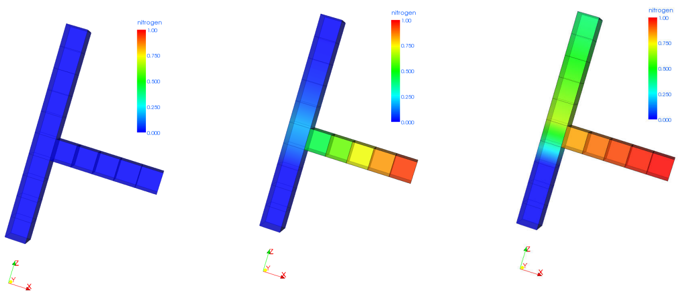

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Figure 3. Nitrogen mass fraction

As shown in the figures, the helium gas injected from the bottom face starts to mix with the hydrogen gas at the lower part of the main pipe and the nitrogen is mixing in the right side branch pipe. As the gases continue to be injected from the two inlets, the hydrogen gas is discharged from the pipe, then the helium and nitrogen gases fill up all the computational cells. Since the helium to nitrogen gas mass ratio is 1 to 7, the nitrogen mass fraction is appeared to be dominant at the upper half of the main pipe. All of the test results are qualitatively in agreement with the physics of this problem.

4. Conclusions

Mass conservation equation for each non-condensable gas species and the property calculation modules for the gaseous phase are incorporated into the SPACE code. As an effort for verification, the non-condensable gas transport model is assessed for helium-nitrogen mixing phenomena in a simple pipe network. It is concluded from the test results that the SPACE code with the non-condensable transport model works properly for the mixing phenomena of non-condensable gases.

Acknowledgment

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