Numerical Simulation of Gravitonal Turbulent Mixing with the Acceleration Sign Changed

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The problem of turbulent mixing under constant gravity (constant acceleration) creating an unstable situation on a plane interface of two incompressible fluids is studied experimentally in a number of papers [1-4]. Some papers [2,5-8] also study the problem numerically through direct 3D numerical simulations with code TREK.

Refs. [9,10] perform experiments with alternating sign of acceleration resulting in an unstable situation at the interface. The relevant problem is numerically studied in [11] with a turbulence type phenomenological model [12], however the mixing zone decrease effect at the steady-state stage can not be described with the model.

This paper studies the problem of turbulent mixing at a plane interface of two incompressible fluids of density difference n=3 with alternating acceleration sign through direct numerical simulation with 3D code TREK. The computation is parallelized into several tens of processors.

The problem is set up much like in refs. [6-8]: at the initial time two semi-spaces separated with plane $z=z_c=0$ are filled with resting ideal gases of densities $\rho_1=1$ and $\rho_2=n$ (n=3, Atwood number $A \equiv \frac{\rho_2-\rho_1}{\rho_2+\rho_1}$). If $t \le t^*=3$, gravity $g_z \equiv -g = -1$ is directed from the heavy material to the light; if $t > t^*$, $g_z \equiv g_{12} = 22/75$.

At the initial time the random-number generator sets random density perturbations at the interface (in a layer one cell in thickness): $\delta\rho = \pm\ \rho_1 \cdot \delta$, where $\delta = 0.1$.

The gas dynamics equations for ideal two-component medium (with zero molecular viscosity and heat conductivity) are solved.

The computational domain is a parallelepiped with the vertical side $\Lambda=2$ of side face. Its horizontal face is a square with side $L_x = L_y = 1$.

The initial pressure profile was given reasoning from the hydrostatic equilibrium condition.

The coordinate of the upper face is $z_2 = 0.85$, that of the lower $z_1 = -1.15$.

The initial pressure is such, that for the turbulent flow type under discussion the incompressibility condition was adequately met:

The equation of state is ideal gas with adiabatic constant $\gamma=1.4$.

The computational grid is uniform with $N_x=201$, $N_y=201$, $N_z=401$ cells. The cell size is $h_x = h_y = h_z = 0.005$.

The condition of "rigid wall" type was imposed on all computational domain boundaries.

The computed data is reported in the form of pixel patterns of light material concentrations for different times in different horizontal sections.

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The flow time history observed at the first (unstable) problem step is similar on the whole to the previous computations [2,5-8]: vortex enlargement with time and tapering-off to a self-similar regime at the end of the above step are observed.

The self-similar regime for that step manifests itself, in particular, in the tapering-off to the linear time function of turbulent mixing zone width L_t (t):

$$F \equiv \frac{1}{t_0}\sqrt{\frac{L_t}{Ag}}, \tag{1}$$

where $t_0 \equiv \sqrt{\frac{L_x}{g}}$, $(\tau \equiv t / t_0)$.

Here the slope angle dF/dτ determines coefficient $\alpha_a = \left(\frac{dF}{d\tau}\right)^2$ in the relation for the mixing zone width at the first (self-similar) step:

$$L_{ta} = \alpha_a A g t^2. \tag{2}$$

The calculated $\alpha_a \approx 0.05$ is slightly less than the data of our previous calculations [7,8] and that presented elsewhere [2,5] – the difference is explained by the high magnitude of ε=0.1, the same as in expeiments [9,10].

At the second step, $F(\tau)$ linearly decreases on the whole (to an accuracy of small fluctuations relating to the wave passage) with the slope angle $\alpha^{(-)} \equiv \frac{dF}{d\tau} \approx -0.084$ -

Refs. [9,10] measure

$$f \equiv \sqrt{2A\alpha_s} \equiv \frac{d\sqrt{z_2 - z_c}}{d\sqrt{S'}}, \tag{3}$$

where

$$S' \equiv g_{12}\frac{(t - t_c)^2}{2},$$

t_c is the time of F_2 peak.

From our calculation, the expression for f is

$$f = \frac{dF_2}{d\tau}\cdot\sqrt{A\cdot\frac{2g}{g_{12}}} \approx -0.074,$$

which is somewhat less (modulo) than the value of $f \approx -0.1$ $(\alpha_s \approx 0.01)$ suggested in [9,10] reasoning from the experiments.

For this problem the self-similar regime also manifests itself in tapering-off to the time-dependent value

$$E_m(t) \equiv \max(E)$$

– the scaled turbulent energy maximal in the TMZ width:

$$E \equiv \frac{k}{L_t g}$$

With the change in the acceleration sign, the E_m first noticeably drops and then increases slowly, with severe fluctuations.

The paper treats squared density and mass flow fluctuations σ maximal in TMZ.

It is shown that at the second step the resultant flow on the whole reverses sign relative to the normal (steady) situation (to an accuracy of the wave passage related fluctuations).

The paper makes comparison to the results of the calculations by the $k-\varepsilon$ turbulence model performed by the adequate, 1D EGAK-T computation on Lagrangian computational grid.

The flow time history observed at the first (unstable) step of the problem is similar on the whole to the previous computations: the tapering-off to the self-similar regime with time is observed.

For that step it manifests itself, in particular, in the tapering-off to the linear time function F of turbulent mixing zone width L_t (t).

However, at the second step (on the acceleration sign change), although the TMZ width growth rate slowing is noticeable, it can be seen that the $k-\varepsilon$ turbulence model can not decrease the width, its growth slows down and tapers off to a constant at late times, although an abrupt decrease in the turbulent energy is observed on the acceleration sign change.

References

1. Read, K.I. Experimental investigation for turbulent mixing by Rayleigh-Taylor instability. Physica D12, 45, 1984.
2. Linden P.F., Redondo J.M., Youngs D.L. Molecular mixing in Rayleigh-Taylor instability, J.Fluid Mech.(1994), vol.265, pp.97-124.
3. Dimonte G., Schneider M. Density ratio dependence of Rayleigh-Taylor mixing for sustained and impulsive acceleration histories. Report to 8th International Seminar on Turbulent Mixing of Compressible Matter. 8th IWPCTM, Pasadena, USA, 2001.
4. Kucherenko Yu.A., Shestachenko O.E., Piskunov Yu.A., Sviridov E.V., Medvedev V.M., Baishev A.I. Experimental study of the self-similar regime of different-density gases in the Earth's field of gravity. Proceedings of the 6th Zababakhin Scientific Talks. Snezhinsk, 24-28 September, 2001.
5. Youngs D.L. Numerical simulation of mixing by Rayleigh-Taylor and Richtmyer-Meshkov instabilites. Laser and Particle Beams. 1994. Vol 12. №4. P. 725-750.
6. Stadnik A.A., Statsenko V.P., Yanilkin Yu.V., Zhmailo V.A. Direct numerical simulation of gravitational turbulent mixing. 5rd International Workshop on the Phisics of compressible turbulent mixing, Stony Brook (USA), (1995-20).
7. Sinkova O.G., Stadnik A.L., Statsenko V.P., Yanilkin Yu.V., Zhmailo V.A., Three-Dimensional Direct Numerical Simulation of Gravitational Turbulent Mixing. 6rd Inter. Workshop on the Phis. of compr. turbulent mixing. Marseille, France. 1997.P.470-479.
8. Yanilkin Yu.V., Statsenko V.P., Rebrov S.V., Sin'kova O.G., Stadnik A.L. Study of gravitational turbulent mixing at large density differences using direct 3D numerical simulation // Report to 8th International Seminar on Turbulent Mixing of Compressible Matter. 8th IWPCTM, Pasadena, USA, 2001.
9. YU.A. Kucherenko, V.E. Neuvazhaev, A.P. Pylaev. Behaviour of gravitational turbulent mixing region under conditions leading to separation. 4rd International Workshop on The Phisics of compressible turbulent mixing, Cambridge, England, 1993. pp.70-80.
10. Y.A. Kucherenko, S.I. Balabin, R.I. Ardashova et al. Determination of Space and Time Distributions of the Averaged Density of Substance in the Turbulized Mixture Region at the Stage of Separation. 6th International Workshop on The Phisics of compressible turbulent mixing, Marseille, France, 1997. pp.258-265.
11. Z. Zhang and J.Wang, Numerical Simulation of Rayleigh-Taylor instability with the simplified Reynolds Stress Model, 6rd Inter. Workshop on the Phis. of compr. turbulent mixing. Marseille, France. 1997. pp.569-574.
12. Andronov V.A., Bakhrakh S.M., Meshkov E.E., Nikiforov V.V., Pevnitsky A.V., Tolshmyakov A.I. Experimental study and numerical simulation of turbulent mixing in 1D flows. DAN SSSR, V.264, No. 1, 1982, pp. 76-82.
13. Yanilkin Yu.V., Nikiforov V.V., Bondarenko Yu.A., Gubkov E.V., Zharova G.V., Statsenko V.P., Tarasov V.I. Two-parameter model and method for computations of turbulent mixing in 2D compressible flows. 5rd International Workshop on the Physics of compressible turbulent mixing, Stony Brook (USA), (1995).