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ENTRAINMENT BY GRID-GENERATED TURBULENCE IN ROTATING STRITIFIED FLUIDS

By Akira MASUDA*

An experiment is made of entrainment in two-layer or three-layer stratified fluids in a rotating system, where turbulence for mixing is produced by an oscillating grid in the upper layer. Flow visualization by dye, aluminium powder, and shadow graphs reveals peculiar characteristics of turbulence in rotating stratiaied fluids: strong spike-like turbulence above the interface and weak thin filaments elongated downward just beneath the interface. It is found that rotation causes even the downward entrainment, which is never observed in non-rotating stratified fluids.

Key words :Entrainment, Rotating and stratified fluids, Grid-generated turbulence

1. Introduction

The climate is greatly influenced by the heating from the ocean, while that heat budget is controlled by ocean mixed layers. Therefore mixed layers have recently attracted more and more attention of meteorologists and oceanographers.

In modeling the mixed layer, the most difficult is how to express the entrainment velocity, the rate of increase in the depth of the mixed layer, in terms of overall paramesers such as the Richardson number. Although many researchers have investigated this problem experimentally or semi-empirically (Turner[1], 1968, or Kato and Phillips[2], 1969, for example), they have neglected the rotation of the earth, another important factor in geophysical flows, except for the inertial current induced by the surface stress; none of them have considered the direct influence of the rotation of the earth on turbulence and entrainment. This treatment is presumably reasonable for most ocean cases. It is not justified, however, *a priori*. For example, the rotation might have possible effects on the turbulence structure when the mixed layer is sufficiently deep that the Rossby number is not large enough.

Apart from the practical application, entrainment in rotating stratified fluids is of much theoretical interest in itself. For, the rotation is expected to add a few new aspects to the usual mixing of stratified fluids, besides the well known

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indirect effects of inertial currents. First, the turbulence within the mixed layers will assume the two-dimensional form rather than the three-dimensional for sufficiently high rotation. That is, eddies will be elongated vertically (or along the direction of the rotation vector); turbulence intensity will decrease less in the vertical direction, which seems favorable for mixing. The columnar eddies, however, may not be efficient in entratining the lower fluid by scraping, because their vertical velocity is small. Second, the rotation allows the propagation of inertial waves. Let us note that Linden[3] (1975) has suggested that if the water below the mixed layer is stratified continuously, internal gravity waves radiated from the mixed layer deprive it of considerable amount of kinetic energy available for the entrainment and consequently retard the deepening of the mixed layer. Inertial waves due to rotation in the present experiments may play the role of internal gravity waves due to continuous stratification in Linden's experiments, even for the homogeneous lower layer. Thus we infer the enhancement of entrainment on one ground, whereas suppression from another reason.

Does the rotation work positively or negatively for mixing, indeed? The motivation of the present paper is to answer these fundamental questions and thus to understand the effects of rotation on the mixing, by means of visualization experiments for rather high rotation. Because simpler conditions are better as a first step we use an ordinary method of oscillating a grid to produce the turbulence for mixing. Though this artificial technique requires much care when we apply the result thus obtained to the real ocean ,that is very easy to carry out in a small tank, and moreover avoids inertial currents, which are undesirable for the present purpose. Likewise we adopt the simplest stratification of two or three homogeneous layers with the prescribed density difference.

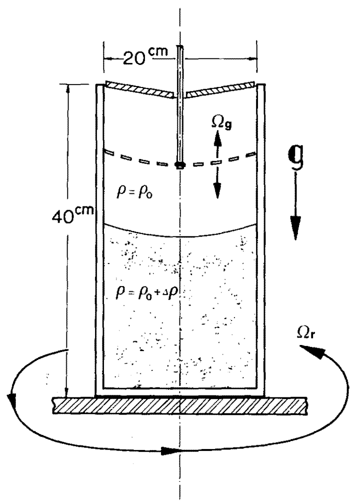

Figure 1. Schematic diagram of experimental apparatus.

2. Experimental arrangements

The experiments were carried out in a rectangular glass tank 20.0×20.0 cm in cross section and 40 cm deep (see Fig. 1). It was placed on a turntable at the center. Turbulence for mixing was produced by a grid, which was oscillated by an electric motor mounted at the top of the tank. The grid consisted of 1 cm wide and 20 cm long thin aluminium plates in a 4×4 array with 5 cm between the center. The dimensions of our apparatus are almost the same as those used by Turner[1] (1968).

The surface and interface of rotating water are paraboloids. Therefore a grid was made to have a curvature corresponding to the rotation rate $f_r = 0.5$ Hz, the highest value in our experiments, in order for the grid to keep an equal distance from the interface. This bent grid was used only when $f_r = 0.5$ Hz ; otherwise a flat grid was substituted, since the curvature was negligible.

The typical experimental procedure is as follows. First, the tank is put in the tap water with density ρ_0 , sometimes dyed and sometimes containing aluminium powder. Next, heavier salt water with the prescirbed density ρ_0

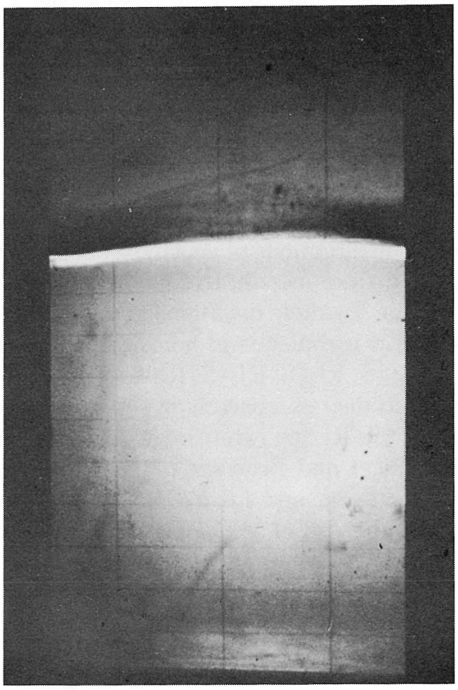

Photo. 1. Instability observed during the spin-up stage. Note the black thin oblique streak above the interface.

$+\Delta\rho$ is introduced into the bottom of the tank. Thus we set up two homogeneous layers with an interface; the upper layer is 17 cm thick, while the lower layer is 20 cm deep at the center of the tank when the system is rotating. Four pieces of light lids are placed on the water surface, to eliminate undesirable effects of the free surface and the air above the tank. Then we begin to revolve the turntable; acceleration follows untill the system achieves the assigned rotation rate. It takes an hour or more to spin up the water slowly without much disturbance (A kind of instability was observed during the accelerlation period, which resulted in a little mixing, Photo. 1). After the water is spun up completely, the grid in the upper layer* begins to oscillate with the stroke $a = 2$ cm at the frequency $f_g = 1.5$ Hz. Then the turbulent upper layer deepens by eroding the lower layer.

Three kinds of visualization were made: (1) alluminium powder to see the whole pattern of turbulence, (2) dye in the upper layer to see the entrainment, and (3) shadow graphs to see the detailed density structure near the interface. We denote those methods of visualization simply by (Al), (Dy) and (Sh). A camera or video-camera was set to the turntable together with necessary sources of light, to take photographs or video records. The entrainment velocity was determined from a sequence of photographs of (Dy), by judging the average height of the ragged interface. Though this estimation is rough, it suffices for our purpose of qualitative comparison.

3. Results

Before proceeding to the results, let us take a more general view of the present experiments. That is, the subject is considered as an extension of the simple grid turbulence to the directions of geophysical importance; from homogeneous to stratified fluids and from inertial to rotating system. We denote stratification by S and rotation by R; their negations by $\overline{\mathrm{S}}$ and $\overline{\mathrm{R}}$. The symbol [S, R], for example, means the grid turbulence in homogeneous non-rotating fluids.

Among the four cases, [$\overline{\mathrm{S}}$, $\overline{\mathrm{R}}$], [S, $\overline{\mathrm{R}}$], [$\overline{\mathrm{S}}$, R], and [S, R], the first is known best and the second has been studied extensively in the context of geophysical application. On the other hand, [$\overline{\mathrm{S}}$, R] has rarely been investigated; the only published papers are those by Hopfinger and Browand[4] (1982) by Hopfinger, Browand and Gagne[5] (1982) and by Dickinson and Long[6] (1983). As regards [S, R], I know none except the work in progress at the Johns Hopkins University, which was informed by accidental private communication** after the present experiments had been finished.

To make clear the characteristics of [S, R], it is necessary to compare them

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* Turner (1968) and others have used another oscillating grid in the lower layer to keep the density interface at a constant depth.

** Prof. Phillips kindly let us know during his stay at our institute that Prof. Long and his colleagues had studied [S, R] and were taking their hands to [S, R].

with those of [$\bar{S}$, $\bar{R}$], [S, $\bar{R}$] and [$\bar{S}$, R]. Therefore we present the following photographs of visualization by (Al) for [$\bar{S}$, $\bar{R}$], [S, $\bar{R}$], [$\bar{S}$,R] and [S, R], by (Dy) for [S,$\bar{R}$] and [S, R], and by (Sh) for [S, $\bar{R}$] and[S, R]. Fig. 2 illustrates the four classes of experiments and the three methods of visualization, together with probable motivation for each direction of extension.

3.1. Visualization by aluminium powder for [$\bar{S}$, $\bar{R}$], [$\bar{S}$, R], [S, $\bar{R}$]] and[S, R]

Photos. 2 (a) and (b) respectively show typical flow patterns of [$\bar{S}$, $\bar{R}$] and [$\bar{S}$,

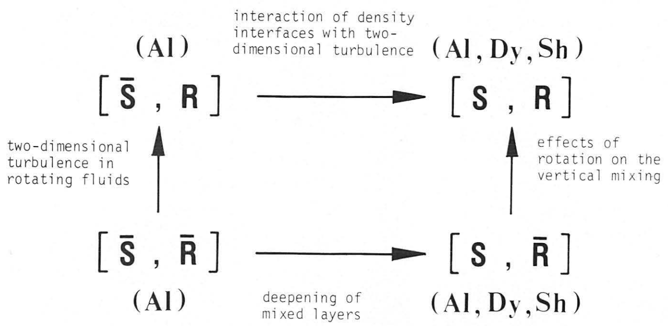

Figure 2. Classification and interrelation of oscillated-grid turbulences, where S denotes stratification, R rotation and "—" their negation.

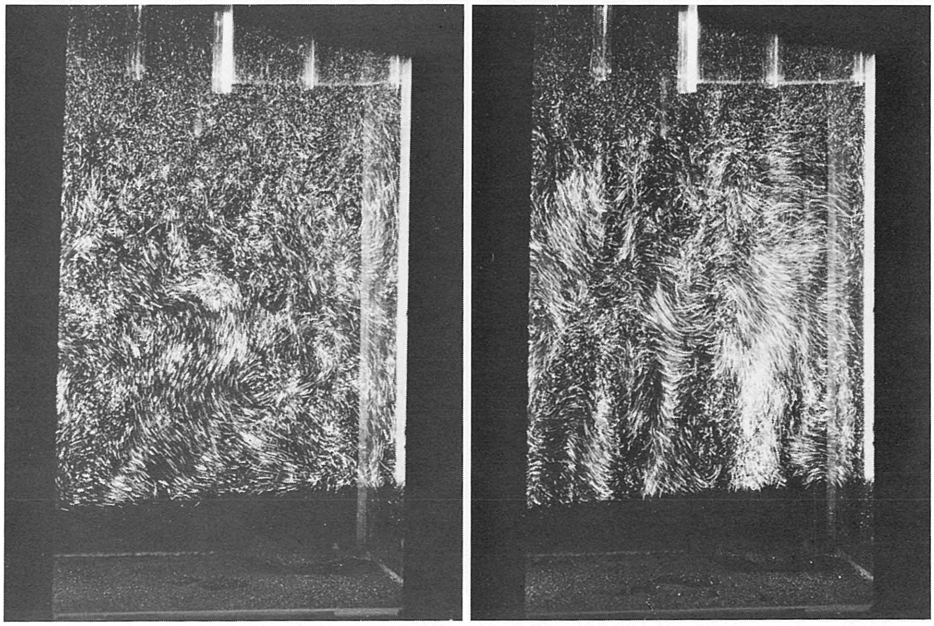

Photo. 2. Grid-generated turbulence for homogeneous water: (a) non-rotating case when $f_r = 0$ Hz, (b) rotating case when $f_r = 0.5$ Hz.

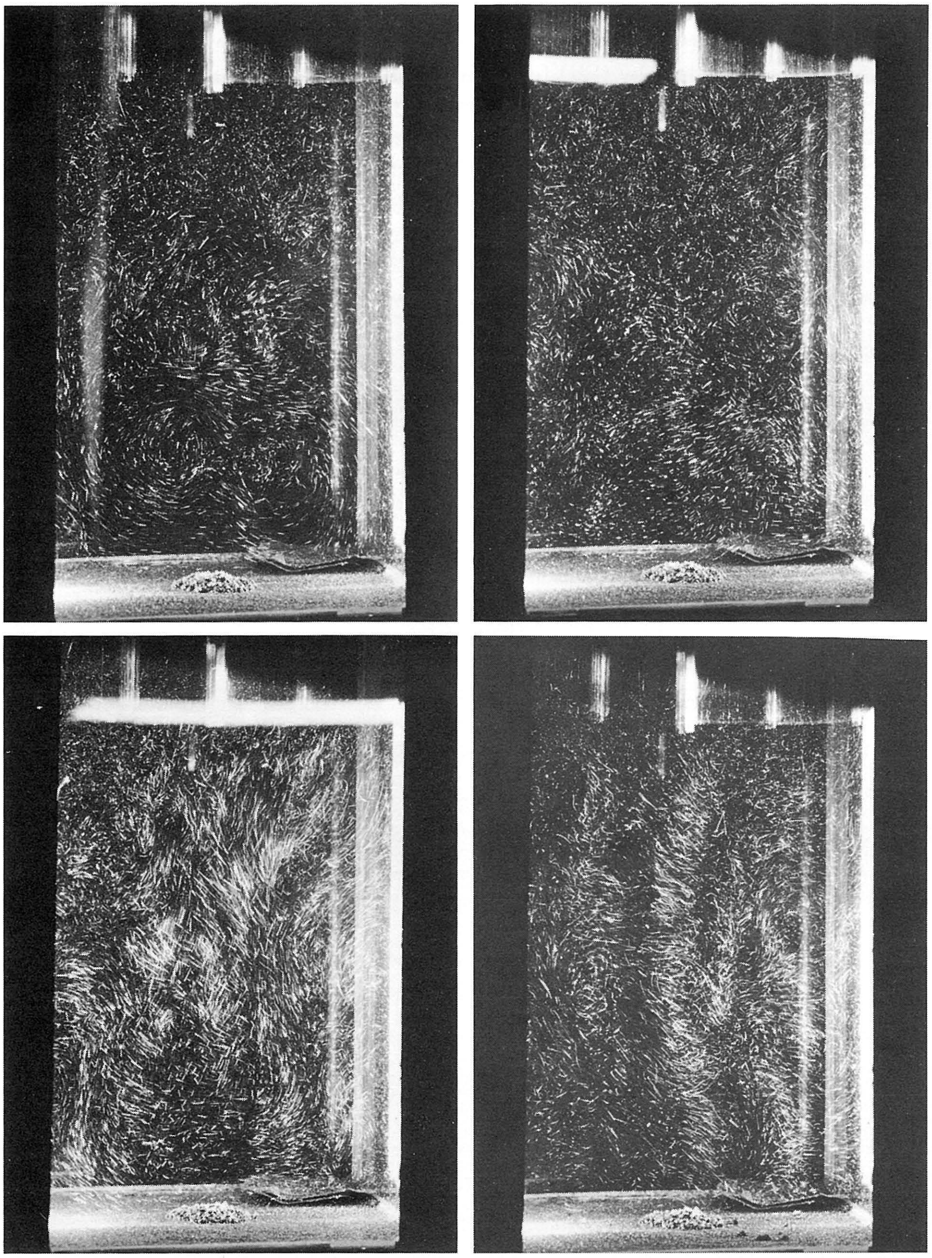

Photo. 3. Change of the pattern of the turbulence from the non-rotating case to the strongly rotating case for homogeneous water: (a) $f_r = 0$ Hz, (b) $f_r = 0.05$ Hz, (c) $f_r = 0.1$ Hz, (d) $f_r = 0.5$ Hz.

R], where f_r = 0.5 Hz in the latter case. We clearly observe three-dimensional character of turbulence in a non-rotating system, while two-dimensional columnar vortices in a rotating system. Photos. 3 (a), (b), (c) and (d) display the change of the flow with the increasing rotation, where f_r = 0, 0.05, 0.1 and 0.5 Hz, respectively; deviation from the three-dimensional turbulence first appears near the bottom and two-dimensional patterns spread over the upper region. Close by the oscillating grid, however, turbulence remains as the three-dimensional one. These properties of $[\overline{S}, R]$ are almost the same as those described by Hopfinger and Browand[4] (1982). Here we should note that even f_r = 0.1 Hz causes rather strong two-dimensionality.

Photo. 4 shows one of the most remarkable though familiar features of $[S, \overline{R}]$ that turbulence is confined to the upper layer and no motion is found in the lower layer except the thin interfacial area.

Photos. 5 (a) and (b) give two examples of [S, R] where f_r = 0.5 Hz and $\Delta\rho/\rho_0 = 2\%$. In this case, the rotation allows the penetration or the propagation of the motion into the lower layer, overcoming the resistance of stratification. Columnar vortices are observed both above and below the interface.

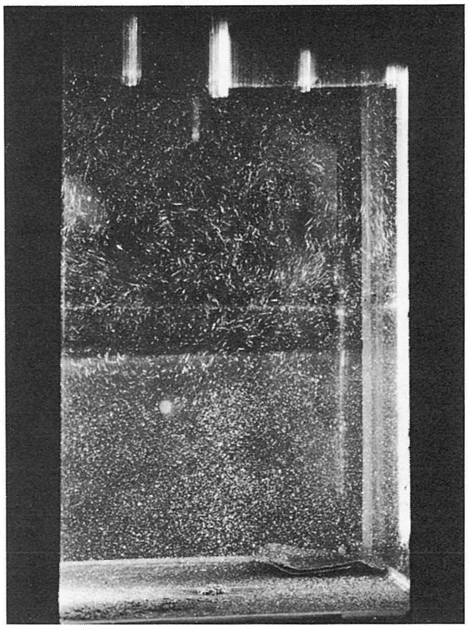

Photo. 4. Effect of the density interface for non-rotating fluids. Note that the turbulence is confined within the upper layer.

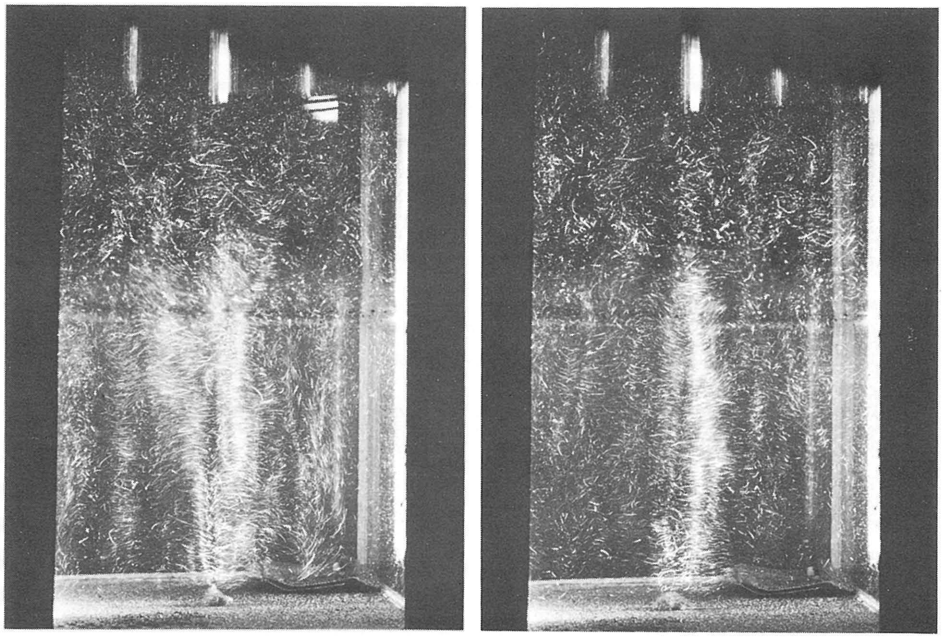

Photo. 5. Turbulence for a strongly rotating ($f_r = 0.5$ Hz) case with the (initial) density difference $\Delta\rho/\rho_0 = 2\%$: (a) earlier stage, (b) later stage.

3.2. Visualization by dye for [S, R] and [S, R]

Photos. 6 (a), (b) and (c) show the height and shape of the interface for $f_r = 0, 0.1$ and 0.5 Hz respectively, where $\Delta\rho/\rho_0 = 1\%$ and the time t from the onset of grid oscillation being 15/4 min. It is difficult to discern (a) from (b), but obviously (c) much differs from the other two. A notable feature is that the upper layer deepens faster near the side boundary than around the center. The most striking in (c), are thin vertical filaments, which are descending into the lower layer. It should be remembered that in [$\bar{\text{S}}$, R] entrainment always occurs upward and consequently the lower layer remains transparent. To the contrary, in [S, R], thin descending filaments mentioned above causes the reverse downward "entrainment", which colors the lower layer gradually. Also we may suppose that those filaments take charge of a kind of turbulent "diffusion" across the interface.

Figures 3 (a) and (b) give some examples of the deepening of the interface h_i by (Dy) method. In (a), where $\Delta\rho/\rho_0$ is varied with $f_r = 0$ Hz, we confirm a natural fact that stronger stratification resists the mixing more effectively. On the other hand, Figure 3 (b) reveals an unexpected result that rotation restrains the deepening when it is small ($f_r = 0.1$ Hz), but promotes when it is large ($f_r = 0.5$ Hz).

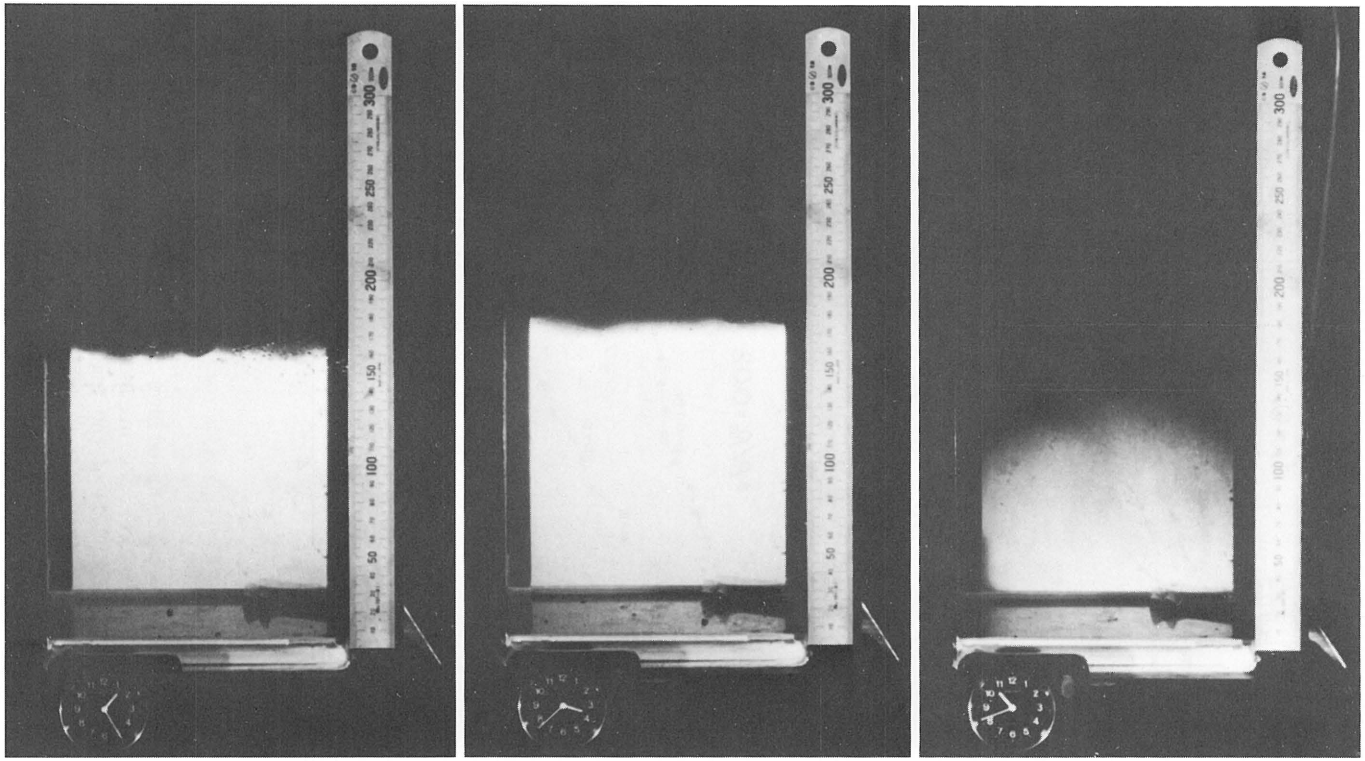

Photo. 6. Visualization of the interface by dye when $\Delta\rho/\rho_0 = 1\%$: (a) $f_r = 0$ Hz, (b) $f_r = 0.1$ Hz, (c) $f_r = 0.5$ Hz. Turbulence near the interface appears less intense in (b) than in (a). In (c), we observe the reverse entrainment due to thin long filaments which penetrate into the lower layer, a peculiar phenomenon unexpected from the usual entrainment.

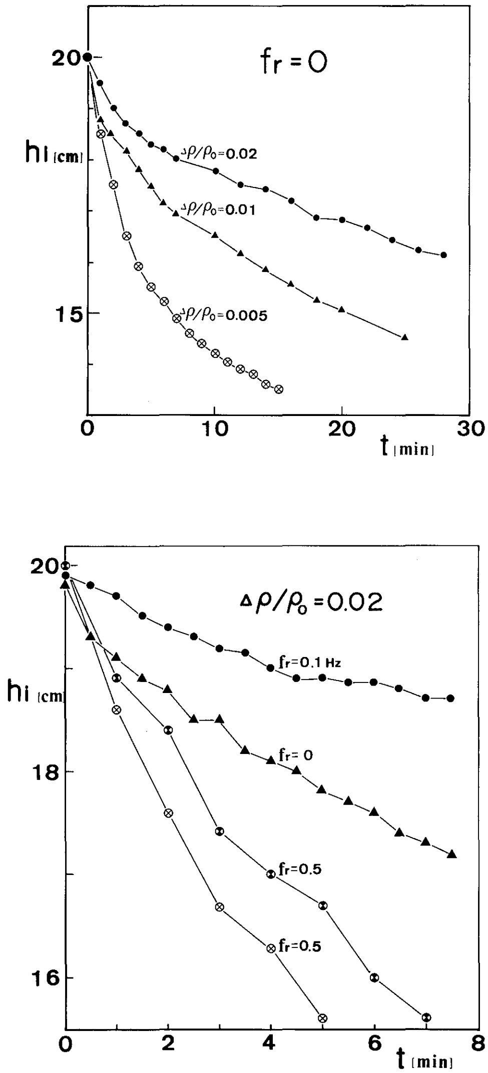

Figure 3. Deepening of the mixed layer, where h_i is the height of the interface, t the time measured from the onset of the oscillation of the grid : (a) effect of the density difference for $f_r = 0$ Hz, (b) effect of rotation for a fixed (initial) density difference $\Delta\rho/\rho_0 = 2\%$.

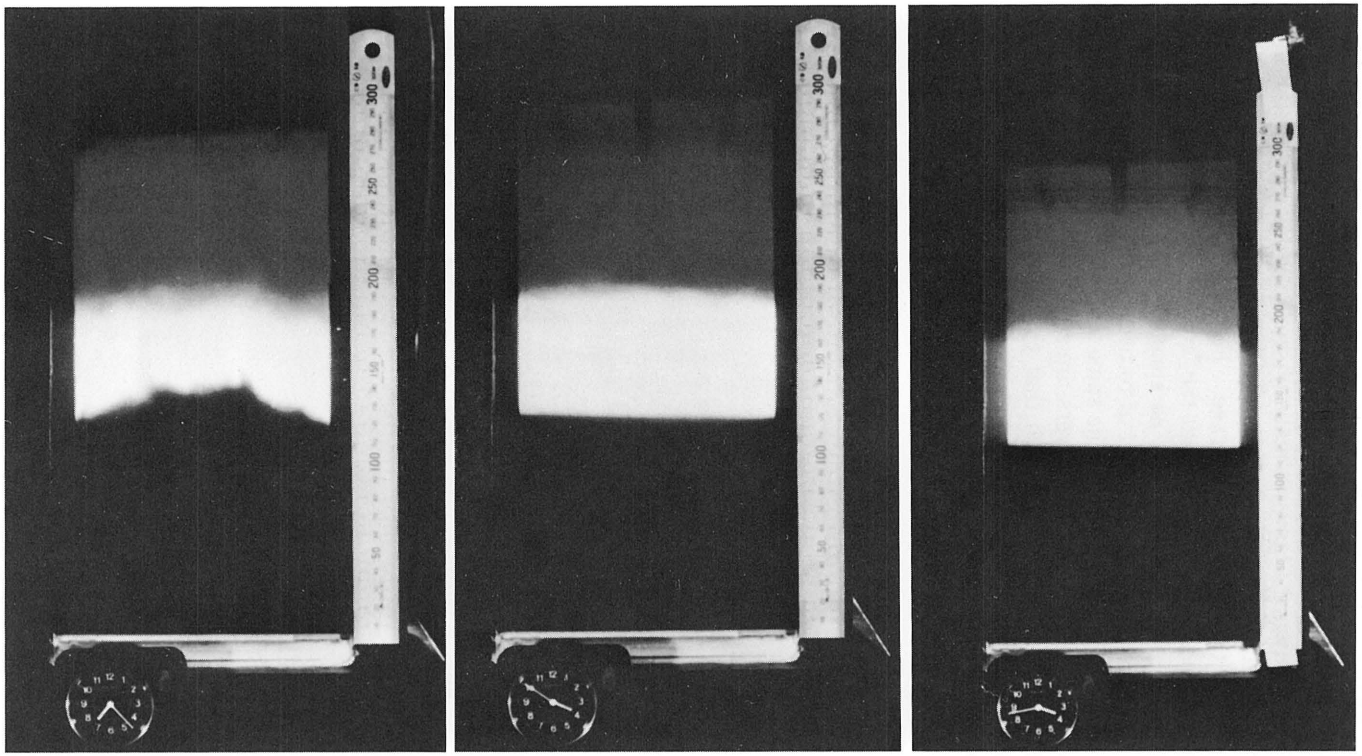

Photo. 7. The same as Photo. 6 when $\Delta\rho/\rho_0 = 1\%$ except the third layer with the same value of the density difference: (a) $f_r = 0$ Hz, (b) $f_r = 0.1$ Hz, (c) $f_r = 0.5$ Hz. In (a) and (b), the lower interface remains still because the disturbance cannot penetrate into the lower layer, while in (c) the second interface is agitated intensely.

We should pay some attention, however, to the case $f_r = 0.5$ Hz, where h_i is difficult to read by eye, partly because the interface takes the from of a dome and partly because thin downward filaments make obscure the location of the interface. One of the two curves for $f_r = 0.5$ Hz corresponds to h_i near the center and the other to h_i on the horizontal average. Furthermore, turbulent "diffusion" due to filaments does not guarantee that the "color" interface represents the density interface accurately. At any rate, no simple conclusion can be derived from Figure 3 (b), such as the positive effect of rotation on mixing or the opposite.

Photos. 7 (a), (b) and (c) show almost the same situations as those in Photos. 6 (a) , (b) and (c), except that the third layers are supplemented. We find that for $f_r = 0$ and 0.1 Hz it is agitated so much that the second layer entrains the third layer. Likewise Photo. 8 demonstrates that even a few more density interfaces cannot prevent the columnar disturbances from penetrating downward if the system is rotating rapidly ($f_r = 0.5$ Hz).

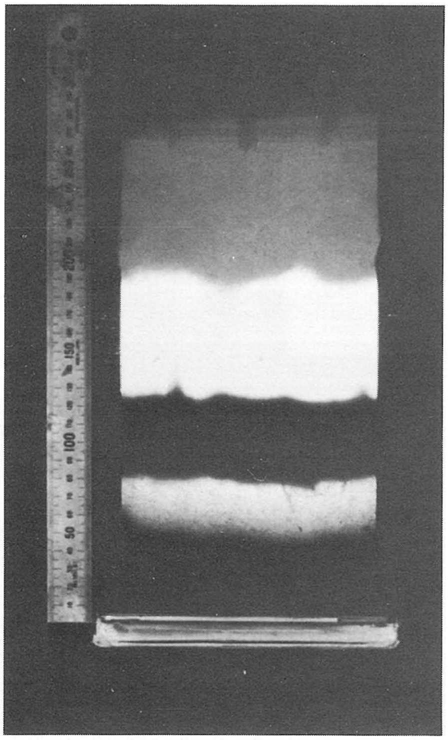

Photo. 8. The same as Photo. 7 except that a few more density interface are added to confirm that the strong rotation makes it possible for the disturbance to break through many density interface.

3.3 Visualization by shadow graphs for [S, R] and [S, R]

Photos. 9 (a), (b) and (c) are shadow graphs for $f_r = 0$, 0.1 and 0.5 Hz when $\Delta\rho/\rho_0 = 4\,\%$. They exhibit fine structure of density near the interface; in the inertial system the fluid entrained from below is lift up to a certain height by three-dimensional eddies, whereas in moderately rotating system of $f_r = 0.1$ Hz density fluctuation is confined around the interface and some white streaks seem to grow downward. For strongly rotating fluids, $f_r = 0.5$ Hz,we notice spike-like patterns above the interface and thin long lines below the interface, where the latters obviously correspond to the colored filaments observed in (Dy).

Photos. 10 (a), (b) and (c) are presented for the same purpose as Photos. 8 (a), (b) and (c). Similarly to (Dy) experiments, non-rotation and small rotation keep the second interface still,but strong rotation disturbes it by making the turbulent motion pass through the barrier of the density interface. In a word, the lower interface is a miniature of the upper when $f_r = 0.5$ Hz.

4. Summary and discussion

Experiments of entrainment by grid-generated turbulence in rotating stratified fluids are carried out in order to investigate (1) effects of rotation on the mixing across a density interface and (2) interaction of two-dimensional columnar disturbances with density interfaces. As a first step to such an unexplored subject, we focus our aims on qualitative understanding of the difference between the inertial and rotating systems.

Simple flow visualization reveals unexpected characteristics of rotating stratified fluids: (1) delicate dependence of entrainment velocity on the rotation rate f_r, (2) spike-like density pattern above the interface, (3) reverse entrainment or turbulent "diffusion" charged by fine filaments like waterspouts, (4) doming of the interface, and (5) penetration of turbulent motion into the lower layers across a few density interfaces.

The most interesting is the presence of thin filaments elongated downward. Do they have corresponding ones in the upper layer or do they exist only in the lower layer? Shadow graphs answer the question positively by showing spike-like density features in the upper layer. Also dye photographs for many layers exhibit vertical filaments rising upward. Then, what mechanism generate them and why do they differ in strength from one layer to another? At the present, I tantatively interpret them as upwelling or downwelling due to Ekmann suction. Interfacial friction causes the positive eddies in the upper layer to induce upwelling of the lower layer, as a typhoon operates the upper ocean; likewise negative eddies yield the downwelling, which brings down the dyed fluid of the upper layer into the lower layer in a form similar to tornadoes.

Weakness of downward thin filaments may be ascribed partly to the weakness of negative eddies, which are responsible for the downwelling. This explanation is supported by video records,which suggest that positive eddies due to

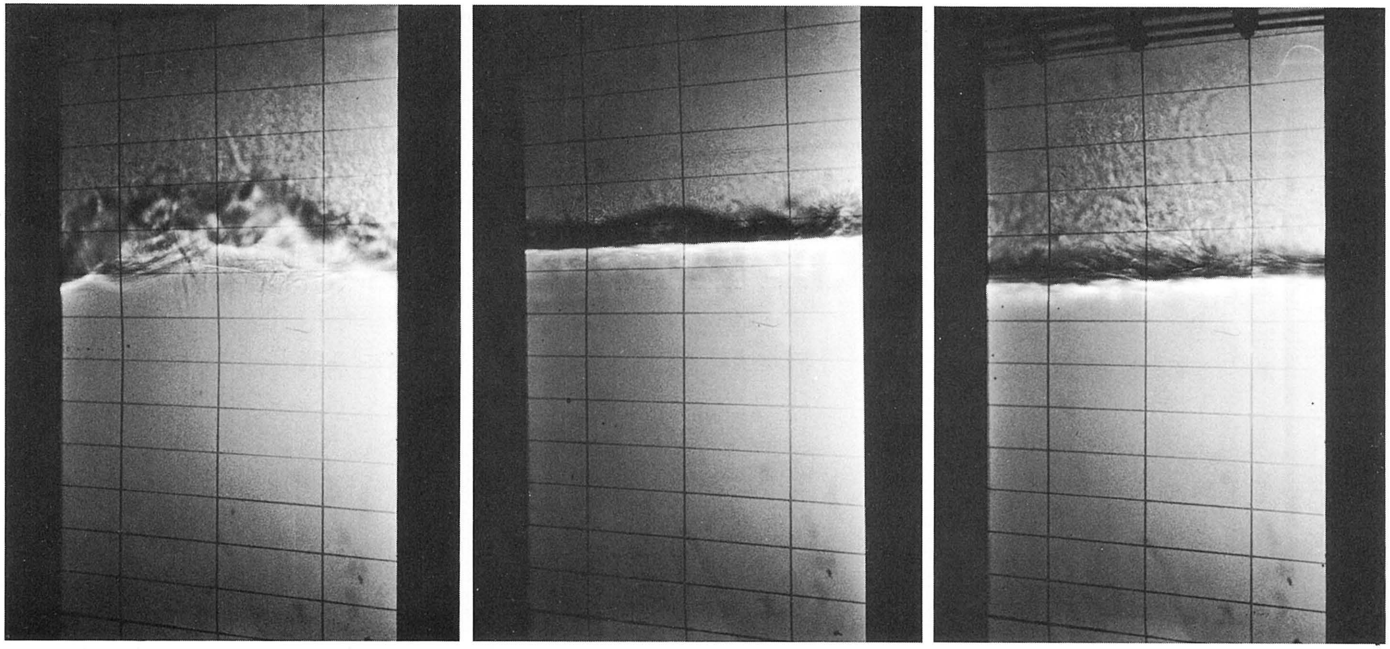

Photo. 9 Shadow graphs around the interface when $\Delta\rho/\rho_0 = 4\%$: (a) $f_r = 0$ Hz, (b) $f_r = 0.1$ Hz, (c) $f_r = 0.5$ Hz. Turbulence intensity decreases for weak rotation (b), while increases for strong rotation (c). Note the spike-like furious structure above the interface and thin long filaments below it.

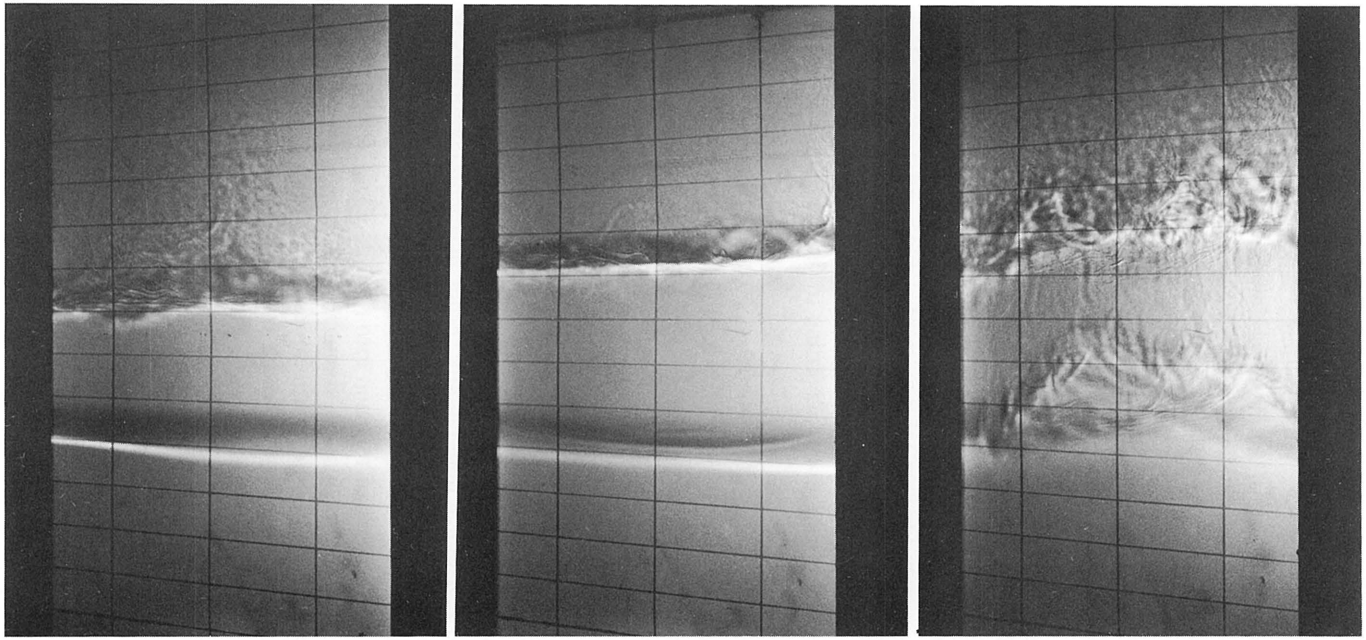

Photo. 10. The same as Photo. 9 except that the third layer is supplemented and that each interface has the (initial) density difference $\Delta\rho/\rho_0 = 1\%$: (a) $f_r = 0$ Hz, (b) $f_r = 0.1$ Hz, (c) $f_s = 0.5$ Hz. The behavior of the second interface is the same as observed in Photo. 7. Note that in (c) the second interface is a miniature of the first.

stretching is much stronger than negative ones due to shrinking.

The efficient mechanism of pumping up the lower fluid may be a reason for the increased rate of entrainment for high rotation. Also the doming of the interface may be a combined effect of Ekman suction and side boundaries; lateral friction reduces the upwelling by slowing down the eddies near the walls and uneven upwelling thus caused induce such a circulation as forms a dome of the interface.

Another remarkable finding is that strong rotation makes it impossible for the density interface to protect the lower layers from the penetration of turbulent motion (Furthermore, the long filaments below the interface imply that rotation allows the material invasion as well). The lower layer is moved by direct stretching (shrinking) action from the above, by indirect ones through Ekmann suction, or by the propagation of inertial waves. It is to be noted that the grid frequency $f_g = 1.5$ Hz is higher than the inertial frequency $2 \times f_r = 1$ Hz. Since the latter is the cut-off frequency for inertial waves, the grid cannot excite them directly. Therefore turbulent (nonlinear) energy transfer to lower frequencies is necessary for the propagation of (linear) inertial waves. Moreover, nonlinearity seems to predominate in the eddy dynamics, according to video records of visualization by (A1).

Non-monotonic dependence of the entrainment velocity on f_r is more difficult to interpret. At any rate, however, it must be a result of complicated rivalry of various effects of rotation, positive and negative, discussed in this section and introduction; those different effects should have different dependence on f_r. It remains as a future problem which value of f_r minimize the entrainment velocity and which mechanism is responsible for that.

At the last of this paper, we should make some cautionary remarks. First of all, we must remember that the arguments mentioned above are mere conjectures to be confirmed by quantitative or more refined experiments and that the results are presented for a few cases under many rather artificial conditions, so that careless generalization or applications must be refrained from. Secondly, the rate of rotation is extremely large as compared to that for the real ocean or atmosphere, to exaggerate the effects of rotation into relief. The Coriolis parameter $f = 4\pi f_r$ often exceeds the buoyancy frequency N in our experiments, whereas $f \ll N$ in the ocean. Thirdly, the artificial method of an oscillating grid imposes external length scales to turbulence, which is more severe and serious in rotating fluids than in non-rotating fluids because the two-dimensional columar turbulence has much longer distance of correlation vertically. In other words, rotation makes the turbulence remember the way it is generated for a long vertical distance. Fourthly, the doming of the interface will be ascribed to the effects of side walls, which are undesirable for the investigation of one-dimensional dynamics. This kind of circulation, however, makes another problem to be studied.

The present experiments are intended to obtain a primary description of the mixing in rotating stratified fluids. Only a few cases are explored by simple visualization. Experiments that follow up the presents ones should be directed for (1) dense covering of a wider range of parameters such as f_g/f_r, Ro and Ri, (2) more refined visualization to clarify the turbulence near the interface, (3) quantitative mesurements of entrainment velocity and turbulent structure above, near and below the interface, and (4) different ways of producing the turbulence such as the shear flow or penetrative convection.

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