SEPARATION AND SORTING OF HEAVY PARTICLES SUSPENDED IN A FLUID BY SETTLING IN A PERIODIC VORTICITY FIELD

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Summary: We propose a new procedure for particle-fluid separation which differentiates particles with different inertia values. We simulate a velocity field which allows us to sort heavy particles suspended in a fluid depending on their inertia values.

Disperse multiphase flows are very common in the environment and many industrial processes, as mining or mechanical and thermal process technology (e.g. erosion phenomena, coal combustion, gas-particle or gas-droplet flow). The agglomeration of particles in a turbulent gas flow is also very important for many chemical engineering processes, e.g. the production of particles by gas phase reaction. Furthermore processes for the separation of solid particles from fluids and its classification are an important field to study [1].

Frequent processes for dust control include suppressing dust production, accelerating particle sedimentation, separating dust from the air stream with air cleaning devices and ventilation [2]. To accelerate the dust sedimentation some options have been studied as air ionization systems. Any mechanical strategies for dust control have been suggested, as fiber filters, water or oil scrubbers electrostatic precipitators, cyclone type dedusters [3].

All those procedures do not differentiate particles with different features. Here we propose a method for particle-fluid separation which differentiates particles with different inertia values. For that purpose we have simulated a velocity field generated by a 2D array of vortices periodically repeated in space.

In order to show the main features of the dynamics of heavy particles in vortex flows we consider the Rankine vortex, defined by a smooth transition from solid rotation close to its centre to an irrotational flow from it. The normalised 3-D velocity field in cartesian co-ordinates relatives to the axis of the vortex is given by $u_x{}^*=-2y^*\Gamma^*/(R_v{}^{*2}+x^{*2}+y^{*2})$, $u_y{}^*=2x^*\Gamma^*/(R_v{}^{*2}+x^{*2}+y^{*2})$, $u_z{}^*=0$ with Γ^* the circulation of the vortex and $R_v{}^*$ the radius of the vortex, so the maximum value of the velocity $|u^*|=U^*$ is given on $r^*= R_v{}^*= \Gamma^*/U^*$.

The motion of small spherical particles in a fluid is governed by a balance between the particle inertia, gravity and drag and buoyancy forces from the relative motion of particle and fluid. If the particle density is greater than the fluid density buoyancy and acceleration forces are not important and Newton's Second Law determines:

$$m_p^* \frac{d\mathbf{v}^*(t^*)}{dt^*} = 6\pi a^* \mu^* \left[\mathbf{u}^*(\mathbf{x}^*, t^*) - \mathbf{v}^*(t^*)\right] + m_p^* \mathbf{g}^* \ , \tag{1}$$

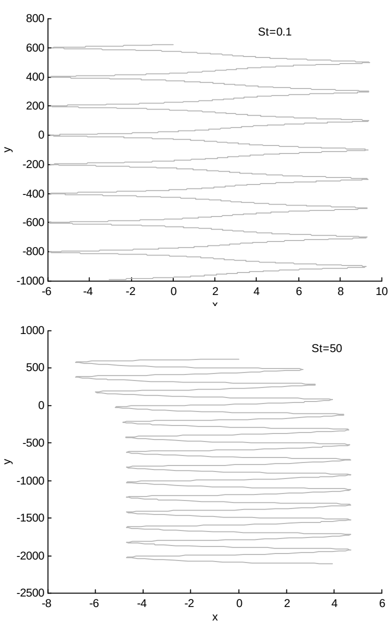
with $m_p{}^*$ particle mass, a^* particle radius, μ^* fluid viscosity, $\boldsymbol{g}^*$ gravitational acceleration and $\mathbf{u}^*(\mathbf{x}^*,t^*)$ local fluid velocity. Here, d/dt^* is the derivative following the particle. We have to write equations (1) in dimensionless form introducing the suitable dimensionless parameters. If the Reynolds number of the particles, based on their diameter and their terminal velocity, is small only two dimensionless parameters are enough to describe the motion of small spherical particles: a gravitational and an inertial parameter. The gravitational parameter could be the ratio of the terminal velocity of the particles in still flow $V_t{}^*$ to the characteristic velocity of the fluid U^*: $V_t=V_t{}^*/U^*=m_p{}^*g^*/6\pi a^*\mu^*$. In the case of turbulent flows, if the time that the particles need to escape from regions of intense vorticity is much greater than the life time of those vortex structures, the inertia of the particles is characterised by the Stokes number $St=\tau_p{}^*/\tau_r{}^*$, where $\tau_p{}^*= m_p{}^*/6\pi a^*\mu^*=V_t{}^*/g^*=(\beta-1)d_p{}^{*2}/(18\nu^*)$ is the viscous response time of the particles and $\tau_r{}^*=R_v{}^*/U^*$ is the characteristic residence time of the fluid flow. Here β is the ratio between the particle density and the fluid density, $d_p{}^*$ is the particle diameter and ν^* is the kinematic viscosity of the fluid. Considering $\mathbf{x}=\mathbf{x}^*/R_v{}^*$, $\mathbf{v}=\mathbf{v}^*/U^*$, $t=t^*U^*/R_v{}^*$ the scaled nondimensional equations of motion are:

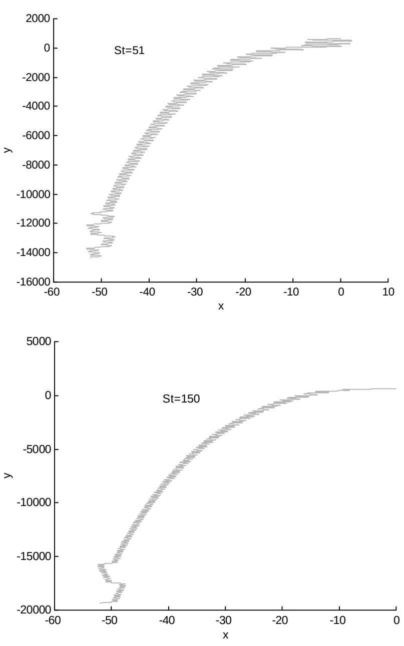
$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{v}(t) \ , \tag{2.a}$$

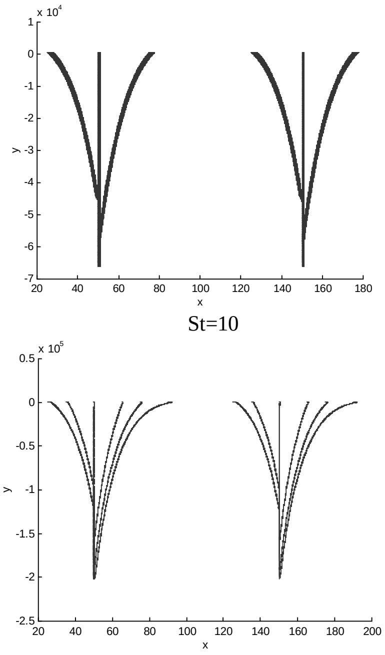
$$\frac{d\mathbf{v}(t)}{dt} = (\frac{1}{St})\left[\mathbf{u}(\mathbf{x},t) - \mathbf{v}(t) + \mathbf{V_t}\right] . \tag{2.b}$$

The trajectories of particles are obtained integrating equations (2) using a fourth order variable step size Runge-Kutta method. The initial condition at the position $\boldsymbol{x_o}$ is that the particles have the velocity of the fluid at $\boldsymbol{x_o}$.

We have simulated two cases. Firtsly the neighbouring vortices were swirling alternatively cyclonically and anticyclonically. For inertial particles there is not possibility of particle trapping due to the centrifugal inertial force, therefore there are not closed trajectories. Figure 1 shows that for small particle inertia the particles follow the flow streamlines surrounding the vortices, but for larger stokes number i.e. for larger particle inertia values figure 2 shows a surprising behaviour; every time the distance between the particle and the vertical row of vortices is greater and at last the particles settle in the central region of low vorticity situated between two vertical rows of vortices due to an inertial bias. It is similar to something observed by Wang and Maxey [4] in an homogeneous turbulent flow generated with direct numerical simulation: the particles group in the "canal" between neighbouring regions of vorticity. The particles tend to regions of high strain rate or low vorticity.







St=10

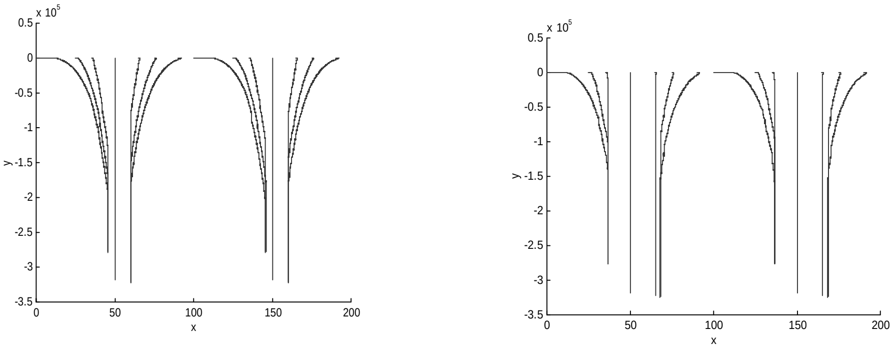
St=300

Figure 1: trajectories of inertial particles with neighbouring vortices swirling alternatively cyclonically and anticyclonically for small particle inertia.

Figure 2: trajectories of inertial particles with neighbouring vortices swirling alternatively cyclonically and anticyclonically for moderate particle inertia.

Figure 3: trajectories of inertial particles with neighbouring vortices swirling anticyclonically for small or moderate particle inertia.

Secondly all the vortices were swirling anticyclonically. In figure 3 we can see that for small or moderate particle inertia values all the particles settle in the central region of low vorticity situated between two vertical rows of vortices. The behaviour of the particles is the same as in the previous case (figure 2). Nevertheless, figure 4 shows a different behaviour for larger particle inertia values, an unexpected and surprising behaviour: for sufficiently large particle inertia the particles do not settle in the central region of low vorticity, they settle on some isolated curves which limit some regions of low vorticity where particles can not enter if they were initially outside those regions. As greater is the particle inertia greater is the width of those regions. At the same time, some empty regions situated under each vertical row of vortices appear. As greater is the particle inertia smaller is the width of these empty regions because the influence of the vorticity field is smaller.



St=600

St=1000

Figure 4: trajectories of inertial particles with neighbouring vortices swirling anticyclonically for large particle inertia.

Therefore is we know the particle inertia we will know the position in which it will settle and vice versa, so this fact suggest to develop a mechanism to sort particles with different inertia values materializing the velocity field mentioned above.

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