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3D vortex structures of the internal waves around a sphere moving in the stratified fluid

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At the present paper the 3D separated and undulatory flows of the incompressible viscous stratified fluid around a sphere are investigated by means of the direct numerical simulation (DNS) on the massively parallel computers with a distributed memory and the β-visualization of the 3D vortex structures at the following ranges of the internal Froude *Fr* and Reynolds *Re* numbers: $0.004 \leq Fr \leq 10$, $Re = 100$ ($Fr = U/(N \cdot d)$, $Re = U \cdot d/\nu$; where d is a sphere diameter, N is a buoyancy frequency).

For solving of the Navier-Stokes equations in the Boussinesq approximation (including the diffusion equation for the stratified component (salt)) the Splitting on physical factors Method for Incompressible Fluid flows (SMIF) with the hybrid explicit finite difference scheme (second-order accuracy in space, minimum scheme viscosity and dispersion, monotonous) has been used [1]. The Poisson equation for the pressure has been solved by the Preconditioned Conjugate Gradients Method. For the visualization of the 3D vortex structures in the sphere wake the isosurfaces of β have been drawn, where β is *the imaginary part of the complex-conjugate eigen-values of the velocity gradient tensor* **G** [2]. The good efficiency of this β-visualization technique has been demonstrated in [3].

The full 3D vortex structure of the flow around a sphere is not clear for many flow regimes [4]. In addition the clear understanding of the continuous changing of this full structure with decreasing of *Fr* is also absent. At the present paper the continuous changing of this full structure is investigated in detail at $Re = 100$ (*for the first time*) by using DNS and the β-visualization technique. At $Fr > 10$ the fluid is practically *homogeneous.* One-thread wake is observed. At $0.9 < Fr < 10$ the *non-axisymmetric attached vortex* is observed in the recirculation zone. A four-threads wake is seen in the fluid at $2 \leq Fr \leq 10$. At $0.03 \leq Fr < 2$ the internal waves with length $\lambda/d \approx 2\pi \cdot Fr$ (in the vertical plane) have been simulated. The V-shaped horizontal vortices associated with these internal waves have been detected above and below threads at $0.2 \leq Fr < 2$. The angle between the ends of these V-shaped horizontal vortices is increased from 42° (at $Fr = 1$) up to 170° (at $Fr = 0.2$).

At $Fr \approx 0.9$ the quasi-rectangular vortex in the recirculation zone is *transformed into two symmetric vortex loops.* At $Fr \approx 0.6$ the four legs of these vortex loops are connected with the corresponding vortex threads induced in the wake along the sphere trajectory. The flow inside these legs is redirected downstream. The vortex loops are shifted from the sphere surface and the primary separation line on the sphere surface vanish. At $Fr \approx 0.4$ a new recirculation zone is formed from the "wave crest" which is situated very close to the sphere. At $Fr < 0.25$ *two steady vertical vortices* (bounded by the internal waves) are attached to the sphere. The obtained horizontal and vertical separation angles are in a good agreement with the experiment [4].

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