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André Seeliger, Rainer Hampel

Image Processing Methods for Experimental Analysis of Particle-laden Coolant Flows

INTRODUCTION

The investigations for debris generation and transport gain in importance regarding the reactor safety research for pressurized water reactors (PWR) and boiling water reactors (BWR) focuses, among others, on all types of loss-of-coolant accidents (LOCA) and short resp. long term behaviour of emergency core coolant systems, as well. As a result of LOCA's solid particles such as insulation materials can be released in the coolant circuit. In these scenarios core safety should be provided. Therefore investigations of methods (analytical and experimental) and tools (simulation codes, models) are necessary which enable two and three-dimensional simulations for stationary and dynamic behaviour of coolant flow with solid particles.
A gist within these investigations is the development of 3-D-models simulating two-phase flow of water and insulation particles in large geometries. The background of experimental investigations consists of the generation of a comprehensive data base developing and validating such CFD-models (Computational Fluid Dynamics) for the description of insulation particle transport phenomena in flow (e.g. drift, subsidence) under various geometric and fluidic boundary conditions, as well as sedimentation, resuspension, agglomeration, clogging and increasing of differential pressure at hold-up devices [1]. Separate effect experiments regarding these processes were carried out at various plexiglass test facilities using modern flow measurement and digital image processing technologies.

A lot of comparable investigations concerning multiphase flows were made. As an example, many activities are dedicated to the observation and analysis of gas-liquid-flows. In these cases a variety of measuring techniques like phase Doppler anemometry (PDA), image processing and wire mesh sensors can be applied [2,3].
The phase Doppler anemometry has been used for experimental analysis of particle-laden flows too. Yet the hereby observed particles are solid, have got a physical stability

concerning abrasion and deformation and no liability to agglomeration [4]. A clear coherence between particle size and shape and the sink rate could be obtained.
But an essential difference compared with the current research objects lies in the consistence and the behaviour of the observed disperse phase of insulation material. So the shape of insulation particles, which consist of mineral wool and occur in different levels of fragmentation from single fibres up to large agglomerations, can vary in a very broad range. Phenomena like particle agglomeration and break-up are possible and should be recognized by the measuring system. Furthermore, the comparatively large particle sizes did not allow an observation via PDA. Therefore, to investigate the movements of particles in a liquid flow, image processing methods had to be applied.

EXPERIMENTAL BACKGROUND

In the run-up of all experimental investigations an amount of insulation material was fragmented in the special test rig "Fragmentation" (Fig. 1) under real accident conditions, e.g. with saturated steam up to 7 MPa (BWR-LOCA). This facility is also designed for experiments with saturated water up to 11 MPa (simulation of PWR-LOCA).

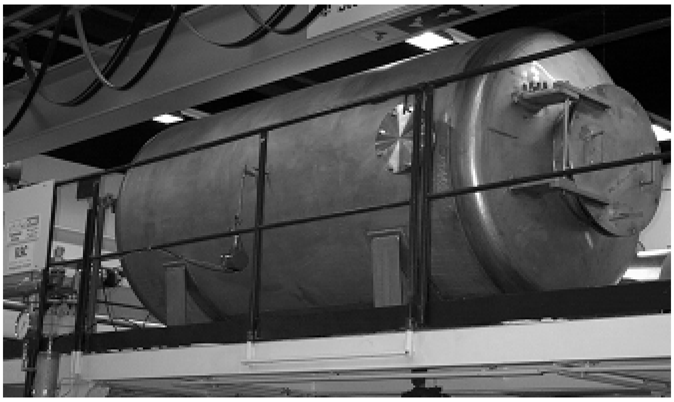

Fig. 1: Special test rig "Fragmentation"

Thereafter, suspensions of water and particles were inserted at the test rigs. The test facility "Column" (Fig. 2) allows the observation of the behaviour of gravitating insulation particles in aqueous solution in 1/2D-geometry. It consists of a rectangular acrylic glass column with the inside dimensions of 0.50 m x 0.10 m x 3.00 m (LxWxH).

Fig. 2: Plexiglass test facility "Column"

The particles were observed during their sinking according to gravitational forces. The thereby used camera system consists of two highspeed cameras which allow to take pictures with a resolution up to 1280x1024 pixels. Because of random programmability of window size, position (region of interest) and clock frequency, the frame rate and the resolution can be adapted to any specific demand.

Fig. 3 shows a snapshot of a recorded sequence taken during a sinking experiment with insulation material. On the right-hand side of Fig. 3 the movement of the centre of gravity is illustrated for four detected particles with different cross sections.

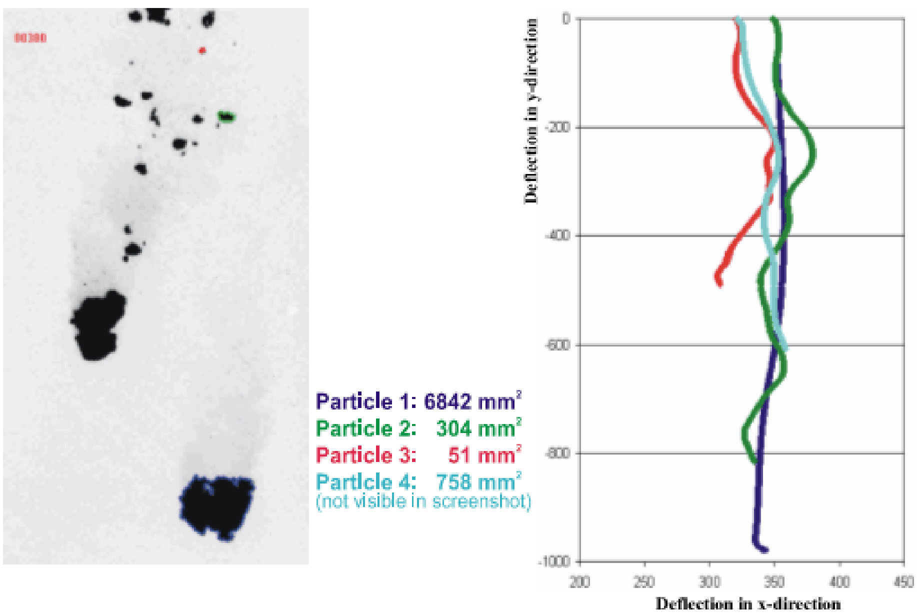

Fig. 3: Example of a sinking experiment

IMAGE PROCESSING METHODS

Each recorded image sequence was preprocessed for improving basic attributes like contrast and brightness. Radial distortion effects caused by optical components of the camera system (e.g. lenses) were compensated by camera calibration. The latter enables the determination of a subset of camera parameters like orientation and relative position of the camera, distortion coefficient, center of radial distortion and focal length. The background subtraction makes it possible to compensate inhomogeneity caused by the lighting of the facility. However, a pristine image of the background must be available to apply this method. This image will be generated by calculating a maximum value image using the complete image sequence.

After applying this algorithm the particles in the sequence show up on a homogeneous and bright background. The objects of interest and the background were segmented for each image of the sequence by the region growing algorithm. This algorithm represents a region based segmentation method and starts with an initial partition of pixels. Neighboring points are aggregated into the same region if the difference of their feature vectors lies within a given interval. The algorithm terminates if every pixel in the image has been assigned to a particle region or the background [5]. Finally, the unique particle regions of an image were specified and primary significant characteristics like contour length, surface area and position in x and y directions of the world coordinate system can be quantified.

A novel software algorithm was developed for tracking unique particles image by image. It underlies a basic principle: The region of an particle object in an image overlaps the corresponding region in the subsequent image when both images are laying one upon the other (Fig. 4). By evaluating the overlapping regions it is possible to recognize an object in consecutive images and finally to trace all detected particles over the sequence. Thereby several attributes of the objects were permanently compared for validating and adjusting the performed assignments.

The algorithm itself was extended to track smaller particles where normally no distinct overlapping regions can be detected. In this case all small particle regions in a surrounding field were considered as possible candidates. Final selection was done by comparing attributes like velocity and the previous direction of movement.

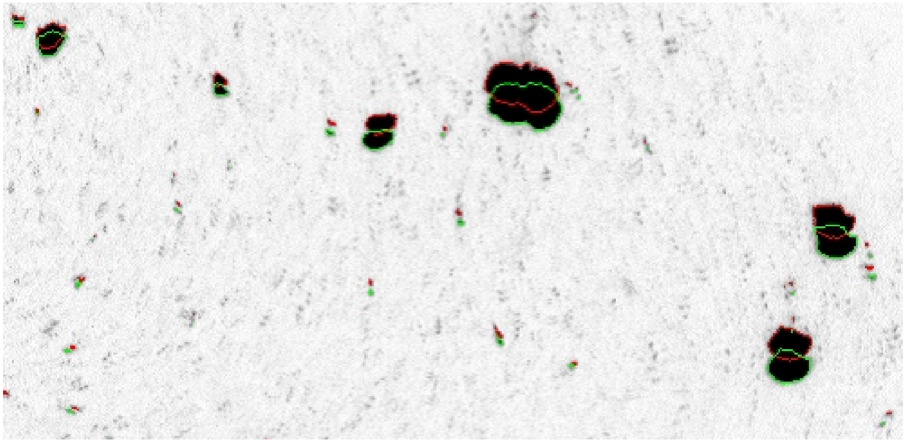

Fig. 4: Visualisation of overlapping particle regions in consecutive camera pictures

Thus, it was possible to detect a whole range of specific effects like particle collision, overlap, break-up and coalescence.

Camera parameters were taken into calculation for obtaining the full-scale data. Several shape factors of the insulation particles were compiled like circularity, convexity, compactness and bulkiness [6]. The shape can also be described using geometrical objects like the largest inner circle, smallest surrounding circle and equivalent ellipse (Fig. 5).

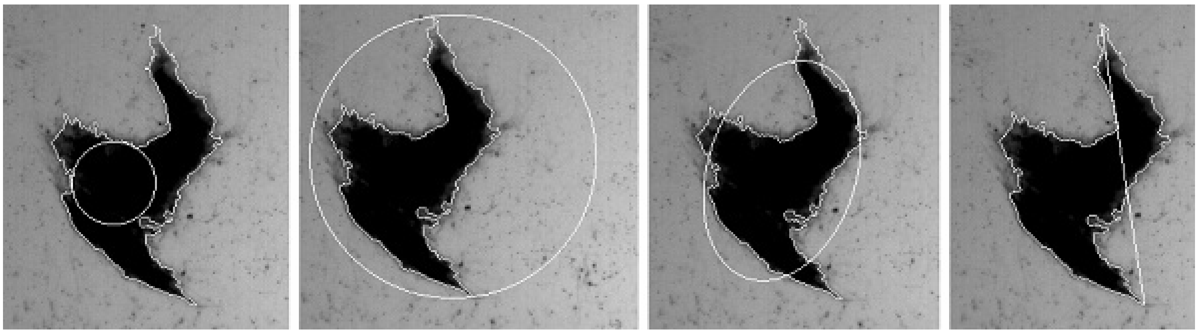

Fig. 5: Graphical representation of a subset of shape factors
(inner circle, outer circle, equivalent ellipse, maximal distance between contour points)

This kind of attributes gives extensive information about the form of the single particle. All attributes of a unique particle varied in a limited range during its sedimentation in the test rig. This effect was caused by eigen-rotations in the three-dimensional space and by minor deformations of the particles themselves.

As an experimental result, data sets of 122 different single particles were recorded. Their velocities were determined involving the recording time of the sequence. Each data set consists of a series of recorded values for every particle attribute. This led to an "all-embracing", but very complex database.

PARTICLE CLASSIFICATION

In the next step a classification of particles was performed. In addition to this, particle attributes with significant influence on the particle sink rate had to be detected. Here, one faces the complexity of the database. Therefore, the average values of all attributes were calculated to reduce the amount of data. Only these averaged data were used for the preliminary classification of insulation particles. The shape factors circularity, compactness and convexity turned out to be suitable for classifying the particle shapes. Circularity indicates the similarity of the particle region with a circle by using the formula

$$C_{circ} = \frac{A}{{d_{\max}}^2 \cdot \pi} \qquad (1)$$

where A is the surface area of the region and d_{max} is the maximum distance from the center of the region to all contour pixels. This attribute especially responds to coves, holes and unconnected regions. The circularity of a circle is 1. If the region is prolate or has holes, C_{circ} is smaller than 1.

The compactness of a particle region is described by

$$C_{comp} = \frac{L^2}{4A \cdot \pi} \,. \qquad (2)$$

Here, L is the contour length. Again, the shape factor C_{comp} of a circle is 1. Compactness responds to the course of the contour (roughness).

The convexity is evaluated by

$$C_{conv} = \frac{A}{A_c} \qquad (3)$$

where A_c is the surface area of the convex hull. The shape factor C_{conv} is 1 if the region is convex (e.g. a rectangle or circle). If there are indentations or holes, the factor is smaller than 1.

A fuzzy-c-means clustering algorithm according to [7] was applied to the feature space of circularity, compactness and convexity to divide the particles into corresponding classes. As a result of an iterative search process, a partition into five classes was obtained. Thus all possible forms of appearance between compact, rigid particles and fluffy, non-rigid particles could be well-differentiated (Fig. 6). Each class represents an appropriate structure of the assigned particles.

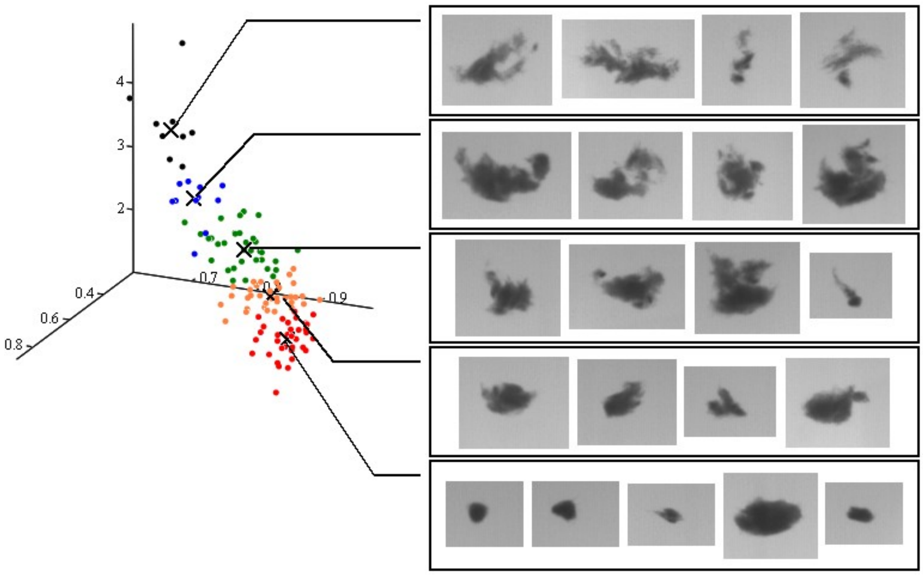

Fig. 6: Clustered feature space of chosen shape factors with some representatives of the hereby defined particle classes

A significant linear correlation between the chosen shape factors and the sink rate could not be obtained, but a dependence between the particle structure and the sink rate on the particle was obvious: Considering drag forces, dilute nettings of fibres never can reach the maximal sink rate of rigid and compact particles.

Assuming an own sinking behaviour of each type of particle, it seemed to be meaningful to create a Takagi-Sugeno (TS) fuzzy model for every defined class. The attributes surface area and contour length were selected as adequate model input parameters, because they represent the essential information about the particle's dimensioning. Therefore, each model should enable us to reveal the information about the sink rate by using these attributes. The premise part of each model is automatically generated from given input-output data by an unsupervised clustering algorithm presented by Wong and Chen in [8]. A verification of the created model combination was done by using all recorded datasets from our experimental investigations. The comparison between the calculated and measured sink rates showed a predominant concordance (Fig. 7). The maximum variance amounts to 0.031 m/s. Taking into account that only averaged input values were used, this result is very good.

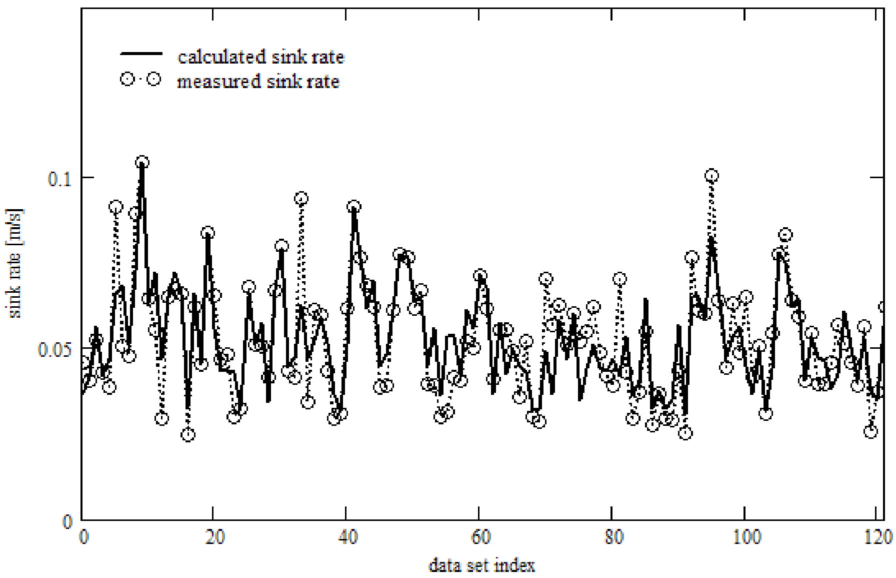

Fig. 7: Model output and measured particle sink rates (isolation material MD-K)

CFD-MODELLING

Particle-related data were also applied for model parameterization in ANSYS CFX. This CFD-application offers the possibility to create MUSIG (Multiple Size Group) models. Phases with similar material properties but different sizes of their components can be combined to one disperse phase. The usage of this model enables the aimed integration of all defined particle classes in numerous simulations with passable computational costs. The definition of appropriate break-up- and coalescence rates allows to regard the corresponding phenomena within such a complex disperse phase.

The usage of CFD-models often goes along with some compromises concerning their parameterization. Therefore, an accurate verification of the simulation results is absolutely essential. As a consequence, data with reference to the whole disperse phase (instead of particle-related data sets) were needed. Hence, additional observations were made with a multiple camera system. The taken images were continuously combined to a mosaic image regarding to matching areas. Consequently, a monitoring of the entire test rig could be performed.

To determine the area fraction of the observed particles related to several levels in the test rig, a special algorithm was developed. An experimental analysis yielded discrete-time values which subscribe the particle throughput for each level. Based on these data a quantitative verification of the numerical simulation results is possible. For this, the postprocessing in ANSYS CFX was realised by considering all predefined levels as shown in Fig. 8.

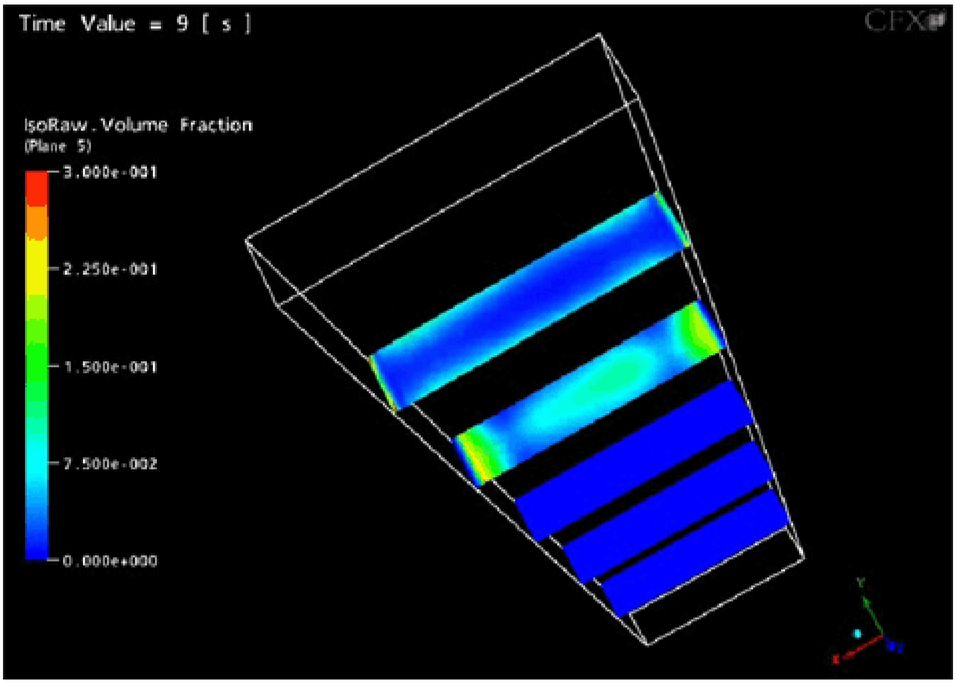

Fig. 8: Level-related interpretation of the simulation results in ANSYS CFX

RESULTS

The application of fuzzy methods to particle sink rates estimation was successful. All particle attributes with significant influence on the sink rate were correctly detected which was confirmed by good matches between the output of the constructed TS fuzzy models and experimental data. We can state that a useful tool was elaborated that allows the prediction of particle sink rates by using shape factors, surface area and contour length of arbitrary particles as input values.

As a part of current research, various types of insulation materials with respect to their behaviour in a coolant flow have been tested. The combinations of TS fuzzy models enables us to compare the different insulation materials without processing the entire contents of large databases. The gained insights have an important influence on the future development and validation of CFD-models used for numerical simulations.

OUTLOOK

Experimental results with references to a three-dimensional geometry will be the optimal basis for the verification of CFD-models. Therefore, current investigations aim at a stable three-dimensional reconstruction of particle objects by using stereo camera system. It requires a certain amount of corresponding points in the taken stereo images. The detection of these points will be performed inside a defined correlation window. So far, the best matching results were achieved by allocating normalized cross correlation. Depth information is calculated in the form of a disparity map, which allows depth image generation by taking camera positions into account (Fig. 9).

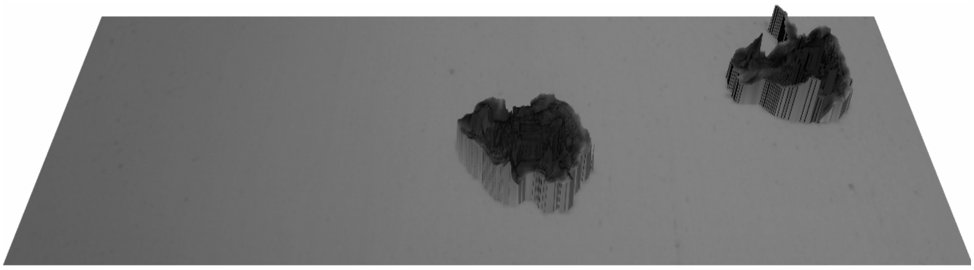

Fig. 9: Surface plot of a particle-laden flow, based on a depth image

For a complete shape reconstruction a subset of all visually detectable parameters will be used. According to the semitransparency of fibre agglomerations, gray values inside particle regions allow a geometrical approximation of hidden surfaces. Thus the collected and prepared experimental data will allow an optimal verification of the numerical simulation results. Regarding to interactions between the disperse particle phases an adequate implementation for the MUSIG model has to be found. At last the CFD-Code has to be optimised for an adequate correlation with experimental data.

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