Abstract: This work describes the flow around a sphere with a longitudinal hole inside. Such ring-type particles are useful in many applications like chemical reactors as catalysts (seed particles) to increase the reacting surface in the multi-phase flow. Both heat transfer and the flow structure in and around those catalysts are of interest for fixed bed reactors as well as floating bed systems with solid particles. The focus of this work is the analysis of the 3D flow structure in the borehole and the outer flow around the particle and its influence on particle motion and rotation as well as the change of heat transfer involved herein. Since internal and external flow may induce Lift- and Magnus-forces we expect a complex interaction of particle motion and flow field which is tested in a special flow tank. Refractive index matching is used in combination with Light-Sheet Scanning and 3D Least Squares Matching to obtain the flow field around a silicone sphere with a longitudinal hole. The results show that the flow through the hole imposes pressure forces that lead to particle rotation and drift in a non-trivial way. Thereby, drag and lift-forces as well as torque are changed by an order of magnitude and cannot be represented by semi-empirical equations of the global body shape anymore.

Introduction

Particle laden flows occur in many technological processes such as, e.g., in fixed bed or fluidized bed reactors (for a recent published review the reader is referred to van der Hoef et al. 2008). In reformers, catalysts (seed particles) are often used to increase the reacting surface in the multi-phase flow. From numerous studies by reforming catalyst producers it has been shown that catalyst particle can largely influence the heat transfer into the reformer-tube (Yin et al. 2007). Typical shapes of the particles are spheres or cylinders with a certain number and size of longitudinal boreholes and additional external features on the surface. Certain aspects of the catalyst particle design may positively influence the heat transfer from the shell side to the tube side in fixed bed. On the other hand, in fluidized bed reactors catalyst particles form individual clusters that may rise in the middle of the reactor and settle down again near the lateral walls (Noymer & Glicksman 1998). Therefore, both heat transfer and the flow structure in and around single catalysts and clusters are of interest. The design of the catalyst particles has been - up to now - established by trial and error in pilot plant scale setups. The only currently available data in this area has been empirically collected and correlated. However, commercially available catalyst designs may not represent an optimum and performance must always be tested for any change of species or plant scale. Because of their huge influence on the reactor’s performance, any physically based knowledge of the details about the flow through such catalysts is of strong interest for future energy savings. Spherical particles with longitudinal holes are of importance because of their good mechanical stability similar to solid spheres and because they do not change the packing density much. In addition, manufacturing of such ring-type particles is possible for various outer and inner diameters of the ring. It opens the chance for future applications to design the catalysts according the specific conditions in the reactors to obtain a more controlled heat transfer.

As much as such particles may have potential as catalysts in the applied process technology as little is known about the flow around and inside the ring as well as the heat transfer depending on the ring diameter and orientation. Features to be investigated in fluidized beds are the orientations of the rings in the flow, the forces acting on the ring and the resulting motion behavior. In addition, as the formation of clusters is a typical feature in fluidized beds (see Noymer & Glicksman 1998), flow paths through the cluster of such catalysts needs to be studied, too. For simulations of such complex flows and total heat transfer it is not yet clear to what extend the internal flows structures change the heat transfer in comparison to the often applied approximation of porous flows. However, it was concluded from detailed simulations that heat transfer effectiveness can be improved with few large holes rather than with porosity (Nijemeisland 2004). This hints on the relevance of channeling and preferential flow path formation within such
clusters which cannot be treated as isotropic porosity. In addition, because the typical size of such catalysts is in the range of 1-10mm, inertia effects of internal flow cannot be neglected.

There are very few detailed simulations which provide information on the heat transfer and flow around such catalyst particles. Moran & Glicksman (2004) investigated numerically the flow around a porous sphere but they ignored the internal flow in the cluster. Maheshwari et al. (2006) determined the drag and heat transfer for three spherical particles which were arranged inline in a homogeneous flow. While this work shows the interactions of the wakes, it does not allow any conclusions on the dynamic behavior of such a cluster. Richter et al. (2011) examined the flow around a sphere with a longitudinal hole. It could be shown that heat transfer can be increased up to 40% when compared to a sphere with the same outer diameter. Again, the sphere was fixed and no fluid-structure interaction was taken into account. Nicolle & Eams (2011) studied the flow through a cluster of cylinders on the basis of a two-dimensional CFD-simulation. The influence of the specific form of the cluster on the internal flow decreased with increased volume fraction of the solids. However, the results for this two-dimensional problem do not apply for three-dimensional, spherical particles. As for all previous cited studies, the solids were held fix in the simulation domain.

Parallel to the increased computational power for 3D CFD simulations of flow in clusters (Beestra et al. 2006), experimental methods have been developed which allow the investigations of 3D flow processes in transparent clusters, too. Such measurements are typically carried out in a system with transparent glass particles using the method of refractive index-matching. Earlier examples of two-dimensional flow studies have been published by Zachos et al. (1995) and Tschikango et al. (2006). The 3D flow around individual non-spherical particles or bubbles was first documented in 2000 in detail experimentally (Brücker 2000). The mechanisms of path instabilities have been brought for the first time in greater detail in connection with the wake dynamics of this body (Brücker 1999). Recently, 3D Tracking PTV was used for investigation of Lagrangian turbulence in a fixed bed system (Klein et al. 2013). The particles were made from hydrogels to achieve a good match between refractive index of the ambient water with the spherical particles. However, such particles are not stable when a hole is cut out to obtain the shape of more complex catalysts such as the ring-type particle. Instead, the method of index matching using silicone as the material for the solids and a water-glycerine mixture as the carrier fluid is more appropriate for such studies. There are a few studies which have shown the potential of this method for flow studies in complex geometries such as in silicone models of the lung bifurcation or the nasal cavity (Adler & Brücker 2007). For volumetric PIV measurements of the flow in the ring-type particles, 3D Scanning PIV can provide this information easily without any problems of multi-camera calibration in such flows. Using this method we can identify flow patterns inside the particles, look at the effects of catalyst degradation and at the effects of particle stacking and orientation. This method is based on the experiences we have been developed over the last 10 years and the application of such measurements in multiphase flows (Brücker 2000, Kitzhofer et al. 2010, Hess et al. 2011, Brücker et al. 2013). A further extension would be the analysis of the influence of the particle geometry on the near-wall heat transfer. In addition, we are interested in the influence of orientation of the catalysts in a cluster and what consequences they have on the global behavior of the cluster. A first step towards a detailed understanding of the time-dependent fluid-structure interaction of a single freely mowing catalyst particle in flow is presented herein.

**Experimental set-up**

The experiments were carried out in a flow tank using the method of refractive index matching between the transparent catalyst particle made from silicone (Elastosil RT 601™, measured refractive index after curing n ≈ 1,4137) and the ambient liquid which was a water-glycerin mixture (refractive index n ≈ 1,4135). The liquid was at rest and relative motion between particle and liquid was induced by a downwards-directed impact imposed onto the particle, which was initially held below the liquid surface. The particle was casted in a split mold with a rod in the middle, acting as a casting core. Both, the mold and the rod were made of plastics. To prevent any reflections from inside of the silicone body, care was taken to ensure cleanness of the silicone. The mixed liquid silicon was evacuated at an absolute pressure of 20 mbar before casting to remove any air bubbles. After the casting process, the silicone particle was cured in an oven at 65 °C for 5 hours. Afterwards the molds were removed with the use of glycerin as a lubricant. The final ring-type particle had an outer diameter of about 3.5 cm and an inner bore of 1.7 cm. Pictures of several casted particles are shown in Figure 1. In the experiments, the particle is pushed down into the basin where the liquid is seeded with small traces particles and illuminated with a light-sheet. A typical particle image taken for the flow measurements around the particle is shown in Figure 2. It shows that the hole inside the particle is well seen as a region where tracer particles are present and the contour of the silicone body is visible due to a lack of particles inside of the silicon.
The catalyst particle was pushed by a magnetic actuator from a position below the liquid surface down into the basin (Figure 3, 4). The 3D flow around the sphere was measured with 3D Scanning PIV using a polygon scanner and high-speed imaging (see Hess et al. 2011). Figure 3 shows a sketch of the experimental setup from the top view with the illumination path. A high-speed Nd:YLF-LASER in combination with a rotating polygon mirror generated 50 parallel and partially overlapping light sheets per volume scan at 132 Hz. Each light-sheet in the scan had a thickness of about 3.1 mm and an overlap of 75% with the previous and the successive one. The light sheet images were recorded with a high-speed camera (Phantom 12.1, Vision Research, resolution at 1024×768 px) synchronized with the pulse-laser running at 8200 fps. This leads to an illuminated volume of about 86×63×42 mm.

**Volumetric reconstruction**

Due to the high spatial resolution of the scanning, voxel-based reconstruction of the particles can be achieved by stacking each light sheet to a voxel space (Hess et al. 2011, Brücker et al. 2013). This requires the following boundary conditions: a) the light sheet intensity profile needs to be homogeneous from pulse to pulse such that the illumination remains approximately constant over the height and width of the sheet; b) the shift of each consecutive light sheet should be constant over the whole scanning depth; c) the spacing must be adjusted in such a way that each light sheet overlaps the subsequent light sheet for at least 66% in width; d) the scanning velocity needs to be much higher than the flow velocity within the measurement volume (see Hess et al. 2011). All these conditions were fulfilled within our scanning experiments using the polygonal mirror. To calibrate the position of each light sheet within the measurement volume, an additional setup with a known and fixed depth was used.
volume and to check the correct overlap, a target was inserted in the basin and illuminated by the scanning light sheets. Figure 5 shows an arrangement of all light sheets in one image. In order to gain a better visibility, every sheet was displayed with an additional shift in the image for half the width of the sheet in horizontal direction and every 2\textsuperscript{nd} sheet was dislocated vertically for 300 px, otherwise the overlap would not allow to recognize the spacing of successive sheets.

\textbf{Figure 5:} Arrangement of the light sheets in a single scan. The images are overlaid in a staggered arrangement to illustrate the shift of the originally overlapping light-sheets. Jitter of the positions is less than 0.1 px in the image plane. Note the homogeneity of the light-sheet intensity and thickness over all planes within the scanning procedure.

Due to the overlap of the light sheets and multiple stacked images, the particle reconstructions from the plain stacking procedure resulted in ellipsoidal shape. However, the intensity distribution of each ellipsoidal can be used to apply a Gaussian regression in order to replace the ellipsoids with spherical blobs (Brücker et al. 2013). Going in scanning direction line by line through the voxel volume, a Gaussian fit determined the center of each ellipsoidal particle fragment with better resolution and re-ordered the voxel intensities in the line such that the particles appeared as spherical blobs, see Figure 6. Finally, a weighting function was applied to the voxel volume in the different coordinate directions to re-locate the particle center position in the other directions and to enforce a Gaussian blob at each particle center with the size of 3\times3\times3 voxel.

\textbf{Figure 6:} Gaussian regression to replace ellipsoidal particle reconstructions with spherical Gaussian blobs at position of maximum of the Gaussian fit. Left row shows the ellipsoidal particle shape over 4 light sheets and its fitted Gaussian intensity distribution with \( I_{\max} \) representing the new center of the particle. Right row shows the spherical particle with its center at \( I_{\max} \).

\textbf{Figure 7:} Time series of the reconstructed 3D voxel volumes of the ring-type particle from top left image to bottom right (time step is \( t=0.1 \) s).

Figure 7 shows a time series of the reconstructed voxel volumes. The silicone catalyst particle dived in (upper left image), reached the bottom dead center position and started its rise to the top of the reconstructed volume again. Note the hull shape of the silicone sphere in the particle reconstruction which stems from particles sticking to the silicone
Particles in the hole were reconstructed as well due to the applied refractive index matching method. Note that the particle also showed a rotational motion. The direction of the rotation was clockwise throughout the complete measurement. To visualise the particles motion the center position and its rotation angle was evaluated, too.

### Velocity field computation

The reprocessed voxel volumes of each consecutive time steps were analyzed using 3D-LSM to evaluate the flow fields, velocities and the velocity gradient matrix. The LSM is an iterative process where the grey values of voxel cuboids from one time step are shifted, rotated sheared and stretched until they best fit the voxel representation of time step two (see Westfeld et al 2010). One advantage of this method is that the velocity gradient matrix is a direct solution of the algorithms and it must not be computed with all its problems with numerical derivations. Typical cuboid sizes of 61³ voxel were applied for the LSM in our voxel fields. With a median seeding density of about 0.075 particles per pixel the overlapping percentage of the cuboid was set to 80 % resulting in about 110,000 vectors for each time step at adequate computational costs. This corresponded to a spatial resolution of approx. 0.5 vectors / mm³ that ensured an adequate spatial resolution to investigate the flow around the particle and insight of the hole. A range validation and an outlier interpolation were used to filter out velocities higher than 0.2 m/s and replacing their positions with the average value of their neighbors. Finally, a temporal low pass filter was applied to reduce velocity fluctuations. Therefore, a local regression using weighted linear least squares and a 1st degree polynomial filter with a range of 5 time steps for each velocity component was applied on each vector position. The resulting data field showed smooth behavior in its temporal distribution as well as its spatial formation.

### Results

Major focus is laid upon the analysis on the interaction between the particle motion (translation and rotation) and the surrounding flow. Figure 8 shows the path of the ring-type particle during its dive. One can recognize that the vertical impact leads to a downwards diving motion with an overlaid lateral motion resulting from generated lift. Surprisingly, the particle returns back to the top of the basin approximately along the same path that it has moved in the phase of downwards motion. Thus, the lift force must have changed direction after the bottom dead center has reached. Angular velocity increases from the beginning from zero to a maximum of 380°/s at a time t=0.22s after impact. Then angular velocity drops to values of about 220°/s until the particle leaves the measurement volume again. Mean angular velocity of the catalyst particle is 275°/s.

**Figure 8:** Diving path of the ring-type particle after being pushed down into the basin from a position below the liquid surface (particle center position at impact t=0 is 0 mm) color indicates time (blue = start)

**Figure 9:** Rotational speed of the particle during its dive, shown as a black profile. Depth position of the particle over the measurement duration is shown in red (particle center position at impact t = 0 is 0 mm).

The sphere’s rapid increase and decrease of rotational speed needs further examination of the details of the flow around the particle. Two exemplary velocity fields are displayed in figure 10 and 11 together with the surface of the particle to demonstrate the flow situation as well as the particle/flow interaction.
Figure 10: 3D velocity field around the particle at $t = 0.17$ s after impact. At this position the particle still dives into the basin. The rotational speed of the particle increases.

Figure 11: 3D velocity field around the particle at $t = 0.35$ s after impact. At this position the particle is near its bottom dead center and the hole is aligned with the vertical. The rotational speed of the particle has decreased.

Figure 10 shows the flow at time $t = 0.17$ s after the beginning of the measurement. At this position the ring-type particle still moves downward into the basin while the rotational speed of the particle increases. At the front part of the outer surface of the ring the flow shows the behavior of a plain displacement flow. However, flow in the cross section of the sphere indicates that the lower half of the ring acts like an airfoil in pitching motion. In the hole on the left side of the particle a large leading vortex is induced while on the right-hand side of the ring a trailing vortex has shed into the wake. This causes a lift force ($F_L$) on the front part of the particle. Since, the load application point is located at the lower part of the ring and not on the particle’s center of gravity it induces a torque on the particle. This torque enforces the rotation of the ring (see the sketch in figure 12). Furthermore, the particle rotation induces another force on the particle, the Magnus-force ($F_M$). This force also contributes to the particle’s lateral motion to the left.

Figure 12: Left: sketch of the flow behavior in the cross section of the catalyst particle at time step 23 ($t = 0.17$ s). The lower half of the ring works like an airfoil in pitching motion causing generation of a leading and a trailing edge vortex. As seen on the right with a visualisation of the Lambda 2 criteria.

Because of continuing rotation of the particle the angle of attack for the half of the ring increases similar to an airfoil in pitching motion. Suddenly, lift force drops sharply when the leading edge vortex in the hole starts to detach ($t > 0.35$ s). The particle’s hole is yet positioned almost vertical and bottom dead center is reached. As a consequence of the deceleration of the particle, the fluid in the wake behind the ring starts to overtake the ring at the inner and outer side. A larger part of the wake fluid attached to the aft part of the particle is guided through the hole towards the front and leads to a jet-like flow as visualized in figure 11. Furthermore, on the right-hand sight of the measurement volume a second strong flow current enters the measurement volume. From figure 13 on the right side, it can be identified as part of the far wake region of the ring which now starts to interact with the particle, as the iso-contour of the Lambda 2 kriteria indicates. This counter flow on the particle’s right-hand side causes a velocity gradient along the particle. Accordingly,
it induces a Saffman force \( (F_S) \) on the particle while moving upwards causing the change of direction of the lift force after path reversal (see figure 13).

**Figure 13:** Left: sketch of the flow behavior in the cross section of the ring-type particle at time step 46 \( (t = 0.17 \text{ s}) \), overtaking the particle itself causing a gradient in the flow field. Right: iso contours Lambda 2 indicating the incoming wake that starts to interact with the particles motion. The vectors on the y-slice also show the two vortices.

The Proper Orthogonal Decomposition is one common method to perform a modal reduction of a snapshot series of observables (e.g. velocity field). For more information the reader is referred to (Berkooz et al. 1993) and (Andrianne et al. 2011). In fluid dynamics it is used to extract dominant flow characteristics by identifying coherent structures. The mean flow field is subtracted from each snapshot to achieve a time series of fluctuations on which the decomposition is applied. Figure 14 shows the temporal averaged flow field, which characterizes the displacement flow generated by the diving particle. The POD-technique ranks the spatial structures according their fluctuation energy. In figure 15 the energy distribution is illustrated, showing an exponential decrease within the first 10 POD-modes, which cover 94.1 % of the mode energy.

The applied POD-algorithm results in orthogonal structures (Topos or POD-Modes) and their temporal behavior (Chronos or temporal POD-coefficients). The coefficients are generated by projecting each orthogonal structure onto each snapshot. Thus, a snapshot can be reconstructed by summing the mean flow field and all modes multiplied by the coefficient of the particular snapshot. An overview of the first four POD-modes (Topos), their corresponding temporal coefficients (Chronos) and the associated energy fractions are shown in Fig.16.

The resulting modes of the POD analysis are used to identify the most energetic flow structures and to distinguish the different phases of the dive. The first four resulting modes together with their temporal development and their ratio of the total energy are shown in figure 16. Note that these modes already represent over 80 % of the flow energy, indicating their importance to the flow field. Here mode #1 is the most important, containing over 40 % of the total energy. Looking at its temporal formation, it starts playing a major role only after time step 40 \( (t > 0.45\text{s}) \). This is when the fluid in the wake of the particle starts to overtake the ring along the outer side. Mode #2 is of importance between time step 40 and 70 \( (0.3\text{s} < t < 0.53\text{s}) \). The particle has reversed its vertical motion and starts to rise while interacting with its former wake. Both flow features can be clearly seen in the modes. Mode #3 still contains about 13 % of the
The first four POD-modes and their temporal development

Discussion

This work shows the complex path of a ring-type catalyst particle when interacting with its surrounding flow in a dive. The particle is represented by a silicone sphere with a longitudinal hole which is pushed into a refractive index matched water glycerin mixture. The time-trace of the trajectory of the particle as well as its rotation is analyzed. A single camera setup together with a polygonal scanner is used to reconstruct the 3D measurement volume by the so-called stacking technique (Hess et al. 2011). Afterwards, the velocity fields are calculated via a 3D least squares matching algorithm. The results demonstrate that the front part of the ring acts as an airfoil when the hole inside is aligned perpendicular to the relative flow. This causes a self-enforcing instability similar to a pitching motion of an airfoil. As a result, a lateral drift as well as a torque is imposed on the particle motion. On the other hand, once the longitudinal hole aligned close to the flow direction, the rotational motion of the particle diminished and the path stabilized. Deceleration of the particle due to buoyancy caused the wake to overtake the particle during path reversal laterally at one side, thus inducing Saffman forces that lead to lateral drift anew. Overall the experiments showed a complex interaction between the motion of the particle and the surrounding flow. Even under laboratory conditions the particles trajectory as well as the surrounding flow fluctuated between the measurements. Hence, the results are only examples of the possible flow.
situations in industrial applications. In case of particle swarms and clusters, additional particle interaction might increase the degree of possible interactions. It needs to be further investigated whether such catalyst particles at higher void fractions still align with the main flow direction. As a consequence, total heat transfer may largely differ depending on the number and size of such catalyst particles in the flow.

REFERENCES


