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Gravitational Effect Formulation on In-House Air-Particle Flow Solver

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Abstract. Distribution control of particles in air is only simulated in current years when computational power is slowly fading from being an issue. This work is preformed specifically to analyse the effect of additional gravitational effect feature in our newly developed in-house fluid-particle software. The effect is included in the Eulerian-Lagrangian solver so that it capable of simulating heavy particles in environmental air flows. Flow distributions of heavy particles such as liquid aerosol, sand or granular fertilizer are greatly affected by gravitational effect as compared to relatively buoyant particles such as smoke and light dust. Transient particle distribution in a ventilated room is simulated in this work. 10,000 particles that represent homogenous 2 mm Hemlock wood dust were randomly distributed in 3.3x2.8x5.9 m^3 ventilated room that consist of two ceiling air intake and four bottom wall ventilation outlets. Homogeneous Hemlock wood solid sphere particles with diameter of 2 mm is simulated while the air intake is equivalent to 0.0944 m^3/s. Simulation without the particle gravitational effect shows physically irrational results where 26 % of particles stayed at the top half of the room. Simulation with particle gravitational effect shows otherwise where 92 % of the particles settled at the bottom half of the room when measures at the same transient duration. The introduction of gravitational effect in the newly developed in-house air-particle solver can be considered as the turning point where simulations of environmental air-particle related studies such as dust ventilation, aerosol control or even granular fertilizer distributions out of boom sprayer are possible.

Introduction

Eulerian-Eulerian technique involves almost similar equation to solve both phases. In each phase, different parameters are used to discriminate the interactions [1,7]. However, interaction between particles, particle and walls and even particle and the fluid itself require further intensive technique that proficiently distinguishes the dissimilarity between fluid and particle characteristics.Patankar and Joseph [2] are among the pioneers to commence the application of Eulerian-Lagrangian technique in dealing with fluid-particle interactions. Fluid phase is modelled using long-established momentum and continuity equations while the particles' behaviour is modelled using a set of equations that comply with Newton's equations of motion. Splitting scheme by Karniadakis [3] is proven to be relatively efficient velocity-pressure coupling solver for fluid flow simulations. However, this scheme is yet to be coupled with the advantages of Lagrangian particles simulations and thus yield more efficient Eulerian-Lagrangian technique.

Particle-laden flow behavior has been studied earlier by experimental means mostly using particle imaging velocimetry (PIV) and particle tracking velocimetry (PTV). Experimental data is always essential in analyzing actual phenomena and validating simulation hypothesis. Simple yet complicated experimental setup to study particles behavior submerged in a lid-driven cavity by Tsorng [4] is referred by other researchers to validate their simulation results. Fig. 1 illustrates the experimental three-dimensional trajectory of a solid particle in lid-driven cavity by Tsorng for fluid Reynolds number 470.

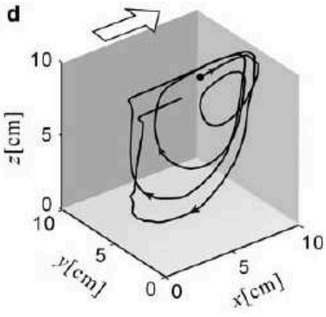

Fig. 1: Three-dimensional trajectory of solid particle for Re = 470, result (from [4], Fig. 11).

Particle conformity to fluid flow is vital in various phenomena such as sedimentation, deposition, ventilation and waste management. Nevertheless, there are only limited academic resources discussing the characteristics and behaviours. However, there are few works have been done on particle conformity to fluid flow in the past few years. In 2009, Kosinski et al. [5], among others, made a qualitative comparison of a single solid sphere particle path in a lid-driven cavity between his numerical solutions with experimental results by Tsorng et al. The main purpose of this work is to introduce particle weight effect on a newly developed fluid-particle solver. The flow solver which is based from Splitting method by Karniadakis et. al [3] has been successfully integrated with another phase solver where Lagrangian solid particle is introduced to form a viable two-phase Eulerian-Lagrangian particle-flow solver. In order to prove the effectiveness of the code, qualitative comparisons with both numerical solutions by Kosinski [5] and experimental result by Tsorng [4] were performed. An important introduction of gravitational effect feature is analysed in this work in order to improve the solver feasibility upon environmental air-particle related case studies. Air and particle distribution analyses on studies such as dust ventilation, aerosol control or even granular fertilizer blower distributions are expected to be covered by this solver advancement.

Methodology

Mechanics of particle motions are used in attaining the particle trajectory. Consider a particle of mass m moving through a fluid under the action of an external force F_E. Let the velocity of the particle relative to the fluid be u, the buoyant force on the particle be F_B and the drag be F_D, then we have,

$$m\frac{du}{dt} = F_E - F_B - F_D \tag{1}$$

The drag force in the above equation is,

$$F_D = C_D u^2 \rho A_p / 2 \tag{2}$$

where C_D is the drag coefficient, A_p is the projected area of the particle in the plane perpendicular to the flow direction. Drag coefficient is a function of Reynolds number. The particle Reynolds number is denoted as,

$$N_{\mathrm{Re},p} = \frac{uD_p\rho}{\mu} \tag{3}$$

Where u is the velocity of approaching stream, D_p is the diameter of the particle, ρ is the density of fluid and μ is the viscosity of fluid. Stokes' law applies for particle Reynolds number less than 1.0. The drag coefficient is simply,

$$C_D = 24/N_{\mathrm{Re},p} \tag{4}$$

The essential part of this work is on the introduction of F_B in equation (1) exerted by the gravitational effect. The motion from gravitational force is,

$$\frac{du}{dt} = g\frac{\rho_p - \rho_f}{\rho_p} - \frac{C_D u^2 A_p \rho_p}{2m} \tag{5}$$

The gravitational effect comparison assessed in this work is based on either this equation is evaluated or not in the solver. The ventilated room case study in this work is based on the experimental setup by Murakami et al. [8]. The geometry however was rounded to the nearest 10 cm increment. The air intake was placed 10cm to one side of the larger wall from the centre line to create the asymmetric flow pattern. Transient flow simulation was executed with time ranging from zero to 700 seconds. 10,000 particles that represent homogenous 2 mm Hemlock wood dust were randomly distributed in the 3.3x2.8x5.9 m^3 ventilated room that consist of two ceiling air intake and four bottom wall ventilation outlets. Homogeneous solid sphere particles with diameter of 2 mm were simulated while the air intake was equivalent to 0.0944 m^3/s. All air and particle parameters were based on the ambient temperature of 15°C and 1 bar pressure. Velocity profile inside the room was visualized through two velocity contour slices placed at the horizontal centre of the room and at the centre of the four ventilation opening as shown in Fig. 2. The quantitative evaluations of total number of particles at each level of the room elevation were made for the data at 14.22 seconds after the simulation time started.

Results and Discussion

Fig. 2 shows the particles distributions with and without the introduction of gravitational effect to the particle solver. The images showing the particles distributions and velocity contour slices were captured at time 0, 3.56 and 7.11 seconds. The top two images in Fig. 2 illustrate the initial condition of the ventilated room. 10,000 homogeneous particles with diameter of 2 mm were placed randomly throughout the room at time 0 second. The time recorded for all the particles to settled at the room floor was 4.12 seconds only. This controlled experiment was performed to measure the effect of air ventilation flow and the effect of gravity force without the intervention of flow drag force. The two images at the centre of Fig. 2 show the early movement of the particles at time 3.56 seconds for both with and without gravitational effect. Particles on both conditions exhibit a similar pattern when blown out toward the walls. The particles with gravitational effect in the centre-right image however deposited more on the bottom half of the walls. The centre-left image on the other hand illustrates more even distribution of particles even though the inlet flows were directed downward. Both centre images prove that at this early stage, particles were pushed away from the room centre area where the inlet blowers were placed. The particles that reach the walls were forced to move along the walls and finally deposited the edges of the walls.

At time 7.11 seconds from the start of the transient response, particles distributions with and without gravitational effects were pointed up in bottom-right and bottom images in Fig. 2 respectively. The particle distributions were observed to continue the flow pattern. The particles with gravitational effect in the bottom-right image demonstrated the same behaviour with more particles was settled at the edges of the room walls but at lower position of the room. Following the same distribution pattern, bottom left image in Fig. 2 prove that without gravitational effect, particles were evenly distributed to all vertical walls of the room and finally evenly deposited at the edges of these walls.

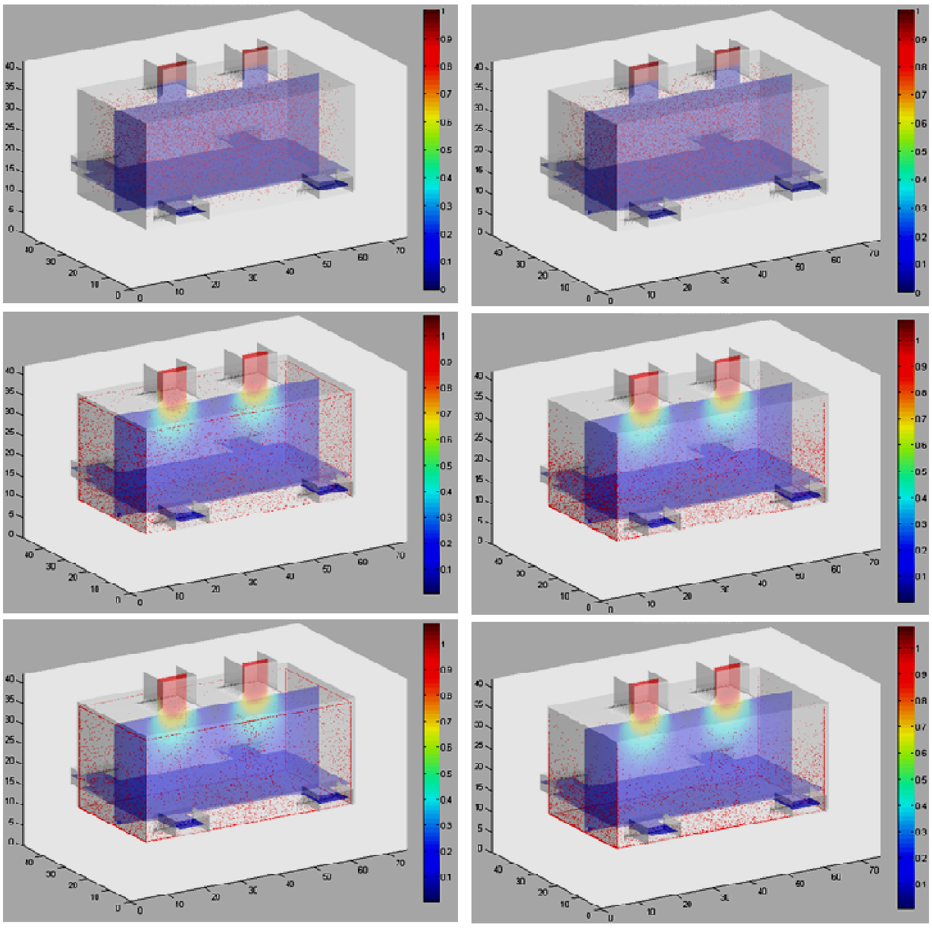

Fig. 2: Particles distributions and velocity contour slices with (R) and without (L) the introduction of gravitational effect for time 0 second (T), 3.56 second (C) and 7.11 second (B).

Fig. 3 shows the total number of particles at each level of the room elevation for the simulations with and without the gravity force consideration. The two spikes at the top and bottom of the elevation show that most of the particles were settled at the top and bottom edges of the room. After the same period of time, both simulations with and without the gravitational effect resulted in more than half of the total number of particles were already at the bottom of the room. The graph reveals that particle simulation without the effect of gravity force in this case study demonstrated a totally different phenomenon as compared to the other simulation. This over-assumption solver recorded more than 20% of the particles settled at the ceiling of the room while the solver with gravity force algorithm showed that these 20% particles were distributed mostly at the bottom half of the room. Interestingly, both qualitative comparison in Fig. 2 and quantitative comparison in Fig. 3 have proven that gravitational effect is essential when it comes to particle simulations in environmental case studies. Simulation of relatively light particles where the particle flow is proven to conform to the fluid flow can be performed with solvers without the gravity force consideration.

Conclusion

The main objective of this paper, which is to evaluate the introduction of gravitational effect on the newly developed Eulerian-Lagrangian fluid-particle solver, was successfully achieved. Gravitational effect is proven to be essential for particle distribution analysis and can only be neglected when a simulation is done with relatively very small particle body force effect. The introduction was also proven to be feasible through validation with experimental and other simulation results. The establishment of gravitational effect in the in-house software offers wider discovery prospect for Eulerian-Lagrangian technique in environmental air-particle related case studies.

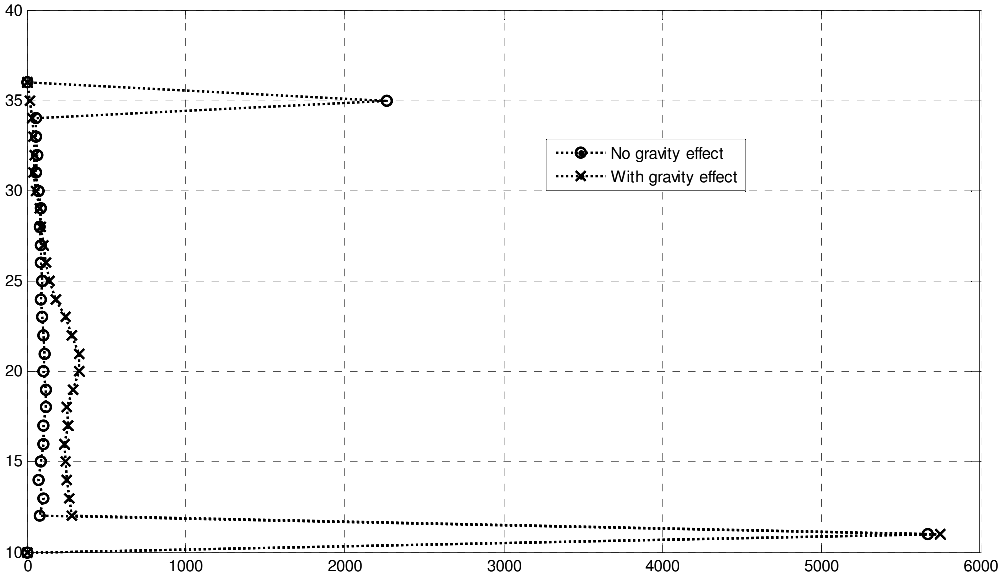

Fig. 3: Total numbers of particles at each level of room elevation with and without gravity effect.

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