

Lecture 1:

## Forces on particles and bubbles

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In order to describe the motion of particles and bubbles in fluids it is necessary to consider all relevant forces, external and fluid dynamic forces. Starting with the well-known BBO equation the lecture will summarise these forces emphasising the extension to higher particle Reynolds numbers. Note that the BBO equation is only valid for Stokes flow (i.e.  $Rep < 0.5$ ). Such an extension to higher particle Reynolds numbers is based on resistance coefficients which have to be determined either experimentally or through direct numerical simulations (DNS). The main fluid dynamic forces considered for solid particles are the drag, added mass and history force as well as transverse lift forces in shear flows and due to particle rotation. The importance of these forces are analysed and suggestions are provided. Finally also some fundamentals on the behaviour of air bubbles in liquids are provided emphasising the mobility of the interface between bubble and surrounding liquid. The state-of-the-art regarding the different forces acting on bubbles is presented and their importance is highlighted.

### Literature

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Lecture 2:

## **Numerical methods for multi-phase flows**

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Numerical calculations of multi-phase flows become more and more of importance. The methods to be used depend of course on the type and structure of the multi-phase flow considered. Therefore, at the beginning a classification of multi-phase flows will be provided. Then numerical methods will be summarised mainly suitable for dispersed multi-phase flows. For such applications the numerical method naturally depends on the scales of flow and dispersed phase. A full DNS (direct numerical simulation) entirely resolves both the fluid scales (i.e. Kolmogorov scale in turbulent flow) and the contour of the particles. Thereby also the flow around the particles is captured. In case fluid particles are considered (i.e. droplets or bubbles), suitable methods are needed to track or capture the interface. Interface capturing methods reconstruct the interface (e.g. volume of fluid, VOF) from the distribution of the volume fraction of one phase. Moreover, the Lattice-Boltzmann method will be introduced where the dispersed phase (i.e. particles) may be treated as point-masses or may be fully resolved by the grid.

For macro-scale simulations (i.e. an entire process or equipment) of dispersed multi-phase flows the particles have to be treated as point-masses or point-particles. The two approaches to be used for such calculations are the Euler/Euler and Euler/Lagrange method. Naturally, also turbulence cannot be resolved so that a suitable turbulence model is required, e.g. LES-sub-grid scale model or k- $\epsilon$  turbulence model (RANS). The Euler/Euler or two-fluid approach considers the dispersed phase as a continuum requiring a number of closures regarding the particles fluctuating motion and the fluid-particle velocity correlations. In the Lagrangian approach the dispersed phase is simulated by tracking a large number of representative particles through the flow field and the particle-phase properties have to be determined by a statistical sampling procedure. The coupling between fluid flow and particle phase is normally done via the PSI (particle source in cell) method. Consequently a converged solution of the multiphase system is obtained through an iterative process, i.e. sequential calculation of fluid flow and particle phase.

Lecture 3: **The Euler/Lagrange approach and applications to technical processes**

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The Euler/Lagrange approach is a hybrid technique where the continuous phase is calculated on a fixed grid in an Eulerian frame and the dispersed phase is simulated in a Lagrangian fashion by tracking a large number of computational particles through the flow field. A converged fully-coupled solution of the two-phase flow system is reached by sequentially solving the Eulerian and Lagrangian part, accounting for the source- or coupling-terms in the conservation equations of the fluid phase; i.e. the influence of particles on the fluid flow. Calculations of turbulent flow fields can be done by applying direct numerical simulations (DNS), large eddy simulations (LES) or Reynolds-averaged methods (RANS) combined with an appropriate turbulence model. Based on that and the considered flow configuration, the coupled Euler/Lagrange calculations are done fully-unsteady, quasi-unsteady or steady. The Euler/Lagrange approach is only applicable to multiphase flows with dispersed particles (i.e. solid particles, droplets or bubbles) which are treated as point-masses. The great advantage of the Lagrangian approach is that the discrete nature of the particles is maintained, allowing a detailed modelling of all relevant elementary processes (e.g. particle-wall collisions, inter-particle collisions, agglomeration or coalescence), and in addition the particle size distribution can be easily resolved. It should be emphasised that there is no limitation on the applicability of the Lagrangian approach with respect to the particle volume fraction as it is quite often stated in the literature. The limitations are only seen in the required computational time, the number of particles which may be handled and the modelling requirements.

One may identify basically three methods in treating the particulate phase, namely, the classical Lagrangian tracking without inter-particle collisions, the hard-sphere approach (Lagrangian tracking with inter-particle collisions or often named discrete particle method (DPM)) and the soft sphere approach which is often implemented by the discrete element approach (DEM). In the DPM only binary instantaneous collisions between neighbouring particles are considered describing the momentum exchange through the application of Newton's second and third law. Depending on the type of flow calculation being used (e.g. DNS, LES or RANS) and the particle system considered a deterministic or stochastic collision model may be applied. Naturally, in the case of point-particle DNS all real particles have to be tracked and only a deterministic collision model is applicable.

In the DEM multiple particle contacts or collisions are resolved, requiring a rather sophisticated modelling of the contact forces often accomplished through a spring, dashpot and friction slider system for each contact. In this approach all real particles have to be considered, limiting the computable size of the system.

The Euler/Lagrange approach applied in the present study is based on a RANS approach for the continuous phase (i.e.  $k$ - $\epsilon$  turbulence model or Reynolds-stress model) and the Lagrangian approach using the concept of parcels (i.e. each computational particle or parcel represents a number of real particles with identical properties). Recent advances in modelling particle dispersion in turbulence, particle-wall collisions accounting for wall roughness and inter-particle collisions on the basis of a stochastic approach are introduced and illustrated.

Finally, the importance of these elementary processes for predicted particle-laden flows are highlighted based on some typical industrial confined flow configurations. Examples are a particle-laden free jet, pneumatic conveying in channels and pipes, unsteady swirling flow and particle dispersion in a stirred vessel. The computational results are validated based on available experiments.

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Lecture 4: **Inter-particle collision phenomena in turbulent particle-laden flows**

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Collisions between solid particles in a particle-laden turbulent flow play an important role in numerous technical processes, such as for example dilute-phase pneumatic conveying. The consequences of inter-particle collisions are redistribution of the particle phase (i.e. influencing particle concentration distribution in the equipment), redistribution of particle momentum, particle agglomeration and possible particle breakage. For analysing the influence and importance of inter-particle collisions on the characteristics of particle-laden flow processes the Euler/Lagrange approach was used. Thereby, numerical computations were conducted on two levels. Point-particle DNS (direct numerical simulations) were performed for examining the effect of inter-particle collisions on the particle phase distribution in homogeneous isotropic turbulence (Ernst & Sommerfeld 2012). The fluid flow is simulated by the Lattice-Boltzmann method using a pseudo-spectral forcing method for exciting turbulence. A large number of particles were tracked through the flow field by only considering the drag force. Inter-particle collisions were detected based on a deterministic time-sequenced collision detection approach. It is well known that for small and large Stokes numbers (Stokesian particle response time to Kolmogorov time scale) the particles are quite homogeneously distributed in this turbulent flow. However, for particle Stokes numbers around one strong particle accumulation is observed in regions of low vorticity and high strain rate. Inter-particle collisions of course affect the spatial distribution of the particles depending on the overall particle volume fraction. This phenomenon was quantified using the degree of accumulation and the correlation dimension.

For the numerical calculation of technical or industrial processes DNS for the flow is not feasible. Therefore, the Reynolds-averaged conservation equations (mostly termed RANS) in connection with an appropriate turbulence model (here the  $k$ - $\epsilon$  turbulence model) are used to calculate the fluid flow. Particles are treated as point-masses representing a certain number of real particles (i.e. the so-called parcel concept) in order to represent the correct particle concentration with a treatable number of computational particles. Lagrangian tracking of the particles is done by accounting for all relevant forces (i.e. fluid forces and field forces) and the influence of turbulence on particle motion is described by a stochastic model (Lain & Sommerfeld 2008, Sommerfeld & Lain 2012, Sommerfeld et al. 2008). For allowing an efficient treatment of inter-particle collisions a stochastic model (Sommerfeld 2001) was used. With this computational approach the influence of inter-particle collisions on the characteristics of pneumatic conveying through a 5 m horizontal pipe, a bend and a 5 m vertical pipe was studied by considering a number of operational parameters.

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