INFLUENCE OF SUSPENDED PARTICLES AND PARTICLE COVER OVER THE DENSITY INTERFACE*

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ABSTRACT

The effect of the particle cover over the density interface between two layers of fluids and of the suspended solid particles in the upper turbulent layer on the turbulent entrainment has been studied experimentally. The entrainment distance D is a function of the time of $\mathscr{H}$ power: $D = kt_{\mathscr{H}}$, where $\mathscr{H} = 0.200 - 0.130\tilde{h}_p$. For suspended particles in the upper layer and pure 2-layer fluid $\mathscr{H}$ is equal to 0.200, but the value of k for the suspended particles is smaller than that for the pure 2-layer fluid. The non-dimensional entrainment velocity is $E = KRi_l^n$, where $n = 1.50 + 0.93\ \tilde{h}_p$. It is shown that the particle cover over the interface changes the power of Ri_l in the entrainment and hinders the turbulent entrainment. The variation rule of E for the suspended particles is the same as that for the pure 2-layer fluid, but the K value of the former is smaller than that of the latter. The turbulent mixing mechanism has been discussed.

Keywords: stratified fluid, suspended particles, turbulent entrainment.

I. INTRODUCTION

The quarterly changes of temprature and salinity in the upper part of the ocean brings about stratifying phenomena, e.g. thermocline and density stratification. Similar situations, such as the inversion layer, are found in the atmosphere. Under the action of shear and convection by wind and sunlight, the ocean surface sustains turbulent mixing and forms a homogeneous mixed layer. Below the mixed layer is the stable stratified fluid or a homogeneous liquid with another density. Between the two layers is an interfacial layer of great temperature or density gradient, called the thermocline or the density interface. Taking the interface as the front, the turbulent layer diffuses downward. Refs. [1,2] dealt with the problems in this respect. Experimental studies[3-10] have been performed to simulate the mixed action of wind by oscillating grid in the stratified fluid for generating turbulent mixing. The grid-generated turbulence is zero-mean-shear turbulence which reveals the characters of homogeneous turbulent motion. Ref. [11] conducted systematically experimental investigation on the entrainment law of the turbulent mixed layer across the interface under various conditions and made clear the relationship between the non-dimensional entrainment

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velocity E and the Richardson number Ri: $E = KRi^{-1.5}$, where the constant K is approximately equal to 3.8. The turbulent diffusion in the atmosphere obeys the same law[12].

Stratifying phenomena are not confined to the ocean and atmosphere. Suspended particles can also form very stable stratification. The motion of silt above river beds and dust in the atmosphere near earth, when sand storm takes place, is an example of stratified flow. Suspended particles in the contaminated water and water-drops in cloud layer are also stratifying phenomena. The heavier ones of the suspended particles fall down to the denser part of fluid and form a layer on the density interface. It is not known as yet how the particle layer covering the density interface influences turbulent mixing and entrainment in density-stratified fluid. To investigate its law is essential not only to geophysics and meterological fluid dynamics, but also to the prediction of environmental pollution diffusion.

We have conducted experimental investigation of the influence on turbulent entrainment in a 2-layer fluid of the particle cover on the density interface and the suspended particles in the turbulent layer. The present paper gives a description of the experimental apparatus, methods and results as well as a discussion of the turbulent mixing mechanism. The results show that the retarding action of the suspended particles and the particle cover on turbulent entrainment is pronounced.

II. Experimental Apparatus

The experiments were conducted in a plexiglass tank 52 cm × 52 cm in cross section and 72cm in height (Fig. 1). The oscillating grid was composed of 2cm-square bars, aligned in a square array of mesh $M = 10$ cm. The grid was mounted on the vertical axis across the center of the tank, movable vertically to attain the designated position. The oscillating transport installation drove the grid to oscillate vertically with stroke, S(the amplitude A being $S/2$), 0—8 cm and oscillation frequency, f, 0—6 cm Hz. Saline water was used as the stratified fluid in the tank. A special input installation was used to let in saline water to make a linearly density-stratified fluid and a 2-layer fluid with two different densities.

The oscillating grid in a 2-layer fluid generates zero-mean-shear turbulence. Ref. [11] gave a general description of the character of this turbulent motion. For the said parameters, the r. m. s. velocity of turbulence can be determined by an empirical relation[8]:

$$u = CS^{3/2}M^{1/2}fz^{-1}, \tag{1}$$

where z is the distance measured from the center plane of the grid, constant C equals approximately 0.30, and integral length-scale l increases with increasing distance z:

$$l = \beta z, \tag{2}$$

where β is a constant related to S, approximately 0.10. To remove the end influence of the grid and make the turbulence homogeneous, the distance between the grid end and the side wall of the tank is maintained at about 2 mm (as small as possible).

III. Experimental Method

(1) *Pouring the stratified fluid.* The tank was filled with a 2-layer fluid in across depth $H = 58$ cm. The upper layer was the homogeneous water with density ρ_1 and the lower layer, homogeneous saline water with density ρ_2. The density difference $\Delta\rho_0 = \rho_2 - \rho_1$ depends on necessity(e.g. sufficient turbulente entrainment distance D to prevent particles from buoying up). Generally speaking, the greater the $\Delta\rho_0$, the smaller the turbulent entrainment velocity (i. e. the going-down velocity of the turbulent layer), and the longer the experimental time. The depth of the upper layer is $d_0 = z_0 + D_0$, where z is the distance from the grid midplane to the free surface, and D the distance from the grid midplane to the interface between the two layers (Fig. 1). The 2-layer fluid may be arranged in the following ways: (i) The interface between the two layers is arranged under the grid, i.e. $z_0 = 6$ cm and $D_0 = 6$cm; (ii) the interface is at the grid midplane, i.e. $z_0 = 9$ cm and $D_0 = 0$.

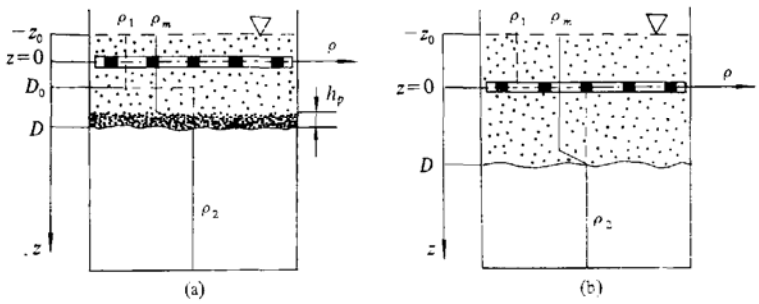

Fig. 1. A sketch of experimental arrangements.
(a) With particle cover; (b) with particle suspensions but without particle cover.

(2) *Arranging the particle cover.* Plastic particles with a diameter 100 μ and a density 1.04 g/cm^3 are spread on the fluid surface. Because the density of the upper layer of water is smaller and the density of the lower layer of saline water is greater than those of the particles, the particles sink down and aggregate near the density interface between the two layers, forming a particle cover (Fig. 1(a)). In the stratification (i), the particle cover remains on the density interface between the turbulent and non-turbulent layers during the experimental procedure (a very small part of the particles suspending in the upper turbulent layer under the action of turbulence).

(3) *Arranging suspended particles.* The first method is to spread particles on the upper layer of fluid when the grid starts oscillating. The particles sink down in the stroke range of the grid and suspend homogeneously in the upper turbulent layer due to the stirring of oscillating grid and the action of the turbulence. Then the suspended particles retard the grid oscillating, which influences the measurement accuracy of the entrainment velocity. The second method is to arrange the 2-layer fluid in stratification (ii) and the said particle cover is at the grid midplane. When the grid starts oscillating, the particle cover will be broken down and the particles suspended

homogeneously in the turbulent layer. Thus, the turbulent entrainment velocity can be measured under the simultaneous action of the suspending particles and the oscillating grid. This method of arranging the suspended particles has been applied to our experiments.

(4) *Experimental plan.* Pure 2-layer fluid experiment (stratifications (i) and (ii)); suspended particle experiment in the turbulent layer without the particle cover (Fig. 1(b)); the particle cover experiment (Fig. 1(a)).

(5) *Experimental manipulation.* Impulsively start the grid oscillating and at the same time run the time reckoner to record the experimental time t. The shadowgraph is used to measure the turbulent entrainment distance (mixed layer depth) D. D is recorded as a function of time t so as to determine the turbulent entrainment velocity $u_e = dD/dt$.

IV. Results and Discussion

1. *Qualitative Observation*

When the density interface is at the grid midplane, the particle cover breaks down promptly after the grid starts oscillating. The particles and liquid are ejected into the non-disturbed region like efflux (see Fig. 2, position corresponding to the grid bars). It takes about 2 s to attain the homogeneous mixture. During the entire experimental procedure, the particles suspend homogeneously in the turbulent layer all the time under the action of turbulence without depositing on the interface. When the density interface is under the grid (i. e. $z_0 = 6$ cm, $D_0 = 6$ cm), the grid starts oscillating, the liquid nearby starts a violent up-and-down movement, being entrained down and forming homogeneous turbulence gradually. The turbulence keeps going down, arriving at the density interface and intruding into the particle cover. A small part of the particles is stirred, going-up and suspending in

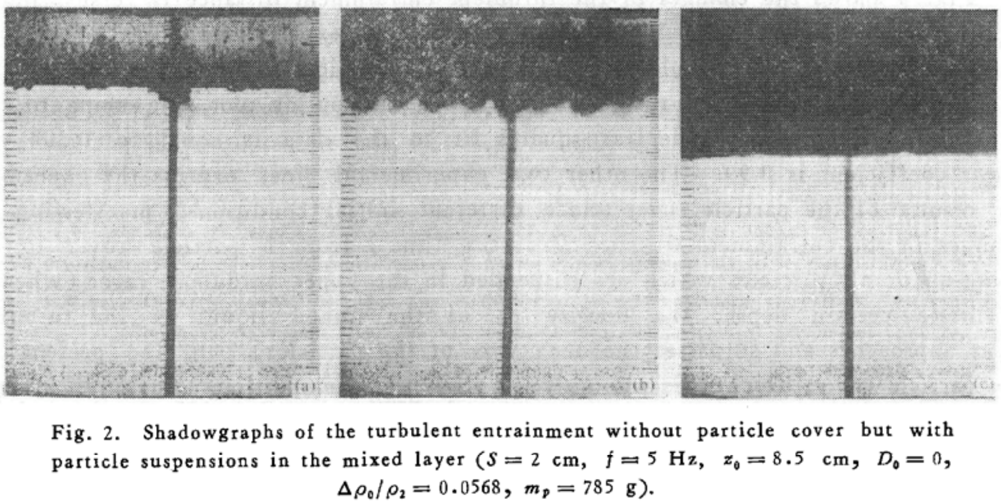

Fig. 2. Shadowgraphs of the turbulent entrainment without particle cover but with particle suspensions in the mixed layer ($S = 2$ cm, $f = 5$ Hz, $z_0 = 8.5$ cm, $D_0 = 0$, $\Delta\rho_0/\rho_2 = 0.0568$, $m_p = 785$ g).

(a) Before starting the oscillating grid; (b) shadowgraph of the 2nd second; (c) shadowgraph of the 3844th second.

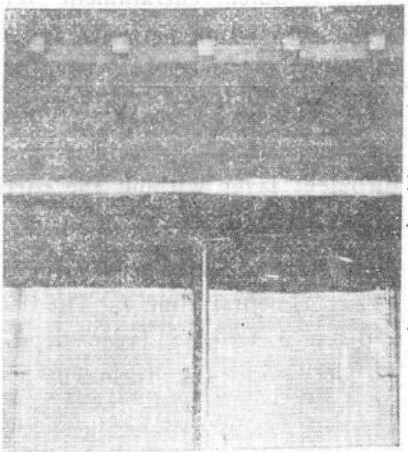

Fig. 3. Photograph of the particle cover ($S = 2$ cm, $f = 4.5$ Hz, $\Delta\rho_0/\rho_2 = 0.0584$, $m_p = 1460$ g).

the upper turbulent layer (or called the mixed layer). But the majority of the particles remain on the interface, forming the particle cover (Fig. 3). The particles in the particle cover present agglutination due to the viscidity of the water and so more starting energy is needed to stir up the particles. The turbulent kinetic energy decreases with the increasing distance from the grid ($u^2 \propto z^{-2}$), so it is not sufficient to start the particles. This is probably the reason for the existence of the particle cover.

2. *The Relation Between the Turbulent Entrainment Distance D and the Time t*

(1) *Changes in the entrainment distance D*

Fig. 4 shows the changes of the turbulent entrainment distance D versus time t in different situations. The symbol Δ expresses the experimental data of the suspended particles in the turbulent layer without the particle cover on the interface between the turbulent and non-turbulent layers. In the log-log plot, the slope of the straight line drawn up by the least-squares fit to the data is equal to 0.204 and linear coefficient is 0.99. The other two experimental lines express the expermental results of the particle cover under different initial conditions, manifesting the changes in the entrainment distance D versus time t from a particle cover to the going-up or all particles which are suspended in the upper turbulent layer (when D attains a certain depth, the density ρ_m of the mixed liquid in the turbulent layer approaches and surpasses the density ρ_p of the particles). In the presence of the particle cover, D changes smoothly. Following the particles buoying up and disappearance of the cover, the two curves tend to be alike and form two straight lines parallel to the line (in the log-log plot).

(2) *The D-t relationship in different situations*

The upper turbulent layer is entrained down continuously with the increasing

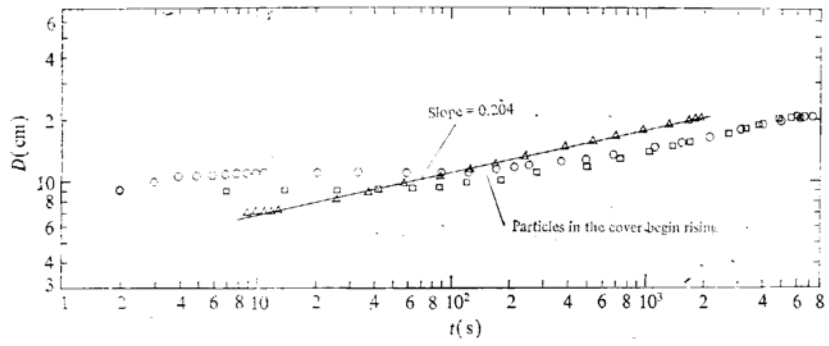

Fig. 4. Entrainment distance D, measured from the grid midplane, plotted logarithmically as a function of time t for 2-layer fluid ($S = 2$ cm, $f = 5$ Hz).

With the particle cover on the interface; ○, $z_0 = 7$ cm, $D_0 = 9$ cm, $\Delta\rho_0/\rho_2 = 0.0909$, $m_p = 724$ g; □, $z_0 = 10$ cm, $D_0 = 6$ cm, $\Delta\rho_0/\rho_2 = 0.0991$, $m_p = 780$ g.

Without particle cover on the interface: △, $z_0 = 8.5$ cm, $D_0 = 0$, $\Delta\rho_0/\rho_2 = 0.0568$, $m_p = 785$ g.

time, and the entrainment distance is measured as a function of time. For the 2-layer fluid, the relation between D and t can be expressed as[11]

$$D = A\left(g \frac{\Delta\rho_0}{\rho_2} d_0\right)^{-3/10} f^{4/5} S^{6/5} M^{2/5} t^{1/5}, (D \gg z_0, D_0), \tag{3}$$

where A is a constant determined by experiments.

The experiments we conducted here are those of 2-layer fluid systems with the particle cover on the density interface and the suspended particles in the turbulent layer. The relation of the entrainment distance D to the time t can be expressed as

$$D = k t^{\mathscr{H}}, (D \gg z_0, D_0), \tag{4}$$

where k is a constant determined by experiments, relevant with the density difference of two layers $\Delta\rho_0/\rho_2$, the stroke of the grid S, the dimension of the geometry of the grid (such as the mesh size M for the square grid), the oscillation frequency f and the thickness of the particle cover (or the bulk concentration of the suspended particles). When only f changes and other parameters remain constant, k is the function of f. The relation of k to f, $k = af^{\alpha}$, can be determined by using the log-log plot and the least-squares fit. In our experiments, the linear correlation coefficient of k and f is 0.99.

(1) *The D-t relation for the suspended particles.* To make a comparison, we have conducted the experiment of pure 2-layer fluid under similar conditions. Figs. 5 and 6 give the D-t relations and the comparison between the turbulent entrainments for the suspended particles in the turbulent layer without the particle cover on the density interface and for the pure 2-layer fluid. In the log-log plot, the D-t relations are expressed with straight lines by using the least-squares fit to the data. The slope of the straight line is 1/5 and its linear correlation coefficient is over 0.99. The entrainment distance D changes by 1/5 power law of t as given in Formula (3), which shows that the law of the turbulent entrainment for the suspended particles in the turbulent layer is the same as that for the pure 2-layer fluid.

Fig. 6 shows that under the same initial conditions, the D-t line for the pure 2-layer fluid is above the line for the suspended particles, with the defference of a constant factor $(1-1.15f^{-0.15})$. From the data listed in Table 1, we see that for pure 2-layer fluid, the 1/5 power of t and the 0.83 power of f agree well with Eq. (3).

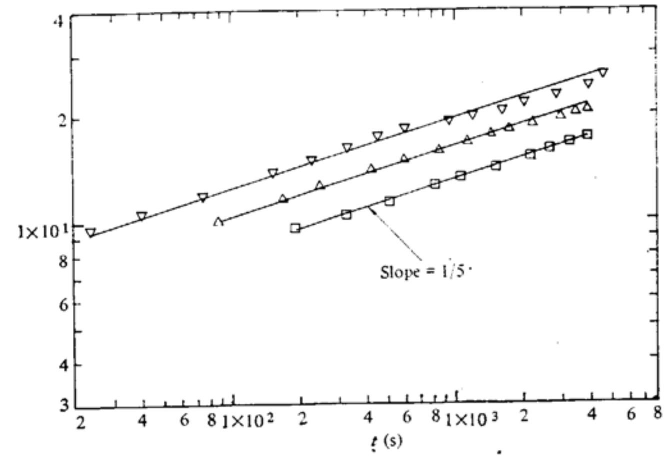

Fig. 5. Entrainment distance D versus time t for the case where there are particle suspensions in the upper turbulent layer of 2-layer fluid system. $S=2$ cm, $z_0=9$ cm, $D_0=0$, $\Delta\rho_0/\rho_2=0.0584$, $m_p=730$ g. □, $f=2.5$ Hz; △, $f=3.5$ Hz; ▽, $f=4.5$ Hz.

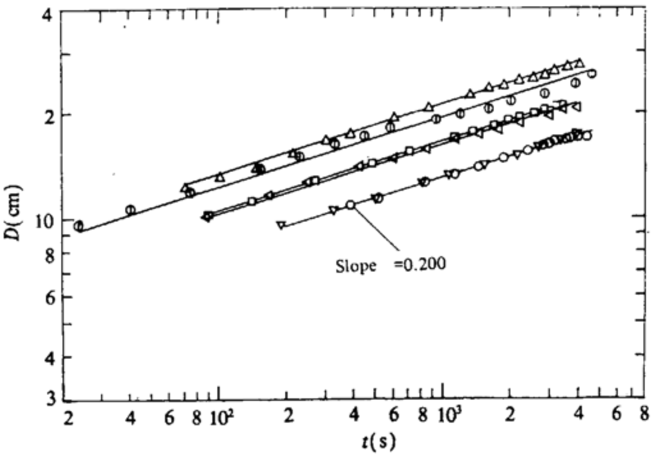

Fig. 6. Comparison between two D-t relations for pure 2-layer fluid system with particle suspensions in upper turbulent layer. $S=2$ cm, $z_0=9$ cm, $D_0=0$, $\Delta\rho_0/\rho_2=0.0584$. $m_p=0$ (pure 2-layer fluid): ○, $f=2.5$ Hz; □, $f=3.5$ Hz; △, $f=4.5$ Hz. $m_p=730$ g: ▽, $f=2.5$ Hz; ◁, $f=3.5$ Hz; ⦶, $f=4.5$ Hz.

(2) *The D-t relation for the particle cover*. Figs. 7—9 give the relations of the turbulent entrainment distance D versus time t for different particle cover thicknesses (expressed in the particle weight) and the pure 2-layer fluid. In the log-log plot, the solid lines are obtained by the least-squares fit to the data with correlation

Table 1

Numerical Values for the D-t Relation (4) ($D = kt^{\mathscr{H}}, k = af^{\alpha}$).

z_0 (cm)	D_0 (cm)	S (cm)	f (Hz)	m_p (g)	$\Delta\rho_0/\rho_2$ ($\times 10^{-2}$)	k (cm · s$^{-\mathscr{H}}$)	$\mathscr{H}$	a(cm · s$^{\alpha-\mathscr{H}}$)	α
6	6	2	2.5 3.5 4.5	0	5.84	2.88 3.66 4.75	0.200	1.31	0.84 (0.80)
			2.5 3.5 4.5	730	5.84	3.05 4.01 4.70	0.187	1.54	0.75
			2.5 3.5 4.5	1460	5.84	3.24 4.15 5.07	0.174	1.61	0.76
9	0	2	2.5 3.5 4.5	0	5.84	3.26 4.17 5.32	0.200	1.51	0.83 (0.80)
			2.5 3.5 4.5	730	5.84	3.25 4.08 5.17	0.200	1,57	0.78

Note. The values of α in parentheses are the theoretical values for Relation (3).

coeffcients r_p being over 0.99. The values of the slope $\mathscr{H}$ are listed in Table 1, the errors being 0.01. The D for the pure 2-layer fluid is proportional to $t^{0.3}$ and agrees very well with Eq. (3), which is consistent with the experimental results of Ref. [11]. From these figures and table we see that, compared with the pure 2-layer fluid, the turbulent entrainment of the particle cover decreases by the power law and the power is dependent on the thickness of the particle cover. The greater the thickness, the smaller the power, which indicates that the particle cover has great influence on turbulent entrainment.

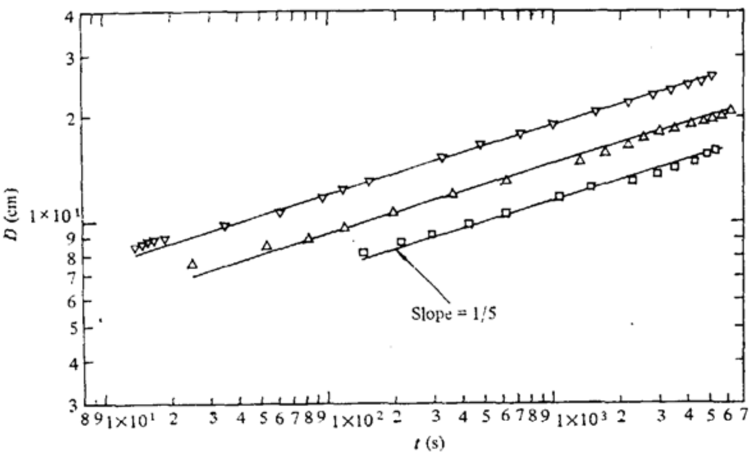

Fig. 7. Entrainment distance D versus time t for pure 2-layer fluid. $z_0 = 6$ cm, $D_0 = 6$ cm, $S = 2$ cm, $\Delta\rho_0/\rho_2 = 0.0584$. □, $f = 2.5$ Hz; △, $f = 3.5$ Hz; ▽, $f = 4.5$ Hz.

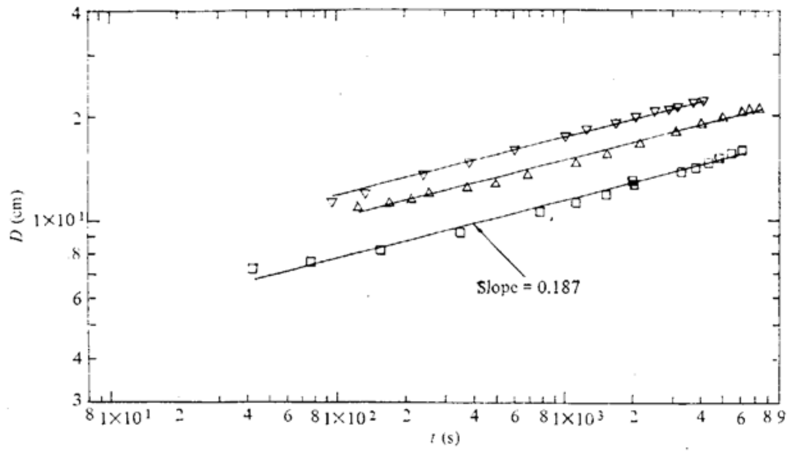

Fig. 8. Entrainment distance versus time t with the interface particle cover ($m_p = 730$ g) in 2-layer fluid system. $S = 2$ cm, $z_0 = 6$cm, $D_0 = 6$ cm, $\Delta\rho_0/\rho_2 = 0.0584$. □, $f = 2.5$ Hz; △, $f = 3.5$Hz; ▽, $f = 4.5$Hz.

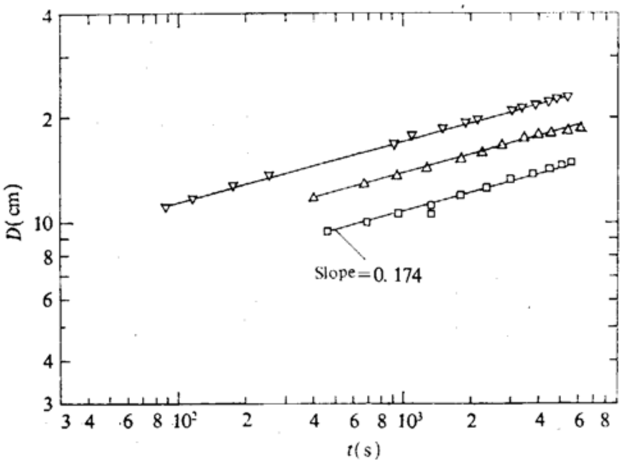

Fig. 9. Entrainment distance D versus time t with the interface particle cover ($m_p = 1460$ g) in 2-layer system. $S = 2$ cm, $z_0 = 6$ cm, $D_0 = 6$ cm, $\Delta\rho_0/\rho_2 = 0.0564$. □, $f = 2.5$ Hz; △, $f = 3.5$ Hz; △, $f = 4.5$ Hz.

The value of α (see Table 1) of the pure 2-layer fluid agrees well with that predicted by Eq. (3). But the value of the particle cover has a considerable deviation, which also indicates that the particle cover changes not only the value of the power of time t but also the relation of the entrainment distance D to frequency.

Table 1 shows that under similar conditions (i.e. z_0, D_0, S, f and $\Delta\rho_0/\rho_2$ are fixed), the values of $\mathscr{H}$, a and α are relevant to the value of m_p. For the sake of convenience, we express m_p with the corresponding thickness of the particle cover:

$$h_p = \frac{m_p}{A\rho_{a,p}}, \tag{5}$$

where $\rho_{a,p}$ is the apparent density of particle deposit, equal to 0.173 g/cm^3; A is the area of the horizontal cross-section of the water. The non-dimensional thickness of the particle cover is

$$\tilde{h}_p = \frac{h_p}{d_0}. \tag{6}$$

Obviously, when the other conditions do not change, $\mathscr{H}$ and a are the functions of $\tilde{h}_p$. Experimental data show that these two relations are respectively

$$\begin{cases} \mathscr{H} = 0.200 - 0.130\tilde{h}_p, \\ a = 1.309 + 1.783\tilde{h}_p. \end{cases} \tag{7}$$

Formulas (7) quantitatively indicate the action by the grid-generated turbulent entrainment on the thickness of the particle cover for 2-layer fluid systems: the thicker the particle cover, the more difficult the turbulent entrainment.

3. *Turbulent Entrainment Velocity*

Experiments of turbulent entrainment always attempt to determine the relationship of the non-dimensinal entrainment velocity E to the local Richardson number Ri_1 ($E = f(Ri_1)$). The entrainment velocity u_e of the turbulent layer going-down

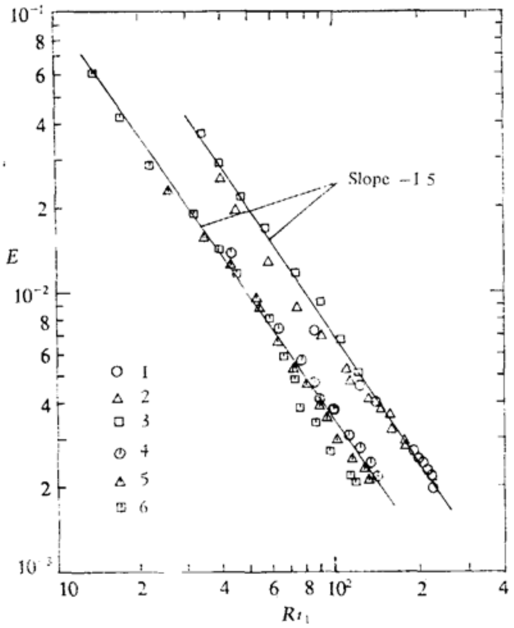

Fig. 10. Entrainment velocity E plotted logarithmically as a function of local Richardson number Ri_1 for the particle suspensions without the particle cover. $S = 2$ cm, $z_0 = 9$ cm, $D_0 = 0$, $\Delta\rho_0/\rho_2 = 0.0584$. $m_p = 0$ (pure 2-layer fluid system): ○, $f = 2.5$ Hz; △, $f = 3.5$ Hz; □, $f = 4.5$ Hz. $m_p = 730$ g: ⊕, $f = 2.5$ Hz; △, $f = 3.5$ Hz; ⊞, $f = 4.5$ Hz.

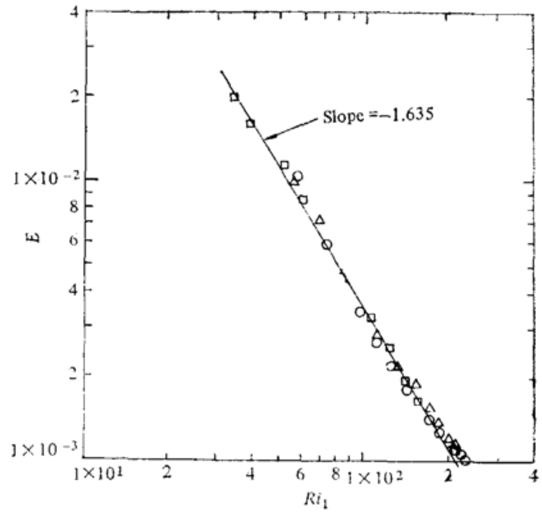

Fig. 11. E versus Ri_1 for the particle cover $m_p = 730$ g. $S = 2$cm, $z_0 = 6$ cm, $D_0 = 6$ cm, $\Delta\rho_0/\rho_2 = 0.0584$. ○, $f = 2.5$ Hz; △, $f = 3.5$ Hz; □, $f = 4.5$ Hz.

can be determined by Formula (4):

$$u_e = \frac{dD}{dt} = k\mathscr{H}t^{\mathscr{H}-1}. \tag{8}$$

The non-dimentional entrainment velocity is expressed as

$$E = \frac{u_c}{u} = KRi_1^{-n}, \tag{9}$$

where K is a constant determined by experiments, relevant to S, f, M, $\Delta\rho_0/\rho_2$ and $\tilde{h}_p$. For a 2-layer fluid $n = 3/2$[11]. The local Richardson number is determined as

$$Ri_1 = g\left(\frac{\Delta\rho}{\rho}\right)\frac{l}{u^2}, \tag{10}$$

where

$$\Delta\rho = (\rho_2 - \rho_1)\frac{z_0 + D_0}{z_0 + D}, \tag{11}$$

$$\bar{\rho} = \rho_1\frac{z_0 + D_0}{z_0 + D} + \rho_2\frac{D - D_0}{z_0 + D}. \tag{12}$$

From Formulas (8) and (9), the relation between n and $\mathscr{H}$ can be determined as

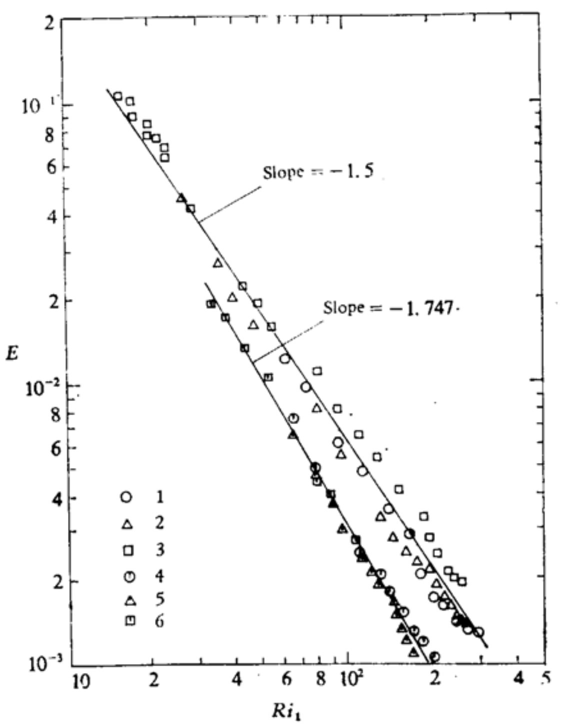

Fig. 12. Comparison between the relation E-Ri_1 for the particle cover $m_p = 1460$ g and that for the 2-layer fluid. $S = 2$ cm, $z_0 = 6$ cm $D_0 = 6$ cm, $\Delta\rho_0/\rho_2 = 0.0584$. $m_p=0$ (pure 2-layer fluid): ○, $f = 2.5$ Hz; △, $f = 3.5$ Hz; □, $f = 4.5$ Hz; $m_p = 1460$ g: ①, $f = 2.5$ Hz; ⚠, $f = 3.5$ Hz; ⊡, $f = 4.5$ Hz.

$$n = \frac{1}{2\mathscr{H}} - 1. \tag{13}$$

Once the value of $\mathscr{H}$ is determined by experiments, the value of n can be predicted by Formula (13).

Figs. 10—12 give the experimental results of the E-Ri_1 relationship. The linear correlation coefficients got by the least-squares fit to the data are all 0.99. The values of K and n are listed in Table 2.

Table 2

Numerical Values of K and n for the Relation $E = KRi_1^{-n}$

z_0 (cm)	D_0(cm)	f (Hz)	m_p (g)	$\tilde{h}_p$	K	n
6	6	2.5—4.5	0	0	6.194	1.500±0.015 (1.500)
			730	0.1331	6.693	1.635±0.020 (1.674)
			1460	0.1662	9.649	1.747±0.020 (1.857)
9	0	2.5—4.5	0	0	7.362	1.500±0.070 (1.500)
			730	0.1331	3.184	1.500±0.030 (1.500)

Note. The values in parentheses are the values calculated by Relation (3).

(1) *The turbulent entrainment velocity for suspended particles*

Fig. 10 gives the change of the turbulent entrainment velocity E with the local Richardson number Ri_1 for the suspended particles in the turbulent layer without the particle cover on the density interface and the comparison with that of the pure 2-layer fluid. Their E value changes by the -1.5 power law of Ri_1: $E = KRi_1^{-1.5}$. The corresponding values of K are listed in Table 2. The line for the suspended particles is below that pure 2-layer fluid, which indicates that the entrainment velocity of the former is lower than that of the latter, with a difference of a constant factor $\tilde{K}$. The entrainment velocity E for the suspended particles can be expressed in terms of the entrainment velocity E of the pure 2-layer fluid: $E_s = \tilde{K}E_0$, $\tilde{K} = 0.432$.

In the case where S, f, M and $\Delta\rho_0/\rho_2$ do not change, the value of K is relevant to the initial mass concentration or bulk concentration of the suspended particles. The relation between K and the initial bulk concentration can be determined from the experimental data: $K = 7.362 - 141.531C_0$, where $C_0 = 0.0295$ (for our experimental conditions). This is the influence exerted by the suspended particles on the entrainment velocity E. The greater the value of C_0, the greater the influence.

(2) *The E-Ri_1 relation for the particle cover*

Fig. 11 gives the change of the turbulent entrainment velocity E for the particle cover ($m_p = 730$ g) with the Ri_1. For clarity, Fig. 12 only gives the experimental results (the E-Ri_1 relation) for the particle cover $m_p = 1460$ g and the pure 2-layer fluid under the same initial conditions (i. e. z_0, D_0 and $\Delta\rho_0/\rho_2$ are similar in both cases). Figs. 11 and 12 show that the line of $m_p = 730$ g is between those of $m_p =$ 1460 g and the pure 2-layer fluid, indicating that the particle cover has pronounced influence on the turbulent entrainment and the influence is relevant to the thickness of the particle cover (or the gross mass m_p of the particles): the thicker the cover, the greater the influence.

Table 2 gives the values of K and n which reflect the influence rule. The value of n is relevant to the thickness of the particle cover and can be obtained from the experimental data:

$$n = 1.5 + 0.93\tilde{h}_p. \tag{14}$$

n is the linear function of the non-dimensional thickness of the particle cover, increasing with increasing $\tilde{h}_p$. But $\tilde{h}_p$ will not increase unlimitedly and when $\tilde{h}_p = 1$, it tuns into another 2-layer fluid system and n will equal 1.5. So, we can conjecture that there exists a certain value $\tilde{h}_{p,c}$ where n attains its maximum and then drops to 1.5.

The constant K has weak relation to $\tilde{h}_p$. In the present experiments, the K value ranges from 6.194 to 9.649 as expressed by

$$K = 6.194 - 5.481\tilde{h}_p + 69.346\tilde{h}_p^2. \tag{15}$$

The variation range of $\tilde{h}_p$ is from 0 to 1. When $\tilde{h}_p$ equals 0.0395, K has its minimum value, about 6.194. In reality, the thickness is 0.003 cm when $\tilde{h}_p$ equals 0.0395, so the particle cover like a pure 2-layer fluid does not exist at all. This means that the K value of pure 2-layer is the minimum as compared with that of the particle cover ($K_{tl} < K_p$).

V. Turbulent Mixing Mechanism

We have described the relationship of the turbulent entrainment distance to time and that of the entrainment velocity to the local Richardson number Ri_l for only the particle cover on the interface between the turbulent and non-turbulent layers and/or only the suspended particles in the turbulent layer. These relations are relevant with the turbulent mixing mechanism. A discussion of such mechanism will help us understand the effect of the particle cover and/or the suspended particles on decreasing entrainment velocity.

The turbulent mixing mechanism in the stratified fluid without particles has been dealt with in Refs. [6,11,13,14]. Experimental observations concern the following main aspects.

(1) When the Richardson number is sufficiently small, the turbulent eddies impinge the interface and make it fluctuated and unstable. The bottom of the interface (the front of the turbulent layer) draws the quiescent liquid in the lower layer and makes it mixed (molecular mixing) with the fluid in the upper layer.

(2) When the density gradient of the stratified fluid is great and the turbulent kinetic energy is intense, the turbulent eddies impinge and distort the interface so as to break it at certain points. Fine filaments of liquid spring into the upper turbulent layer from the lower stratified fluid layer and mix with the turbulent fluid.

(3) The turbulent eddies distort the interface and generate internal waves. The

internal waves break down continuously and bring about mixing.

In the presence of heavier suspended particles in the turbulent layer, it takes much turbulent energy to suspend the particles. So the efficient kinetic energy attaining the interface decreases along with the effect of the stated mixing mechanism. This is the reason why the turbulent entrainment velocity for the suspended particles is lower than that for pure 2-layer fluid.

In the presence of a particle cover, the turbulence loses a part of the energy in the suspension of the particles and then exhausts another part of energy when intruding into the upper part of the cover for overcoming the interaction between the fluid and particles and/or among the particles. The kinetic energy is finally transferred to the lower part of the cover (i. e. the front). This process decreases greatly the turbulent energy in the interfacial layer, thus the front remains smooth (Fig.3), which indicates that the particle cover has great restraint on the stated mixing previously. From experimental observation we see that such mixing process, like that for the pure stratified fluid, can hardly take place. What mainly works is such a mechanism. When the turbulent eddies impinging the interface accumulate a sufficiently large amount of energy, a certain part of interface is distorted intensely. The particle in the distorted interfacial layer will move aside to maintain balance, and so internal waves are broken. Then filaments of liquid are entrained into the upper layer and mixed with the turbulent fluid.

VI. Conclusions

The present experimental study of turbulent entrainment for the suspended particles and the particle cover on the interface shows that the entrainment distance D changes in a power law of time t: $D = kt^{\mathscr{H}}$ and the non-dimensional entrainment velocity E also changes in a power of the local Richardson number Ri_1: $E = KRi_1^{-n}$.

The D-t curve for the suspended particles in the turbulent layer is the parallel motion of that for the pure 2-layer fluid under the same initial condition ($z_0 = 9$ cm, $D_0 = 0$, $\Delta\rho_0/\rho_2 = 0.0584$), which indicates that in the same interval of time, its entrainment distance is much lower than that for the pure fluid. The parallel motion equals the decrease of K and is relevant to the initial bulk concentration of the particles, reflecting the dissipation of the turbulent energy. The power $\mathscr{H}$ and n of t and Ri_1 are the same as those of the pure fluid and equal respectively to 0.2 and 3/2, with only the difference of a constant factor ΔK relevant to the bulk concentration of the particles.

The particle cover restrains the turbulent entrainment depending on the thickness of the cover and the thicker the cover, the greater the restraint action. In comparison with the pure 2-layer fluid under the same condition, its entrainment distance and velocity decrease greatly and change the power law. In the presence of the particle cover, the value of $\mathscr{H}$ is lower than that of pure 2-layer fluid and decreases with increasing thickness $\tilde{h}_p$ of the particle cover. K almost remains constant. The power n in the E-Ri relation increases with increasing thickness of the particle cover and K is relevant to $\tilde{h}_p$. In a word, the partcile cover can efficiently decrease the turbulent entrainment.

REFERENCES

[1] Kraus, E. B. & Turner, J. S., *Tellus*, **19**(1967), 98.
[2] Turner, J. S. & Kraus, E. B., *ibid*. **19**(1967), 88.
[3] Rouse, H. & Dodu, J., *Houille Blanche*, **10**(1955), 405.
[4] Turner, J. S., *J. Fluid Mech*., **33**(1968), 639.
[5] Crapper, P. E. & Linden, P. F., *ibid*., **65**(1974), 45.
[6] Linden, P. F., *ibid*., **60**(1973), 467.
[7] ——————, *ibid*., **71**(1975), 385.
[8] Hopfinger, E. J. & Toly, J. A., *ibid*., **78**(1976), 155.
[9] Wolanski, E. & Brush, L. M., *Tellus*, **27**(1975), 259.
[10] Fernando, H. J. S. & Long, R. R., *J. Fluid Mech*., **133**(1983), 377.
[11] E Xuequan & Hopfinger, E. J., *ibid*., **166**(1986), 227.
[12] Breidenthal, R. E. & Baker, M. B., *J. Geoph. Res*., **90**(1985), 13055.
[13] Long, R. R., *J. Fluid Mech*., **84**(1978), 113.
[14] Carruthers, D. J. & Hunt, J. C. R., *ibid*., **165**(1986), 475.