Step-Like Vertical Structure Formation Due to Turbulent Mixing of Initially Continuous Density Gradients

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Abstract - The results of a simple laboratory experiments on the stirring of continuously stratified fluid by oscillating vertical rods are described and analyzed. It is discovered that, if turbulent stirring is rather weak, the strong linear stratification is transformed into a step-like structure during each experimental run. This structure consists of nearly homogeneous layers separated by thin density interfaces. The initial average thickness of the layers depends quasi-inversely on the buoyancy frequency and is growing with time during the experiment. Thus, the number of layers decreases with time mainly because of merging of layers. The analysis of our laboratory results combined with the analysis of previous studies give strong support for the suggestion that the "staircase" structure formation may be not an exotic phenomenon in the shallow summer pycnocline of Arctic seas under the influence of drifting ice floes (Golovin et. al, 1996). The disintegration of such a pycnocline into a series of turbulent layers separated by thin density interfaces may enhance the vertical transport of sediments and increase the rate of frazil ice formation (Krylov and Zatsepin, 1992).

Introdution

In the polar Arctic seas a shallow (3-10 m) and strong (10-25 sigma-t units) halo-pycnocline is formed during the summer due to ice melting processes and/or river run-off. The drifting ice floes often produce a considerable velocity shear and turbulent mixing across such a pycnocline. On the base of ship observations in Kara sea, it was shown (Golovin et al., 1996) that during these events the vertical density structure of the shallow pycnocline may be changed from "monolith" to the "step-like" form. Such changes in density structure should influence the exchange of properties between the upper and the lower layers, particularly, the heat, salt and sediment fluxes across the pycnocline zone. As a result, the rates of surface and underwater (frazil) ice formation (or melting) may be also changed.

It was suggested that the transformation of the initially continuous density stratification of the halocline into a series of homogeneous sublayers divided by extremely sharp density interfaces is due to the turbulence instability mechanism in strongly stratified fluid (Phillips, 1972; Posmentier, 1977). The qualitative explanation of this instability mechanism is based on the nonlinear dependence of vertical buoyancy flux on the density gradient in turbulent stratified flow. If the stratification is strong (Richardson number is enough high), the slight local enhancement of the density gradient considerably reduces the turbulent exchange coefficient, so that the buoyancy flux in this region is decreased. The local decrease of the buoyancy flux will tend to further increase of the density gradient. So the perturbation will amplify. As the result of the amplification of small disturbances (both positive and negative) initially continuous stratification may disintegrate into a series of quasi-homogeneous layers separated by sharp density interfaces. If the stratification is rather weak (Richardson number is below the critical

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one) the dependence of buoyancy flux on the density gradient is quasi-linear and local perturbations of density profile tends to be smoothen by turbulent diffusion. In this case layers does not form.

This effect was demonstrated in different laboratory and numerical experiments. It was shown that in both cases of shear (Barenblatt et al., 1993; Krylov, 1993; Kan and Tamai, 1994) and shear-free (Ruddick et al., 1989; Park et al., 1994) turbulent flows the formation of step-like density profile structure may occur. In order to explain the mentioned above observations made in the Kara sea the results of laboratory experiments with shear turbulent flows were used by Golovin et al. (1996). It was obtained that in order to satisfy the laboratory criteria of the pycnocline splitting $0.02 < Ri_u < 2$ (Krylov, 1993) (here $Ri_u=(g' \cdot h)/U^2$ -the Richardson number, g' - the reduced gravity, based on the density difference across the pycnocline, h - the thickness of the pycnocline, U - the horizontal velocity difference across it), U must be approximately twice of the ice drift velocity. In other words there must be enough strong current in the water layer below the pycnocline of opposite direction to the direction of ice drift. Although it is quite possible (there was no direct velocity measurements), the suggestion was made that the critical Richardson number Ri_{crit} for step-like structure formation may be a monotonously growing function of the Reynolds number for turbulence (the higher is the Reynolds number, the higher is the value of critical Richardson number), at least for low values of the Reynolds number (Nishida and Yoshida, 1994). In real ocean conditions the Reynolds number for turbulence is larger then in the most of laboratory experiments, so if the mentioned above suggestion is true, the critical Richardson number may also be larger. In these circumstances the shear across the pycnocline, required for the step-like structure formation may be smaller.

In order to check the assumption of the Ri_{crit} dependence on Re and to study more about conformities of the step-like structure formation in turbulent stratified fluid, we provided a series of shear-free experiments described below.

Experemental set-up

The scheme of preliminary experimental set-up is shown on the Figure 1. Here (1) is the tank ($25*16*30$ cm^3), made from 2.0 cm thick organic glass sheet, and filled by linearly stratified salt (NaCl) water solution. The turbulent mixing is produced by the system of horizontally oscillating grids (2). Approximately similar method of mixing was used first by Ruddick et al. (1989). In most of experimental runs there were six grids situated on the same oscillating rod (3) at the distance of about 3.5 cm from each other and from opposite small side walls of the tank. Each grid consists of six cylindrical vertical glass rods 0.7 cm in diameter with the distance of about 2.8 cm from each other. The oscillations are produced by electric motor with eccentric drive (4). The period of oscillations is fixed: $T = 2$ s, the amplitude is changed from one run to another. The larger is the amplitude of oscillations the higher is the intensity of turbulence. In order to make visible the density inhomogeneities in the turbulent stratified fluid the simple shadowgraph device (5) is used. The shadowgraph picture is monitored by video camera and photo camera.

Observation and results

Twenty five experimental runs were provided with six grids on the rod in order to observe different regimes of turbulent mixing in initially linearly stratified fluid. The initial salinity gradient was changed from 1.0 to 12.5 unit/cm and the amplitude of the oscillations - from 0.5

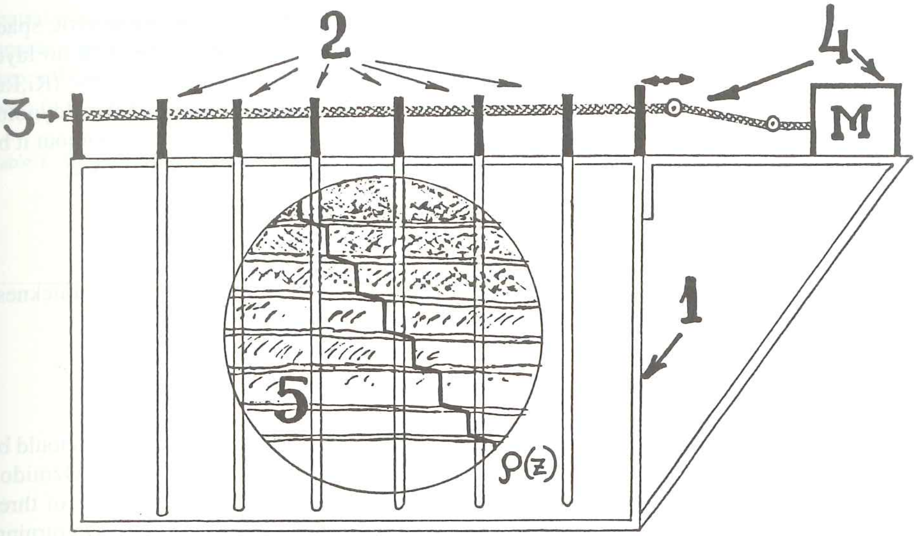

Figure 1: The scheme of experimental set-up (see the text for its detailed description).

to 1.7 cm. It has been discovered that, if turbulent mixing is rather weak, the linear stratification is transformed into the step-like structure (Figures 2 a,b) during each experimental run. This structure consists of nearly homogeneous layers separated by thin density interfaces. The initial thickness of the layers quasi-inversely depends on the density gradient and is growing with time during the experiment. Thus, the number of the layers decrease with time (Figure 2c) mainly because of merging of adjacent layers (vanishing of interfaces) or vanishing of thinner layers (merging of interfaces). Due to the no flux boundary conditions the upper and bottom layers are the most rapidly growing layers. So, the sub-final stage of mixing is the two-layered stratification (Figure 2d).

The main dimensional and non-dimensional parameters are presented in Table1. Here $N = (g\rho^{-1}\delta\rho/\delta z)^{0.5}$ and $\delta\rho/\delta z$ - the buoyancy frequency and the density gradient of the initial stratification, g - the gravity acceleration, $\rho \approx 1$ - the water density, H - the initial thickness of homogeneous layers for each experimental run. The absence in the Table 1 of H value for some of experimental runs means that no distinct layers were observed during these runs.

In order to make quantitative analysis of the data obtained to compare it with the results of Park et al. (1994) who also measured the initial thickness of homogeneous layers (unfortunately the results of Ruddick et al. (1989), are mostly qualitative so it is impossible to compare them with ours), we have analysed our data in terms of non-dimensional parameters. In accordance with the mentioned above authors we choose the Reynolds number of the rod, Re, and the overall Richardson number, Ri, defined as

$$Re = UD/\nu, \quad Ri = (ND/U)^2$$

where $U = 4A/T$ - the velocity scale, A - the amplitude of oscillations, D - the diameter of the rod, $\nu \approx 0.01$ cm^2/s - the kinematic viscosity of the fluid, as the most important non-dimensional parameters. We divided our experimental data and the data of Park et al. (1994) into two parts: the runs with the formation of layers and without them. In our experiment most runs was with layer formation, because our aim was only to determine the boundary in parametric space between to different regimes of mixing, but not to go deeply into the regime with no layer formation. All the points for both experiments are presented on the Figure 3 in the (Ri,Re) plane. For both experiments (that basically are related to different ranges of the Reynolds number) it is possible to separate roughly the points with layering from the points without it by the strait solid line on the Figure 3. This line results in the following power dependence:

$$Ri_{crit} = 1.97 \cdot 10^{-3} \cdot Re^{0.88} \qquad (1)$$

Another important result of our analysis is the parameterization of the initial layer thickness (see Figure 4). It follows from this figure, that

$$H = 2.0 \cdot (U/N) \qquad (2)$$

This relation corresponds well with similar parameterization of Park et al. (1994). It should be mentioned that the parameter U/N is physically analogous to the well-known Ozmidov lengthscale (Ozmidov, 1965). This lengthscale characterize the largest vertical size of three dimensional vortices in the stably stratified fluid, that is the largest vertical size of overturning. However, we did not measured the turbulent energy dissipation and are unable to confirm that the layer thickness is proportional to the Ozmidov length scale, although it seems to be so.

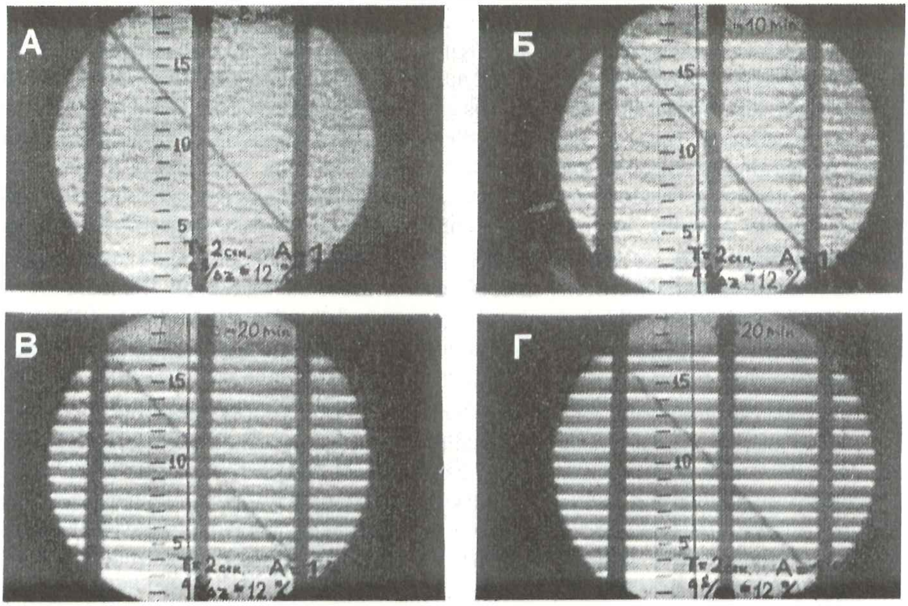

Figure 2: The successive shadowgraph pictures of turbulent stratified fluid in the tank during one of the experimental runs with the step-like structure formation (N = 3.0 rad/s; A = 0.75 cm). A) t = 10 min; Б) 30 min; В) 240 min; Г) 633 min.

In order to find out the role of spatial homogeneity of stirring in the process of layering, we provided the supplementary series of experimental runs in which the number of grids was changed from 6 to 1 for the same other conditions. It was obtained, that the layering event and the initial thickness of the layers does not depend on the number of grids and thus, on the spatial homogeneity of stirring. The decreasing of a number of grids was impressed only in the increasing (quasi-linear) of time period during witch the step-like structure was formed. Next step will be to provide experimental runs with intermittent stirring in order to investigate is there or not any critical time interval of stirring which controls the layer formation process.

Table 1: The dimensional and non-dimensional basic experimental parameters.

Rep	**U/N,cm**	**N,rad/c**	**U,cm/c**	**H,cm**	**Re**	**Ri**
1	0.80	1.8	1.45	1.2	101	0.75
2	0.41	3.2	1.33	0.7	93	2.83
3	0.45	3.2	1.45	0.9	101	2.38
4	0.51	3.1	1.6	1.1	112	1.83
5	0.58	3	1.75	1.8	122	1.44
6	0.68	2.9	2	3	140	1.03
7	0.79	2.8	2.23	3	156	0.77
8	1.03	2.6	2.7	4	189	0.45
9	0.67	2	1.35	1	94	1.07
10	0.84	1.9	1.6	1.5	112	0.69
11	1.05	1.8	1.9	2.2	133	0.43
12	1.46	1.6	2.35	4	164	0.22
13	0.85	1.4	1.2	-	84	0.66
14	1.03	1.4	1.45	1.3	101	0.45
15	1.23	1.3	1.6	2.4	112	0.32
16	1.72	1.1	1.9	3	133	0.16
17	1.3	1	1.3	1.4	91	0.28
18	1.61	0.9	1.45	1.7	101	0.18
19	1.85	0.7	1.3	2.4	91	0.14
20	3	0.5	1.5	-	105	0.05
21	2	0.8	1.6	-	112	0.12
22	0.38	2.6	1	-	70	3.31
23	0.6	2	1.2	-	84	1.36
24	1.8	1.5	2.7	-	189	0.15
25	1.32	2.5	3.3	-	231	0.28

Discssion and conclusions

One of the necessary conditions of the density step-like structure formation is that the energy supply is enough low and only sufficient to overturn a part of the stratified column. But even in this condition the formation f layered density structure from continuous one occurs only when the turbulent vertical mass flux negatively depends on the density gradient. Only in this case the small disturbances of density profile produced by turbulent stirring may grow up (Phillips, 1972; Posmentier, 1977). Another very important factor of layered structure formation and keeping out, is the existence of molecular diffusivity. Due to it the layers may be mixed to the quasi-homogeneous state. Moreover, the quasi-equilibrium state of the whole layered structure is apparently achieved due to molecular diffusivity, that controls the minimal thickness of the density interface and have influence on the mass and admixture fluxes between the mixed layers (Krylov and Zatsepin, 1992).

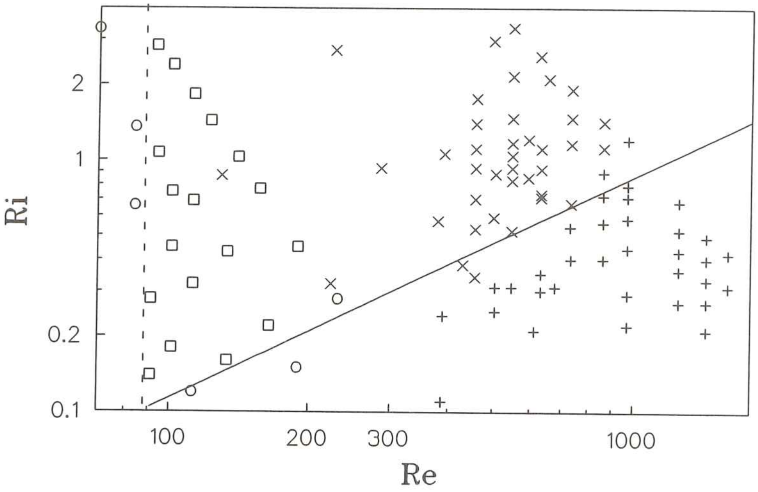

Figure 3: The diagram of the experimental runs in Re - Ri plane: - with layers, o - without layers (our experiment), X - with layers, + - without layers (Park et al., 1994). The dashed vertical line separates the experimental runs without turbulence and layers (Re < 90) from those with turbulence and layers. The inclined solid line separates experimental runs with turbulence and without layers from those with turbulence and layers.

The results of simple experiments described above basically confirm the arguments by Phillips and Posmentier for the turbulence instability and step-like structure formation in the turbulent stratified fluid. It was observed visually that the formation of the initial quasi-periodical disturbances on the density profile is due to the instability of turbulent vertical exchange process. The local overturning first of all occurs near the oscillating rods, where the formation of mixed layers begins. The initial vertically organized structure spreads laterally in the form of quasi-homogeneous intrusions. Sooner or later after the beginning of stirring the layered structure reaches the quasi-stationary stage. During this stage the continuous flux of mass and admixture through the whole water column is maintained due to turbulent mechanism in the mixed layers and predominantly due to molecular one across the density interface.

When the Richardson number is low and the Reynolds high no layering is observed because Phillips and Posmentier mechanism does not work in weakly stratified fluids. The critical Richardson number of layered structure formation is a growing function of the Reynolds number at least for Re = 10^2 - 10^3. Further experimental studies are required in order to obtain $Ri_{crit}(Re)$ for larger values of turbulent Reynolds number (10^3 - 10^4, based on the r.m.s. velocity and the integral lengthscale of turbulence) which seems to be more typical for the real ocean conditions. If the similar dependence will be obtained the application of turbulent instability mechanism for the interpretation of the observed pycnocline splitting (Golovin, et al., 1996) may become more convincing. The vertical scale of homogeneous layers expressed by semi-empirical formula (2) for U = 0.1-1 cm/s and $N = 10^{-1}s^{-1}$, gives the realistic estimate of typical layer thickness in the step-like pycnocline: H = 0.2-2 m.

The results of our laboratory experiment combined with the results of previous studies give

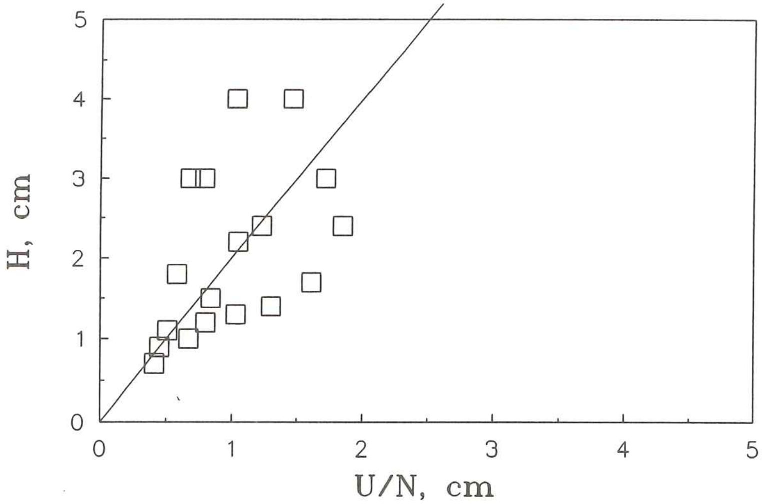

Figure 4: The dependence of the initial layer thickness H on the scaling parameter U/N.

strong support for the suggestion that the step-like structure formation does not depend on the nature of turbulence (shear or shear-free) and it may be not an exotic phenomenon in the shallow summer pycnocline of Arctic seas under the influence of drifting ice floes. The disintegration of such a pycnocline into a series of turbulent layers separated by thin density interfaces may enhance the vertical transport of heat, salt and sediments and increase the rate of underwater frazil ice formation (Krylov and Zatsepin, 1992).

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