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SIMULTANE MESSUNGEN DER PARTIKEL- UND FLUIDGESCHWINDIGKEIT IN ZWEI PHASIGEN ROHRSTRÖMUNGEN MITTELS PIV/PTV

SIMULTANEOUS MEASUREMENTS OF SOLID PARTICLE AND FLUID VELOCITY IN TWO PHASE PIPE FLOWS USING COMBINED PIV/PTV TECHNIQUES

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PIV/PTV, solid-liquid suspension, vertical flow, multiphase flow

Abstract

In this experimental study, the particle image velocimetry (PIV) and the particle tracking velocimetry (PTV) was used to measure the local fluid and particle velocities of solid-liquid suspensions in a vertical pipe flow. The phase separation technique as explained by Gui and Merzkirch (1996) was applied to obtain a multiphase velocity field composed by the fluid flow field and the velocity of the discrete solid particles. Furthermore, the edges of the particles located within the light sheet were detected by an implementation of the Hough transform by Peng (2005). Once the particle centers were determined, an image mask was created and used for the application of the PIV and PTV algorithms.

Introduction

Solid particle production and transport play an important role in the performance of many industrial processes. Food, mining and drilling industries, among others, require accurate determination of the operation parameters for process optimization. Due to the complexity of multiphase flow the important flow variables have been traditionally predicted using empirical correlations, which are normally constrained to the specific conditions of the measured system. More demanding scenarios, which cannot be easily measured, may be evaluated with computational fluid dynamics (CFD) simulations. Nevertheless, the models used in multiphase flow CFD simulations rely on the availability and accuracy of experimental data; both, for the design and for the validation of such models. This requires a better understanding and quantification of the underlying phenomena, which at the same time demands measurements able to resolve the flow fields around the particles.

The use of new experimental methods sheds new light in the analysis of suspension flows. These new methods are in most cases non intrusive and allow to reproduce completely resolved flow fields. Hence, they allow investigating detailed phenomena as hydrodynamic interactions of particles close to walls or particle migration. In particular, lift forces and particle migration for single particles in shear flows have been thoroughly analyzed since the original works from Saffman and Segré & Silberberg in the 1960´s. Nevertheless, for higher concentrated flows these phenomena still need detailed investigations. Zachos et al. (1995) described methods to measure multiphase velocity fields with nominally high concentrations of the solid phase. They used spherical glass particles and a mixture of tetraline and clear coal oil to match the refractive indices and increase transparency. Likewise, Cui and Adrian (1997) reported two more refractive index-matched systems of solids particles in liquids. In addition, different approaches have been used in the combination of the PIV and PTV techniques to investigate multiphase phenomena. Gui and Merzkirch (1996) reported a method where image masks were applied to the PIV recordings in order to eliminate the influence of the dispersed phase on the measurements. The advantage of this method consisted on the application of only one camera and one light source, simplifying in this way the necessary setup to acquire two phase measurements.

The aim of the present experimental study is the simultaneous measurement of the local particle and fluid velocity in low concentrated dispersion vertical pipe flow to study the effects of non-neutrally buoyant particles on fluid velocity fields. The collected data will be later used to validate CFD models, where volume fraction may be taken into account in the study of lift forces and accumulation of particles in specific domains. The setup preparation required a combination of the previously mentioned methods and the refractive index matching of the working fluid and the pipe material. Together with the use of an optical box, the previous setup avoided any kind of reflections on the pipe walls and allowed the acquisition of multiphase velocity fields in the region of interest.

Experimetal setup

The experiments are carried out in the *Vertical Multiphase Flow Loop* at the *Insitute of Applied Mechanics of Clausthal University,* shown schematically in Fig. 1. The construction follows concepts presented by Kriegel and Brauer (1966). Particles (glass spheres) are added to the flow through a feeding device (eductor) and transported through the hoses and later through the test section to a separating container. In this container, particles are redirected to the feeding device while the fluid (light liquid paraffin) enters a multi stage pump (16 stages, nominal flow rate 0,0016 m^3/s). The experimental test section consisting of a Plexiglas® pipe has inner dimensions of Ø 64 x 2000 mm, which allows pipe Reynolds numbers up to 170.

A gear flow meter is incorporated between the pump and the educator. Flow rates indicated by the flow meter are used to calibrate analytical velocity profiles. These are later compared with the values obtained using the PIV system to verify its accuracy.

Due to its convenient refractive index (1,473) light liquid paraffin (Shell Ondina 927) was selected as the working fluid. The use of this fluid supplied a measuring system with virtually no reflections at the wall boundaries. Density and viscosity at room temperature are 865 kg/m^3 and 72 mPa·s, respectively. An electronic thermometer is used to record the working temperatures and calculate the corresponding viscosity and density.

The dispersed phase conisist of solid glass beads (Type P and Type S, from Sigmund Lindner GmbH) with diameters between 2 to 5 mm at a tolerance of ±0,02 mm. Densities of the glass beads were 2.230 kg/ m^3 for borosilicate and 2.500 kg/m^3 for soda lime. The particles were continuously added to the fluid at different concentrations with the particle injection system (eductor). Upstream of the pump, the particles were separated using a filter to avoid damage of the pump and of the particles. The use of transparent spherical glass particles allowed avoiding interferences from particles situated in front of the laser light sheet.

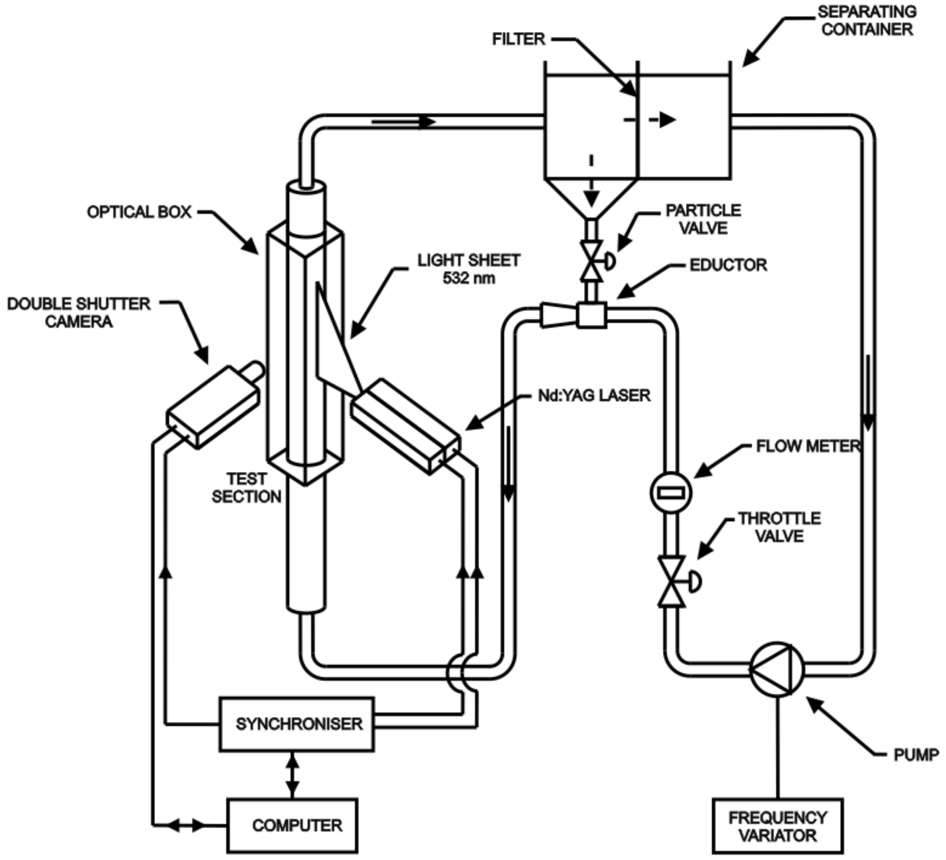


Fig. 1: Schematic diagram of flow loop

Measurement technique

To obtain the two dimensional – two components (2D2C) multiphase velocity a combination of the PIV and the PTV technique as explained by Gui and Merzkirch 1996 is used. The velocity field of the continuous phase is obtained using the cross-correlation algorithm of the PIV system (EDPIV) and the velocities of the particles are obtained using a PTV algorithm. This method required phase separation to avoid influences of the dispersed phase on the continuous phase and vice versa. In this experiment, an object identification algorithm based on the Hough transform is used. Once the objects are identified, their center coordinates determined the positions of circular masks, which were applied on the raw image pair to run the PIV algorithms and subsequently the PTV algorithms. Finally, the results obtained from both methods were combined to obtain the multiphase flow fields. Fig. 2 shows schematically the process used to obtain the flow fields.

Measurements are performed with an ILA PIV system, consisting of a Solo PIV double-pulsed Nd:YAG laser system with up to 30 mJ at 532 nm wavelength, a PCO sensicam qe camera with 1.376 x 1.040 pixels and 12-bit resolution and an ILA miniPIV-synchronizer responsible for timing the camera and the laser.

The laser pulse duration is 5 ns with a peak power of 6 MW and the time delay between pulses is adjusted between 1 to 2,5 ms depending on the fluid velocity. A double-concave lens f=20 mm to spread the laser beam, a focal distance adjustment to set the light sheet thickness in the illumination plane and a 16° cylindrical lens f = 25 mm transform the laser beam into a thin vertical light sheet of about 1 mm thickness.

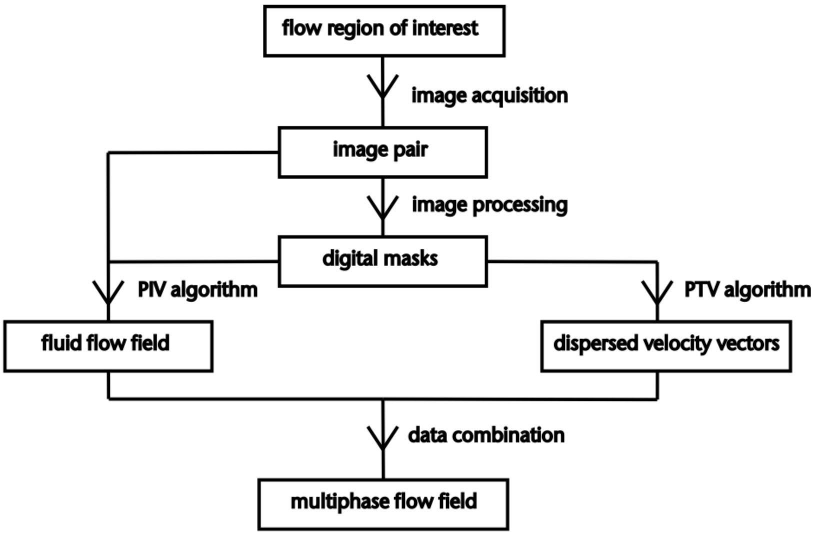


Fig. 2: Schema of the phase separation process

The working fluid is seeded with hollow glass spheres (Sphericel 110P8, from Potters Industries Inc.) with mean diameters of 9-18 µm and an average density of 1.100 kg/m^3. The light scattered by these particles is recorded on the charge coupled device (CCD) sensor of the camera, which is situated perpendicular to the region of interest. In order to capture the image pairs, the camera is used in the double exposure frame-triggering mode with a maximum acquisition frequency of 10 Hz. A Nikon Micro-NIKKOR 55 mm lens is mounted at the camera. The F-number is adjusted to 2,8 and the separation between the region of interest and the camera sensor is approximately 80 cm.

The camera is mounted on a three-axis tripod and the laser on an aluminum profile fixed to the flow loop structure. A flat-faced Plexiglas® optical box positioned over the pipe is used to minimize distortions in the optical measurements. Light liquid paraffin is also used as the liquid medium between the Plexiglas® optical-box and the pipe wall. Velocity fields are taken at a location 1,6 m (25 diameters) downstream of the inlet of the test section. In the measurements, the axis of the pipe is coplanar to the light sheet.

Figure 3 shows a raw image acquired during the measurements. The laser light propagation is towards the left side of the image and the flow is upwards. The image looks like a typical PIV recording with the only difference being the inclusion of bigger dispersed spherical particles. Different illuminations of the particles may be observed based on the position of the same relative to the light sheet plane. In this manner, particles exactly falling under the sheet reflect a higher quantity of light and are accompanied by dimmed light stripes on the left side of the particles. Nevertheless, the tracer particles are still sufficiently illuminated. The strong reflection caused by slight differences in the refractive index, allowed in this case the application of the object recognition algorithm. Likewise, particles in front of the light sheet can also be seen due to differences in the refractive index. These can be divided in two types: particles which allow visual access to the tracer particles and those which do not.

As previously mentioned, the object recognition is done using an implementation of the Hough transform. The CircularHough_grd algorithm by T. Peng is able to detect circular shapes in grayscale images. Nevertheless, before the application of the Hough transform algorithm it is necessary to process the PIV images through a 2-D median filter. This is done to remove the seeding particles of the continuous phase, which in this operation cause detection of inexistent dispersed phase particles. The outputs of the algorithm are the center coordinates of the detected circles and their radii. These data are later used to create masks used in the PIV and PTV algorithms.

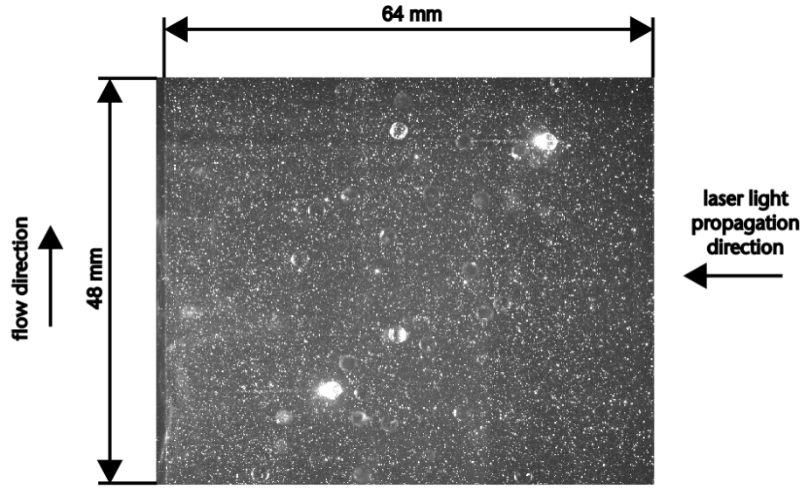


Fig. 3: Image recording with 2 mm particles

The image pairs are evaluated with the PIV/PTV software EDPIV by L. Gui, which includes dedicated tools to work with multiphase flows i.e. mask importation, continuous phase evaluation, particle identification and dispersed phase evaluation. The continuous phase measurements are obtained through a cross-correlation algorithm applied to the masked PIV recordings with rectangular interrogation windows of 8 x 16 pixels corresponding to an area of approximately 0,54 x 1,08 mm^2 in the region of interest. The rectangular interrogation windows allow increasing the accuracy of velocities close to the walls. The dispersed phase measurements are obtained with PTV algorithms applied to the masks, in which a radius of search between 100 and 250 pixels and a particle diameter range between 30 and 40 pixels were set as searching criteria.

Results and discussion

To verify the PIV measurements, measured velocity profiles with PIV are compared with velocity profiles derived from measurements obtained in the flow meter. The flow rates of the latter and the analytical solution of the Hagen-Poiseuille flow are the elements used to obtain these pseudo analytical velocity profiles. The comparisons are shown in figure 4. Agreement of both measurements serves to estimate the accuracy of the PIV measurements as correct. Nevertheless, discrepancies between both profiles exist. These are ascribed to the low resolution of the flow meter used, which measures flows in magnitudes of 1 l/min.

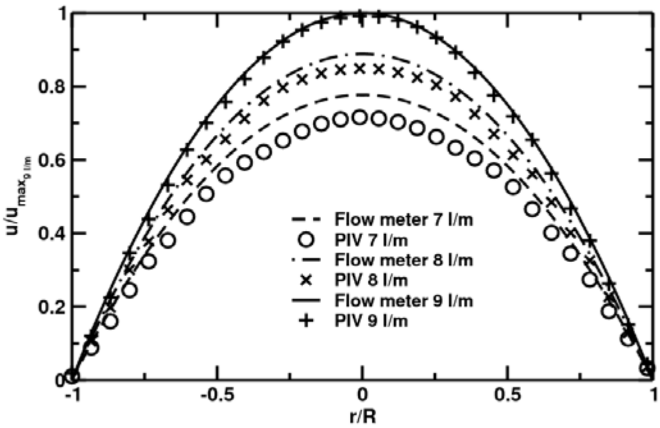
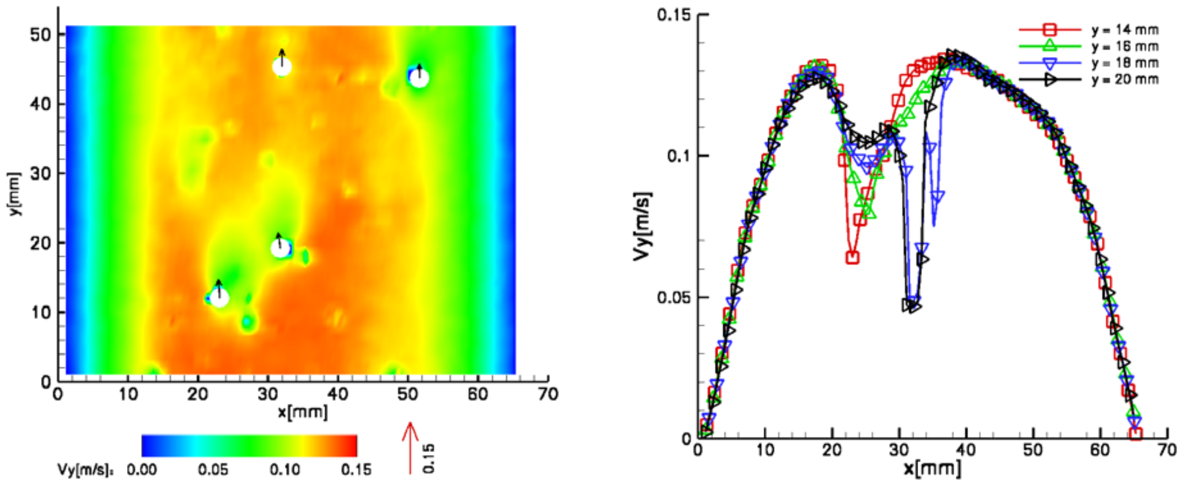


Fig. 4: Comparison of PIV and flow meter measurements

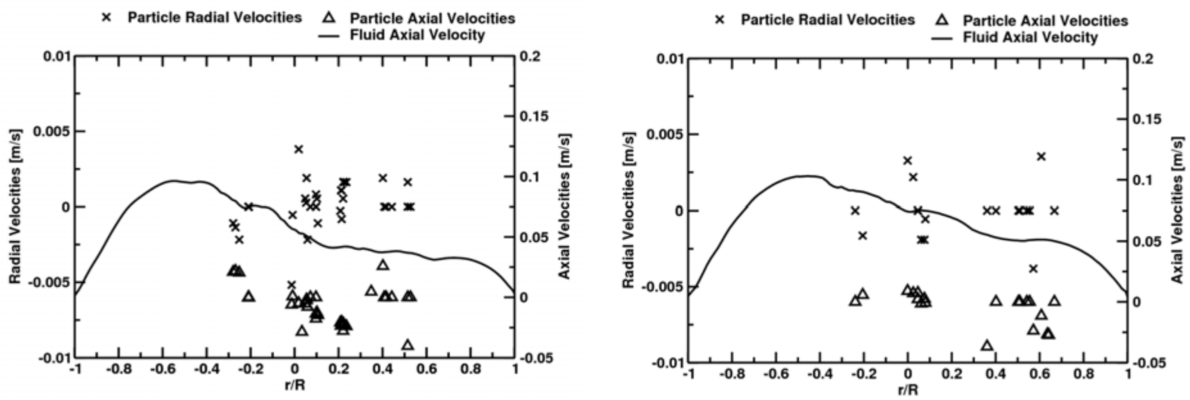
Instantaneous flow fields with discrete solid particle velocities are shown in figure 5. The PIV/PTV evaluation shows the vertical velocities in terms of a contour plot and the particle discrete velocities in terms of vectors. The position coordinates of the vectors are also used to determine positions of circular symbols representing the transported particles. A notable disturbance of the liquid phase velocity field due to the presence of particles is evident. Specifically, particles falling exactly into the light sheet plane showed the characteristic wake of flow fields around rigid particles in its full extension. For particles in front of the light sheet, only part of the wake may be observed. This aspect could be used in future works to determine the relative position of these particles with respect to the light sheet plane.



a) b)

Fig. 5: Multiphase velocity flow field for 2 mm particles and Re = 77. a) Contour plot and particle discrete velocities. b) Velocity profiles at different vertical positions.

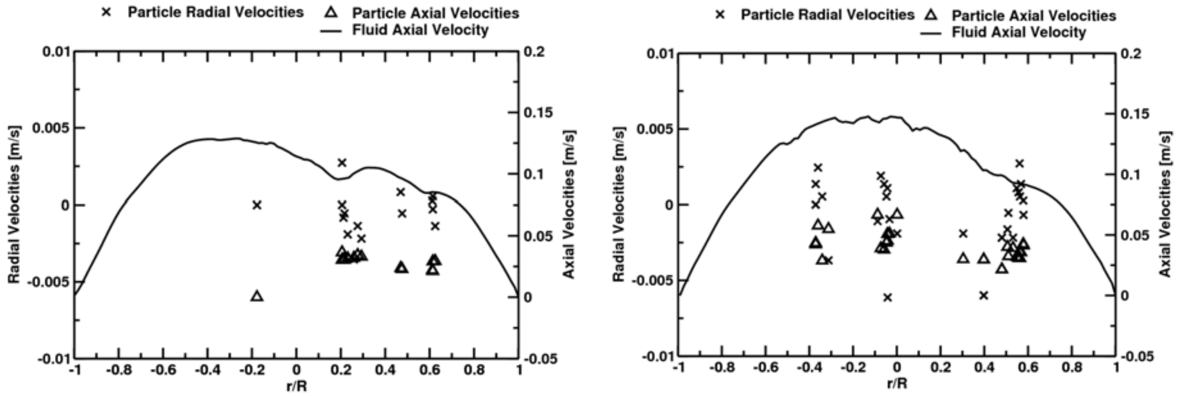
Experimental results for 2 mm particles and flows between Re=40 and 77 are shown in figure 6 and 7. These flows correspond to fluid velocities around the settling velocity of borosilicate 2 mm particles in light liquid paraffin, which according to the Stokes law should be around u_s = 0,0437 m/s at room temperature. The diagrams show particle radial and axial velocities and fluid axial velocities. Positive and negative radial velocities indicate migration of the particles to the right and left sides of the flow field respectively. The fluid axial velocity profiles are averaged from the combined PIV/PTV multiphase measurements.



a) b)

Fig. 6: Particle radial and axial velocities and fluid axial velocities for 2 mm particles in: a) Flow Re = 40 flow b) Flow Re = 50.

A concentration of particles around the axis of the pipe and a boundary at approximately radii 0,6 are observed. Likewise, a flattened average fluid velocity profile caused by the presence of the particles is observed. In particular, regions where more particles are present suffer larger deformation of the velocity profiles. A tendency of the particles to the right side of the flow field is also appreciated in the slower flows.



a) b)

Fig. 7: Particle radial & axial velocities and fluid axial velocities for 2 mm particles in: a) Flow Re = 69 b) Flow Re = 77.

In table 1 the average velocities of the fluid ($\bar{u}_f$), the average velocities of the particles ($\bar{u}_p$) and averaged slip velocities ($\bar{u}_{slip}$) are shown for the different flows. Considering the variation of viscosity with temperatures and the fact that measurements were taken at working fluid temperatures of 32 °C, the settling velocity according to Stokes should be around u_s = 0,0592 m/s. Comparison between the latter and the slip velocities accounts for an average percent difference of 8%.

Re	$\bar{u}_f$ [m/s]	$\bar{u}_p$ [m/s]	$\bar{u}_{slip}$ [m/s]
40	0,0532	-0,0095	0,0627
50	0,0645	-0,0047	0,0692
69	0,0903	0,0272	0,0631
77	0,1008	0,0398	0,0610

Table 1: Average fluid ($\bar{u}_f$), particle ($\bar{u}_p$) and slip velocities ($\bar{u}_{slip}$) for 2 mm particles.

The PIV/PTV methods combined with refractive index matching allowed measurement of multiphase flow fields in vertical pipe flows. Comparisons with parallel flow measuring equipment and analytical solutions proved good agreement. The results are part of a systematic measurement process with different particle diameters, flow rates and concentrations to supply experimental data for CFD models validation. After validation, the CFD models should be used to investigate particle migration and lift forces in geometrically more complicated high concentrated dispersed flows.

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