NUMERICAL VISUALIZATION OF TWO-PHASE PLUME FORMATION IN STRATIFICATION FLOW ENVIRONMENT

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Two-phase plumes driven by buoyancy in a stratification ambient are common flow phenomena found in ocean engineering and other environmental applications[1-2]. Focusing the investigation on the discrete nature of the buoyant dispersed phase and the roles of mass and momentum exchange between the two phases in the plume formation, a numerical model was developed by means of two-fluid flow theory and large eddy simulation technology.

GOVERNING EQUATIONS

The governing equations for the continuous phase, coupled with dispersed phase, in the Eulerian-Eulerian scheme were fully solved based on control volume techniques. For the continuous phase, the equations are:

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial\bar{\rho}\hat{u}_i}{\partial x_i}=\dot{w}_{dco} \tag{1}$$

$$\frac{\partial\bar{\rho}\hat{u}_i}{\partial t}+\frac{\partial\bar{\rho}\hat{u}_i\hat{u}_j}{\partial x_j}=-\frac{\partial\hat{p}}{\partial x_i}+\frac{\partial\bar{\rho}\hat{\tau}_{ij}}{\partial x_j}+(\bar{\rho}-\rho_0)g_i+(\dot{F}_{dco})+F_{tT}\delta_{ij} \tag{2}$$

Here, $\hat{p}$ is a dynamic pressure and F_t a turbulent force[2]. $\delta_{ij}=1$ when i=j=1 and zero otherwise.

$$\frac{\partial\bar{\rho}\hat{\phi}_k}{\partial t}+\frac{\partial\bar{\rho}\hat{\phi}_k\hat{u}_j}{\partial x_j}=\frac{\partial}{\partial x_j}(\bar{\rho}D_k\frac{\partial\hat{\phi}_k}{\partial x_j})+\frac{\partial\bar{\rho}\hat{q}_k}{\partial x_j}+\dot{w}_{dco}\delta_{kl} \tag{3}$$

where $\delta_{kl}=1, when\ l=k$ for mass fraction of the dispersed phase and $\delta_{kl}=0, when\ l\neq k$ for temperature and salinity. $\dot{w}_{dco}$ and $\dot{F}_{dco}$ are the exchange rates of mass and momentum, respectively, between the two phases

The fundamental equations of the dispersed phase are:

$$\frac{\partial\hat{n}_d}{\partial t}+\frac{\partial\hat{n}_d\hat{u}_{dj}}{\partial x_j}=0 \tag{4}$$

$$\frac{\partial\hat{\alpha}}{\partial t}+\frac{\partial\hat{\alpha}\hat{u}_{dj}}{\partial x_j}=-\dot{w}_{dco}/\rho_d \tag{5}$$

$$\frac{\partial\bar{\rho}_d\hat{u}_{di}}{\partial t}+\frac{\partial\bar{\rho}_d\hat{u}_{di}\hat{u}_{dj}}{\partial x_j}=\hat{\alpha}(\rho_d-\rho_w)g_i-(\dot{F}_{dco})_i \tag{6}$$

where $\hat{\alpha}$, $\hat{n}_d$, and $\hat{u}_{di}$ are the volume fraction, number density, and velocity vectors of droplets, respectively. $\bar{\rho}_d=\hat{\alpha}\rho_d$ and ρ_d is the physical density of droplet.

The turbulent transport terms within a scale smaller than the grid size are choused by a so-called " structure-function " model[3] in order to take the effect of stratification into account.

RESULTS

Computation experiments on two-phase plume formation were performed using the LED CFD code developed based on the model and the above equations. The visualization results obviously show the plume behaviors of entrained fluid peeling, stratification, and separation in a cross shear flowing ambient. In the case of quiescent environment, the continuous phase plume is evaluated as a multi-layer plume in nature. The plume trap height can be expressed by buoyancy flux, Brunt-Vaisala buoyancy frequency, and initial interface area when mass transfer is included. The later produces additional-negative buoyancy. This is visualized in Fig.1. The interactions between continue plume (imaging) and the dispersed plume (contour lines) creates the structure.

In case of cross shear flow, the characteristic flow velocity must be another key parameter, taken for predicting the separating position between two plumes. The volume fraction of the dispersed phase (contour line) and the mass fraction of solution of the continuous phase (imaging) are plotted in Fig.2 as an example indicating plume separation. It is indicated that there seems to be no strong coupling between two plumes in this case, except at the location around the dispersed phase releasing exit. The two plumes separate because of cross flow.

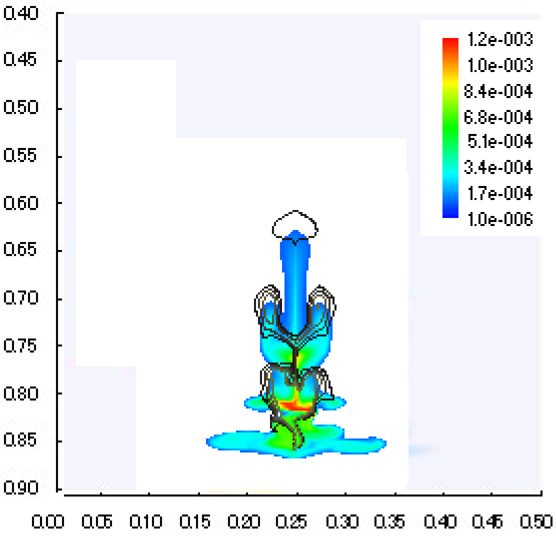

Fig.1, Two plumes formatted in quiescent stratification ambient.

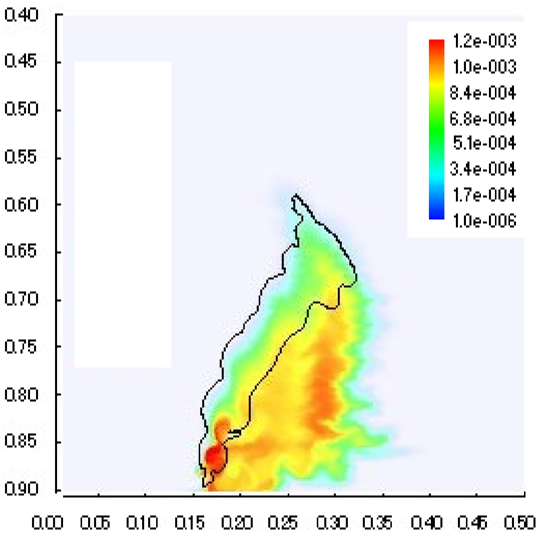

Fig. 2, Two plumes formatted in cross flow stratification ambient

The 3-D view of the continuous phase plume for two initial interface areas with cross shear flow is given in Fig. 3. The larger initial interface area produces a lower trap height plume and wide bottom basis that is caused by enhanced mass transfer and strong peeling.

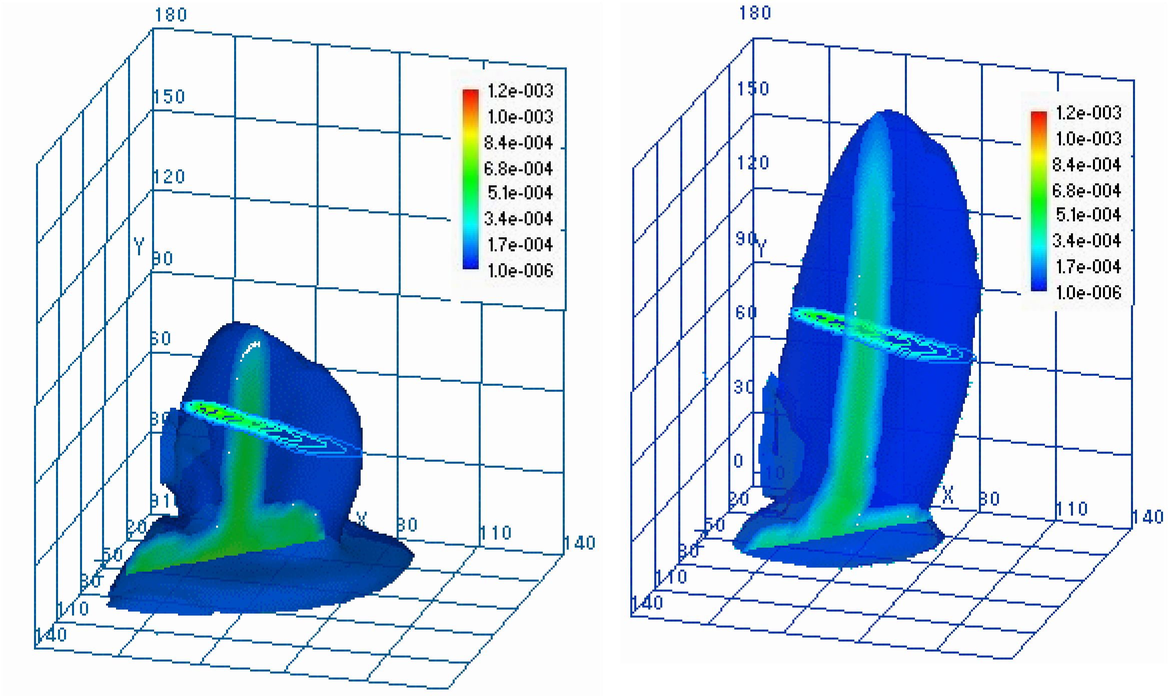

Fig. 3. The 3-D views on continue phase plumes with cross shear flow. The larger initial interface area (left) and standard one (right)

CONCLUSIONS

The 3-D unsteady Large-eddy simulation model and associated CFD code, developed by the authors, are capable of predicting the main mechanism of two-phase plume formation in a stratification environment. The simulation tests also show the potential for other engineering applications as, for instance the simulation of CO2 sequestration in the ocean.

In contrast with single-phase plume, the numerical simulation demonstrate that the initial interface of dispersed phase is an important parameter in determining the plume trap height when coupling the action of additional-negative buoyancy induced by mass transfer.

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