DIFFERENCE IN TURBULENT DIFFUSION BETWEEN ACTIVE AND PASSIVE SCALARS IN STABLE THERMAL-STRATIFICATION

Kouji Nagata and Satoru Komori
Department of Mechanical Engineering
Kyoto University
Kyoto 606-8501
Japan

ABSTRACT

The difference in turbulent diffusion between active scalar (heat) and passive scalar (mass) in a stable thermally stratified flow is investigated. The experiments are conducted in an unsheared thermally stratified water flow downstream of turbulence-generating grid. Passive mass is released into the thermally stratified flow from a point source located at 60mm downstream from the grid. Instantaneous streamwise and vertical velocities, temperature of active scalar and concentration of passive scalar are simultaneously measured using a combined technique with a two-component laser-Doppler velocimeter (LDV), a resistance thermometer and a laser induced fluorescence (LIF) method. Turbulent heat and mass fluxes and eddy diffusivities for both active heat and passive mass are estimated.

The results show that stable stratificaion causes the large difference in eddy diffusivities between active heat and passive mass. The difference suggests that an assumption of identical eddy diffusivity for active heat and passive mass, used in conventional turbulence models, gives significant errors in estimating heat and mass transfer in a plume under stably stratified conditions.

INTRODUCTION

Flows in the ocean and the atmospheric boundary layer are often density-stratified and the diffusion of scalars such as heat and mass is strongly affected by buoyancy. It is, therefore, of great importance to investigate the buoyancy effects on heat and mass transfer in predicting the turbulent diffusion of scalar quantities in the environment. In addition, it is of practical importance in designing industrial heat and mass transfer equipment.

For engineering purposes, time-averaged transport equations for heat and mass:

$$\frac{\partial \overline{T}}{\partial t} + \overline{U_j}\frac{\partial \overline{T}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\alpha\frac{\partial \overline{T}}{\partial x_j} - \overline{u_j\theta}\right), \qquad (1)$$

$$\frac{\partial \overline{C}}{\partial t} + \overline{U_j}\frac{\partial \overline{C}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\mathcal{D}\frac{\partial \overline{C}}{\partial x_j} - \overline{u_jc}\right), \qquad (2)$$

are solved to obtain local time-averaged temperature and concentration, where $\overline{T}$ and $\overline{C}$ are the time-averaged temperature and concentration, $\overline{U_j}$ the time-averaged velocity in the $j-$direction, α the thermal diffusivity, $\mathcal{D}$ the molecular diffusivity of mass, $\overline{u_j\theta}$ and $\overline{u_jc}$ the turbulent heat and mass fluxes, respectively. To numerically solve above equations, turbulent heat and mass fluxes in (1) and (2) must be modeled. To describe the vertical turbulent heat and mass fluxes in a stratified flow, the conventional gradient-diffusion models have been widely used;

$$\overline{v\theta} = -K_H\frac{\partial \overline{T}}{\partial y}, \qquad (3)$$

$$\overline{vc} = -K_S\frac{\partial \overline{C}}{\partial y}, \qquad (4)$$

where K_H and K_S are the vertical eddy diffusivities for active heat and passive mass, respectively. K_H and K_S are usually assumed to be identical (e.g. Yamada and Mellor 1975; Freeman 1977). However, for different initial and boundary conditions, a large difference in the eddy diffusivities for active heat and passive mass under stable conditions is expected (Pearson, Puttock and Hunt 1983). If the eddy diffusivity is different between active heat and passive mass, the predictions of turbulent diffusion of pollutants by the conventional models may have serious errors.

The purpose of this study is to investigate the difference in turbulent diffusion between active heat and passive mass in a stable thermally stratified flow. The measurements were conducted using a combined technique with a two-component laser-Doppler velocimeter (LDV), a resistance thermometer and a laser induced fluorescence (LIF) method (Komori and Nagata 1996).

EXPERIMENTS

Figure 1(a) shows the measuring system and test apparatus. The test apparatus used was a water tunnel made of polymethylemethacrylate (PMMA), 1 m in length and 0.1 × 0.1 m in cross-section. A turbulence-generating grid was installed at the entrance to the test section, and it was of round-rod, square-mesh, single-biplane construction. The mesh size M and the diameter of the rod d were 2.0×10^{-2} m and 3.0×10^{-3} m, respectively. Thermally stratified water flows were generated in the test section downstream of turbulence-generating grid. Hot and cold waters were separately pumped up from two big storage tanks to the head tanks, and then passed through the contraction, which was separated by a splitter plate into upper and lower sections. The water was released as a plume from an injection nozzle located on the centerline of $y = 0$ and $z = 0$ and at 60 mm downstream from the grid ($x/M = 3$) as shown in figure 1(b). To enable us to determine the instantaneous concentration of passive mass in the plume, sodium fluorescein dye ($C_{20}H_{10}Na_2O_5$) was homogeneously premixed in the ambient flow (in both the upper and lower streams) with the initial concentration of 5.0×10^{-5} mol m^{-3}. Experimental conditions including the Reynolds number based on the mesh size, Re_M ($= U_{ave}M/\nu$), and the bulk Richardson number, Ri_b ($= \beta g \Delta \overline{T} M/U_{ave}^2$; β: the thermal volumetric expansion coefficient) are listed in table 1.

Table 1. Flow conditions.

Run No.	U_{ave} [m s^{-1}]	Re_M [-]	$\Delta \overline{T}$ [K]	Ri_b [-]
E-I	0.125	2500	0.0	0.0
E-II	0.125	2500	3.0	7.8×10^{-3}
E-III	0.125	2500	15.0	3.9×10^{-2}

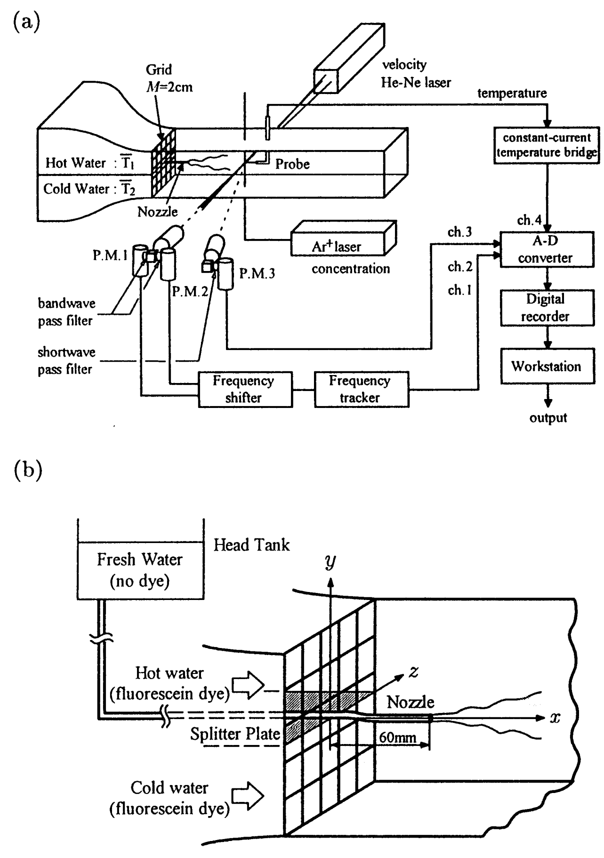

Figure 1. Experimental setup. (a) Measuring system and test apparatus. (b) Injection nozzle and coordinate system.

RESULTS AND DISCUSSION

To confirm the streamwise evolution of the mean concentration field, the mean concentration in a plume was measured at the locations of x/M=10, 12, 14, 16 and 18 in neutral stratification (Run E-I). The vertical distributions of the mean concentration are shown in figure 2. Here, the mean concentrations and vertical distance are normalized by the mean concentration on the plume axis, C_{max}, and half-width of the mean concentration profile, l_c, respectively. The profile of the normalized mean concentration at each location has the same shape described in terms of the Gaussian function. The shape is in good agreement with that derived from the similarity analysis for the mean concentration field in neutral stratification. This suggests that a typical plume is formed in the test section in the region of $10 \leq x/M \leq 18$ and that the effects of disturbances by the inserted nozzle on the evolution of the plume are negligibly small.

Eddy diffusivities for active heat and passive mass were estimated by (3) and (4). Figure 3 shows the vertical distributions of the eddy diffusivities for active heat and passive mass at $x/M = 14$ in neutral, weak and strong stratifications. The difference in the eddy diffusivities exists even for the weakly stratified case. The stronger stratification causes the larger difference in the eddy diffusivities between active heat and passive mass. This means that the turbulent diffusion of passive scalar is less affected by buoyancy than that of active scalar.

The results show that the large difference in eddy diffusivities in stable stratification is caused by stable stratification, and the eddy diffusivity of passive mass can never be given in stratified flows by the same value as the eddy diffusivity of active heat.

CONCLUSIONS

The difference in turbulent diffusion between active and passive scalars in stable thermal stratification was investigated. The main results from this study can be summarized as follows.

1. Turbulent diffusion of passive scalar is less affected by buoyancy than that of active scalar when the initial and boundary conditions for active and passive scalar are not identical.
2. For different initial and boundary conditions between active heat and passive mass, a stable stratification causes a large difference in the eddy diffusivities between active heat and passive mass. The difference suggests that an assumption of the identical eddy diffusivity for active heat and passive mass, used in conventional turbulence models, gives significant errors in estimating turbulent diffusion of heat and mass in a stably thermally stratified flow.

ACKNOWLEDGEMENTS

The authors would like to thank Messrs. H. Horibe and T. Iwabe for their help in conducting experiments. This work was supported by the Japanese Ministry of Education, Science and Culture through grants-in-aid (Nos.09750230 and 09450079).

REFERENCES

Freeman, B. E., 1977, "Tensor diffusivity of a trace constituent in a stratified boundary layer," *J. Atmos. Sci.*, Vol.34, pp.124–136.

Komori, S., and Nagata, K., 1996, "Effects of molecular diffusivities on counter-gradient scalar and momentum transfer in strongly stable stratification," *J. Fluid Mech.*, Vol.324, pp.205–237.

Pearson, H. J., Puttock, J. S., and Hunt, J. C. R., 1983, "A statistical model of fluid-element motions and vertical diffusion in a homogeneous stratified turbulent flow," *J. Fluid Mech.*, Vol.129, pp.219–249.

Yamada, T., and Mellor, G., 1975, "A simulation of the Wangara atmospheric boundary layer data," *J. Atmos. Sci.*, Vol.32, pp.2309–2329.

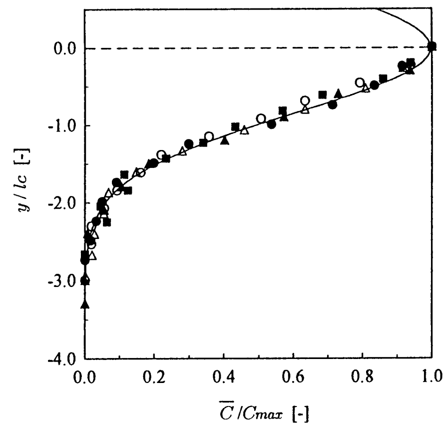

Figure 2. Vertical distributions of the normalized mean concentration in a plume in neutral stratification (Run E-I): ▲, $x/M = 10$; △, $x/M = 12$; ●, $x/M = 14$; ○, $x/M = 16$; ■, $x/M = 18$. The solid line shows the Gaussian curve.

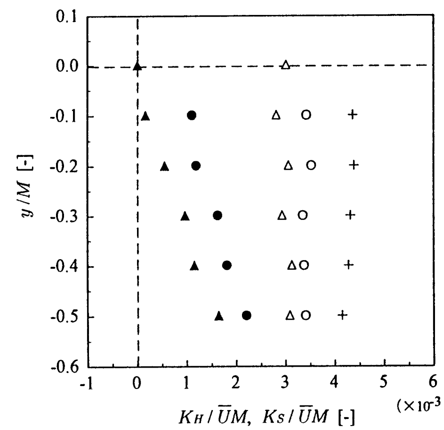

Figure 3. Vertical distributions of the eddy diffusivities for active heat and passive mass at $x/M = 14$: +, K_S in neutral stratification (Run E-I); △, K_H in weak stratification (Run E-II); ○, K_S in weak stratification (Run E-II); ▲, K_H in strong stratification (Run E-III); ●, K_S in strong stratification (Run E-III).