EXPERIMENTAL INVESTIGATIONS FOR FRAGMENTATION AND INSULATION PARTICLE TRANSPORT PHENOMENA IN WATER FLOW

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Abstract

The paper includes the description of separate effect test facilities used for investigations with regard to the fragmentation and the transport behaviour of different insulation materials in multi-dimensional aqueous flow. The instrumentation of the rigs is specified, in particular modern digital image processing technologies. First experimental results are shown and discussed generated at three acrylic glass test facilities. The experimental data could use for CFD-modelling and validation.

1. Introduction

The investigations for debris generation and transport gain in importance regarding the reactor safety research for PWR and BWR considering all types of LOCA as well as short and long term behaviour of emergency core coolant systems. As a result of LOCA's solid particles such as insulation materials can be released in the coolant circuit. In this scenarios core safety should be provided. Therefore investigations of methods (analytical and experimental) and tools (simulation codes, models) are necessary, which allows 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 wide 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. Separate effect experiments regarding these processes were carried out at three acrylic glass test facilities (Column quasi 1/2-D, Ring Channel 2-D, Tank 3-D) using modern flow measurement and digital image processing technologies.

2. Test rig "Fragmentation"

Blast experiments were carried out at the rig "Fragmentation" (Figure 1) to simulate LOCA and to fragment different insulation materials under real accident conditions, e.g. with saturated steam up to 7 MPa (BWR-LOCA). The facility was also designed for experiments with saturated water up to 11 MPa (simulation of PWR-LOCA).

As a result of these experiments fragmented insulation materials were produced. The debris of each experiment was storaged in aqueous solution to apply this debris solution at the various separate effect acrylic glass test facilities.

Figure 1. Scheme of the test rig Fragmentation

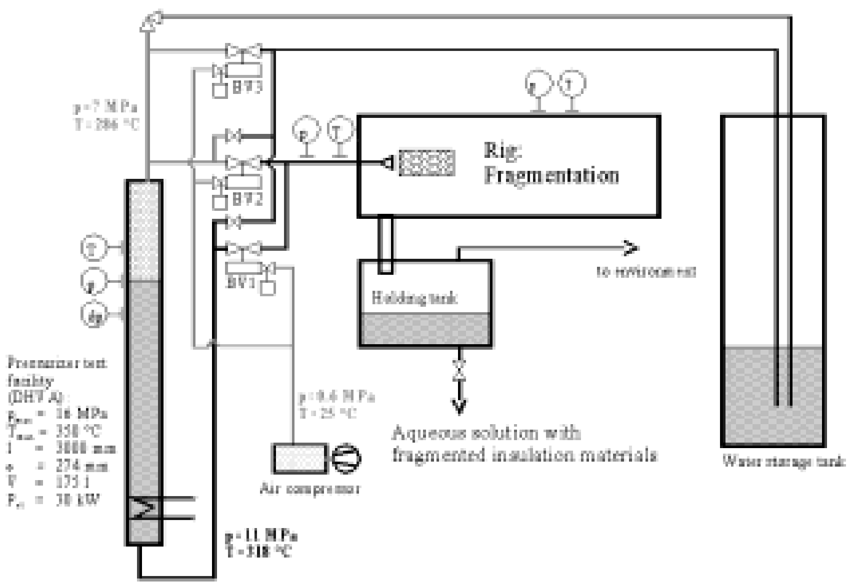
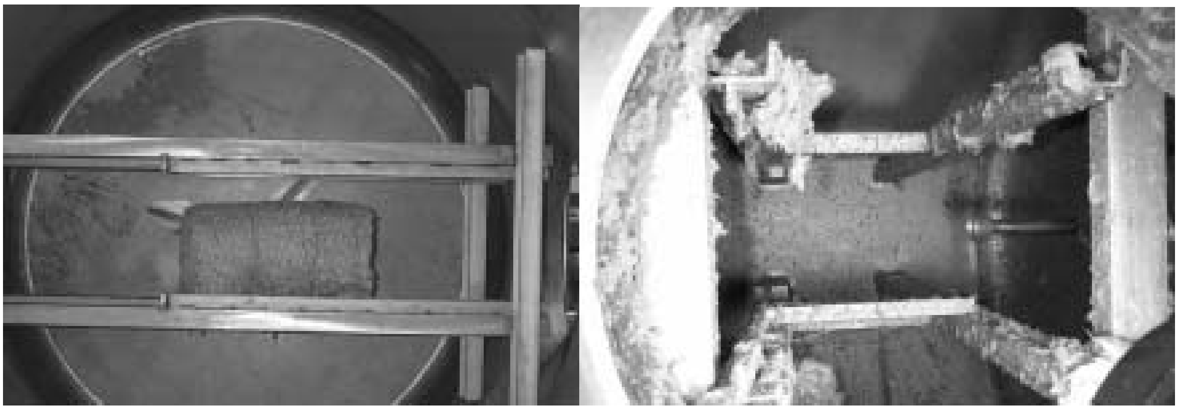


Figure 1. a) Mineral fibre (MD2, 1999) test body **b) Fragments after rupture simulation**
(7.0 MPa; 285°C)

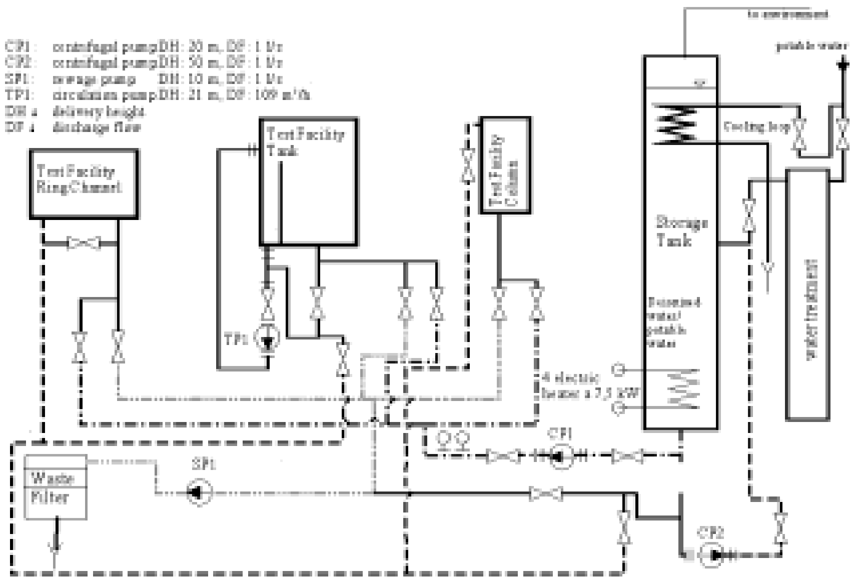


3. Acrylic glass test facilities

3.1 General survey

An overview about the arrangement of several acrylic glass test facilities, the water supply and waste water disposal and the auxiliary components (ball valves, pumps, heaters) are shown in Figure 3. It is possible to feed the facilities with potable water or with deionised water or a mixture of both. A degassing of water can be realised with the electric heaters in the storage water tank. The three acrylic rigs work under atmospheric pressure conditions. The temperatures can vary between 20°C and 80°C.

Figure 3. Scheme of the water system for three acrylic glass facilities "Column", "Ring Channel" and "Tank"



3.2 *“Column” test rig*

The behaviour of gravitating insulation particles in aqueous solution and sedimentation processes were observed at the test facility “Column” in 1/2D-geometry without enforced water flow using an image processing system. The facility consists of a rectangular acrylic glass column with the following dimensions:

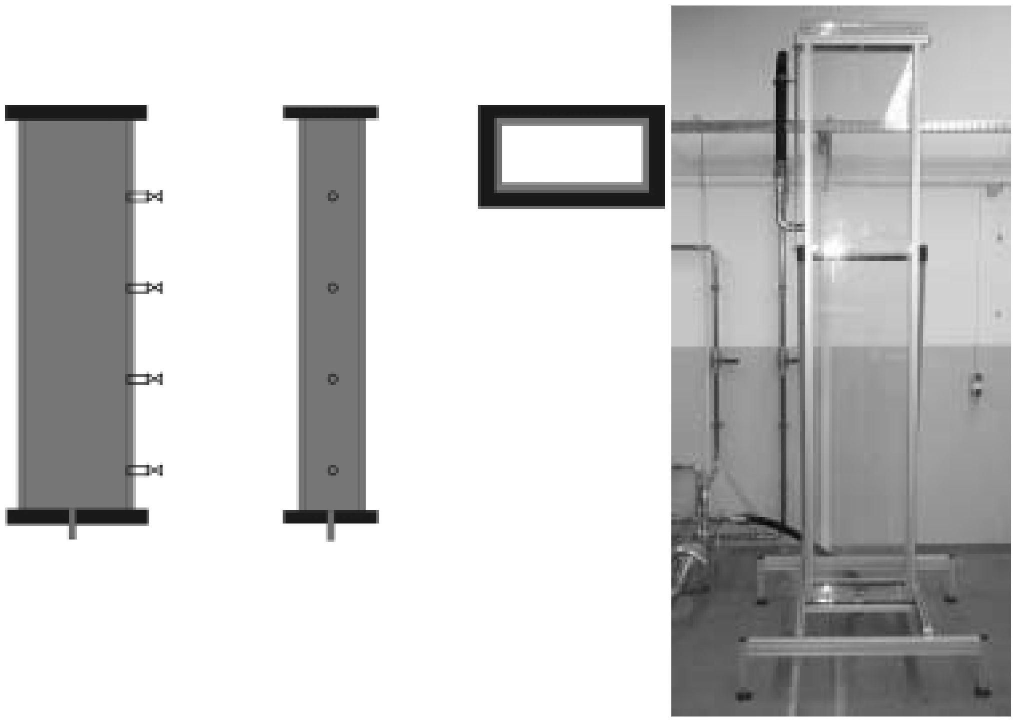
- inner length: 0.50 m;
- inner width: 0.10 m;
- inner height: 3.00 m.

The thickness of the acrylic glass amounts 25 mm.

The mean measured values are:

- x-y-paths of sinking particles;
- sink rates or settling velocities of the insulation particles;
- geometric properties and light densities of the single particles; and
- distribution of particle concentration.

Figure 4. Scheme of the “Column” rig



3.3 "Ring Channel" test facility

The "Ring Channel" was designed as an oval acrylic glass flow channel. The channel consists of two straight sections with a length of 5 m, separated into single segments with a length of 1 m, and two semi-circular segments (Figures 5 and 6). The facility dimensions reads as follows:

- length: 6.20 m;
- width: 1.20 m;
- height: 1.20 m;
- flow width: 0.10 m;
- stretched length of the channel: 13.31 m;
- length of straight channel segments: 5.00 m;
- maximal flow velocity : 0.85 m/s;
- volume (1 m filling height): approx. 1.40 m^3.

Figure 5. Scheme of the facility "Ring Channel"

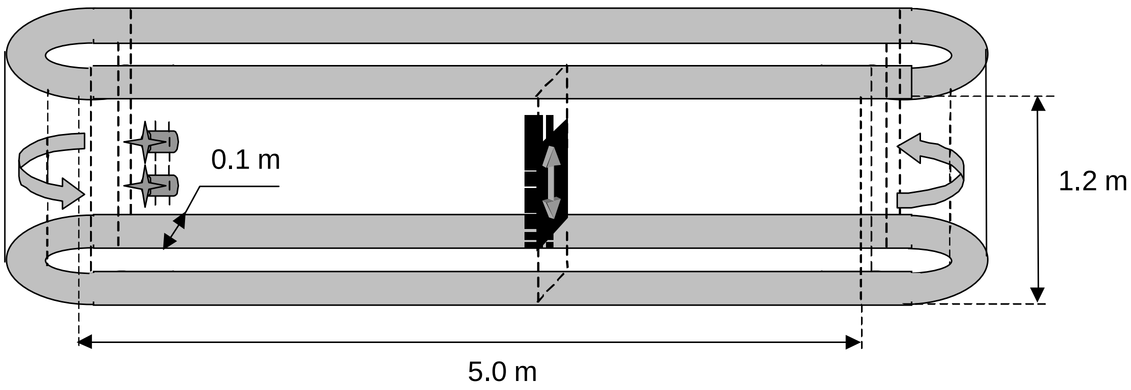
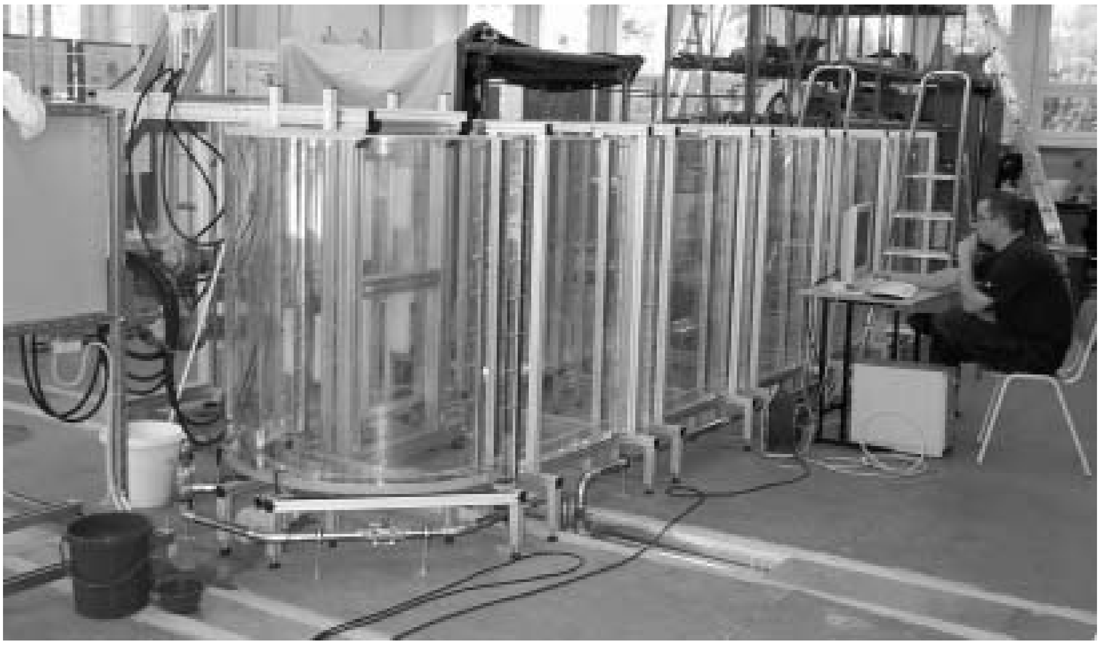
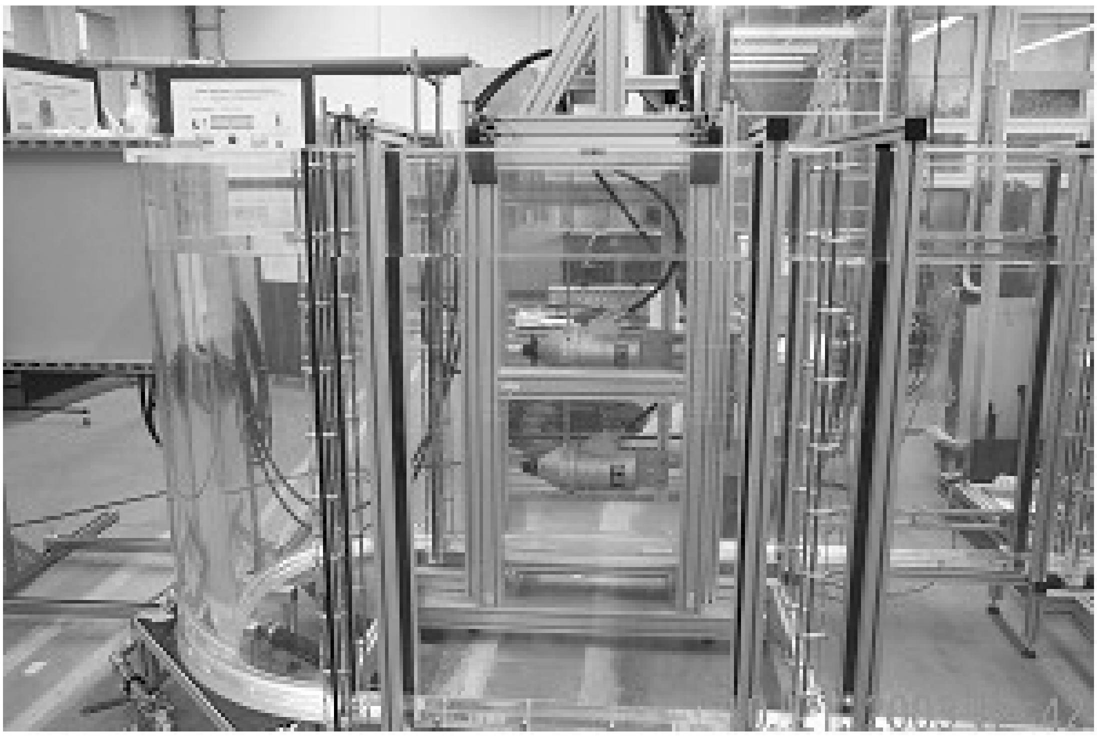


Figure 6. Facility "Ring Channel"



The segments of the facility are designed in form of a rectangular cross section with a wide of 100 mm and a height of 1 200 mm. To generate a defined flow regime two impellers are installed, which have the advantage of a reduced influence on the isolation material (Figure 7). The vertical position of the impellers can be changed. The impeller rotation frequencies can be varied continuously within a range of 0 to 50 rpm.

Figure 7. Acrylic glass segment with impellers (background)

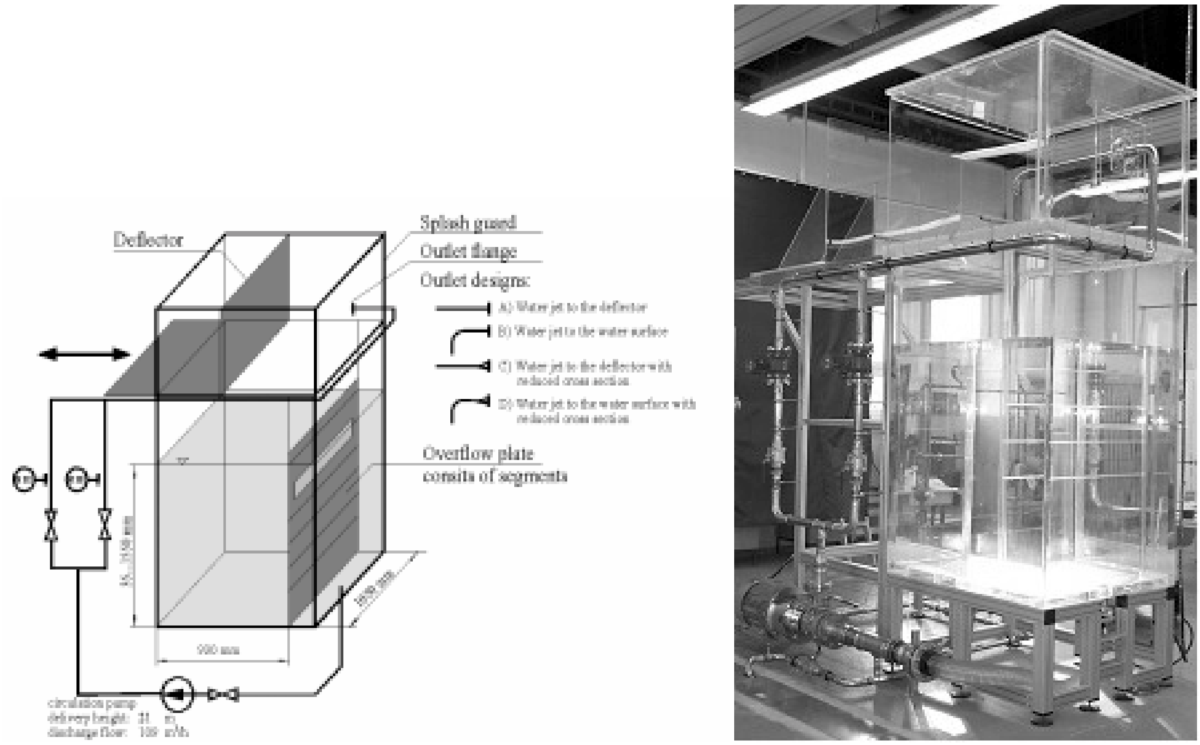


Experiments for the determination of 2D-transport behaviour of different particle sizes in horizontal carrier flow were realised at facility “Ring Channel”. Experimental results were generated with constant cross section area along the whole channel length as well as with barriers and varied cross section areas (e.g. stairs).

3.4 Test rig “Tank”

Experiments performed at the test facility “Tank” included the investigations regarding waterfall effects on a two phase mixture of insulation particles and water under consideration of turbulences in a 3D-flow field. It was taken into account three types of water fall jets (free jet, line jet, area jet).

Figure 8. Configuration of the “Tank” facility

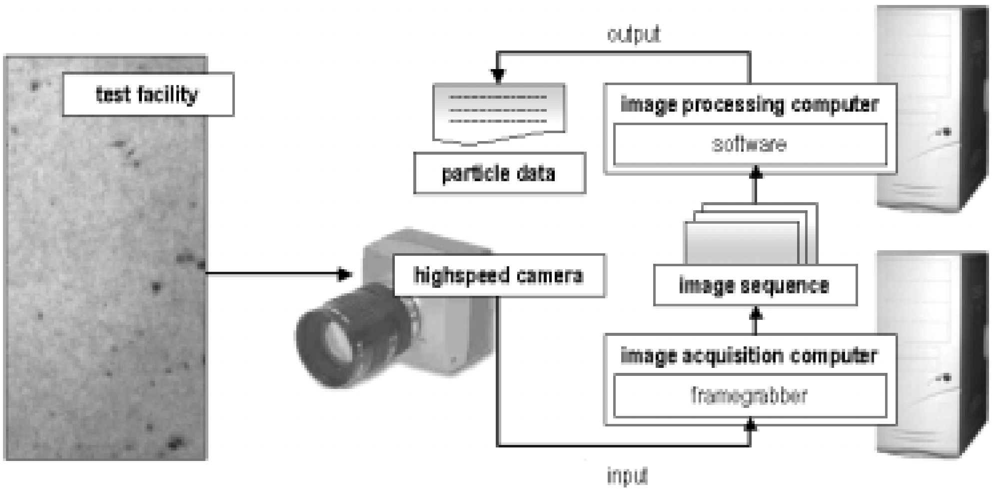


3.5 Instrumentation

The generation of a qualified data basis for CFD-Code model development needs detailed data of the water basis flow and the relative movement of particles in this flow. The velocity profiles of the water basis flow were measured with LDV-technology (Laser Doppler Velocimetry) as well as with a PIV-system (Particle Image Velocimetry). Laser measurement technology also allows the investigation of the intensity of turbulence. Furthermore, the average velocity was measured at different heights with an ultrasonic system in the facility “Ring Channel” using the difference elapsed time method. The total mass flow of the circulation in the “Tank” test rig was detected with MID (magnetic inductive detectors).

Modern digital image processing technologies were applied to measure particle geometries, particle movements and particle velocities using digital highspeed CMOS-cameras. The used image processing system is displayed in Figure 9. It consists of altogether two highspeed cameras, which allow the taking of pictures with a resolution up to 1 280 x 1 024 pixel. Because of random programmability of window size, position (region of interest) and clock frequency, the resolution and the frame rate can be adapted to any specific need. Both cameras can be triggered simultaneously.

Figure 9. Configuration of the image processing system



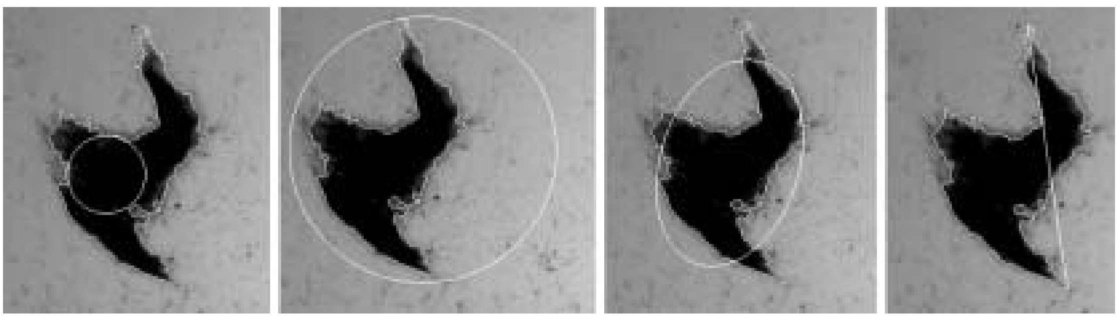
The resulting images underwent a preprocessing for improving attributes like contrast and brightness. Radial distortion effects, caused by optical components of the system, were compensated. In the following operation the objects of interest and the image background were segmented by using several image processing methods like background subtraction and the region growing algorithm.

As a result the unique particle regions of an image were specified. Significant characteristics of the particle objects can be calculated, e.g. contour length, surface area, grey value volume, centre of gravity for area and grey value, position in x and y directions of the world coordinate system (for 2-D geometries), volume, position in x, y and z directions of the world coordinate system (in 3-D geometries).

In addition to these properties several shape factors can be figured out, e.g. circularity, compactness, convexity, largest inner circle of the particle region, maximal distance between two contour points, parameters of the equivalent ellipse and smallest surrounding circle.

Figure 10. Graphical representation of a subset of shape factors

(inner circle, outer circle, equivalent ellipse, maximal distance between contour points)



Applied to a whole sequence, it was possible to trace particles image by image. The velocity of the observed objects could be calculated taken into account the recording time of the sequence. Furthermore, it was also possible to detect a whole range of specific phenomena like particle collision, overlap, splitting and mergence.

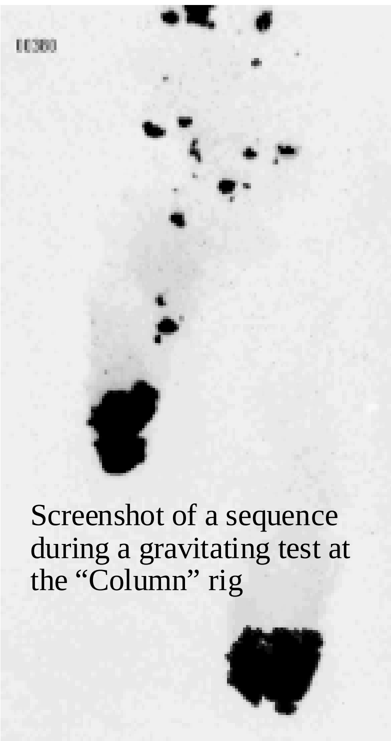
Statistical analyses permitted a classification of flow relevant parameters in clusters which depended on typical geometrical dimensions and on shape factors of different particle sizes.

4. Experimental results

4.1 Results of sinking experiments at facility "Column"

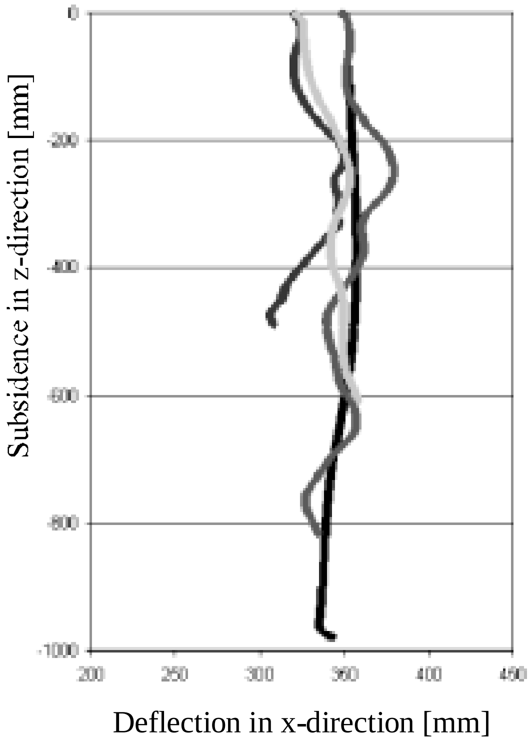
Sinking experiments were carried out with single particle fragments as well as with particle mixtures. Figure 11 shows a screenshot of the detected high speed sequence during a sinking experiment with MD2 insulation material. Analysis algorithms of image processing methods admit the detection of each particle, theirs properties and motions. On the right side of Figure 11 the movement of the grey value centre is illustrated for four particles with different cross sections.

Figure 11. Example of a sinking experiment



Screenshot of a sequence during a gravitating test at the "Column" rig

Particule 1: 6 842 mm²
Particule 2: 304 mm²
Particule 3: 51 mm²
Particule 4: 758 mm²
(not visible in this screenshot)



Taken into account the image system parameters it is possible to determine the time depended motion of the particles and the vectorial velocities, how it is shown in Figures 12 and 13.

Figure 12. Time dependent motion of gravitating particles in z-direction

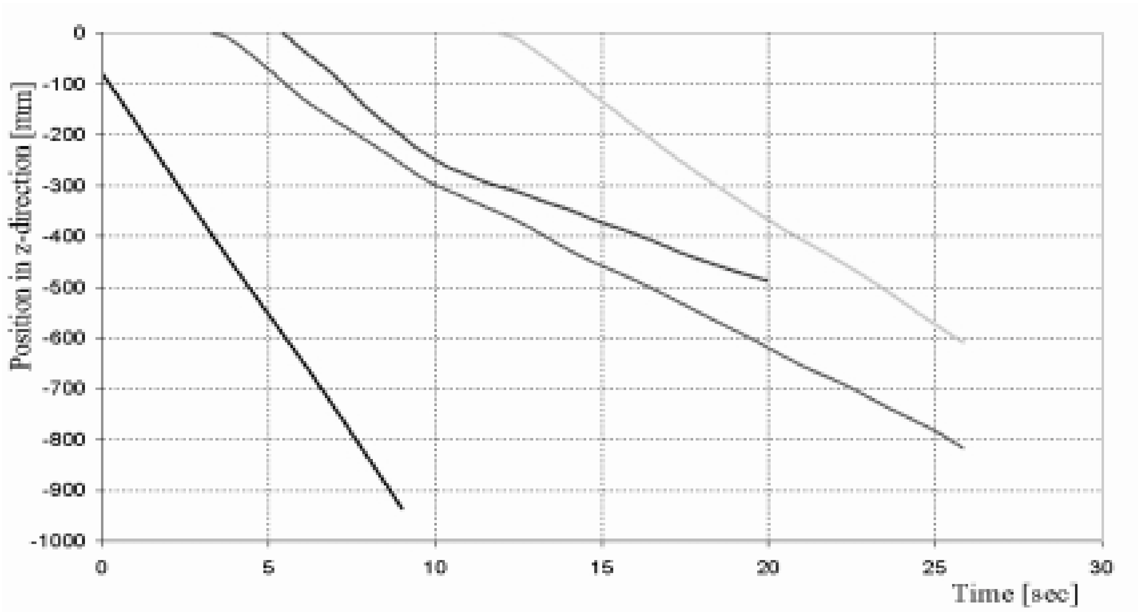
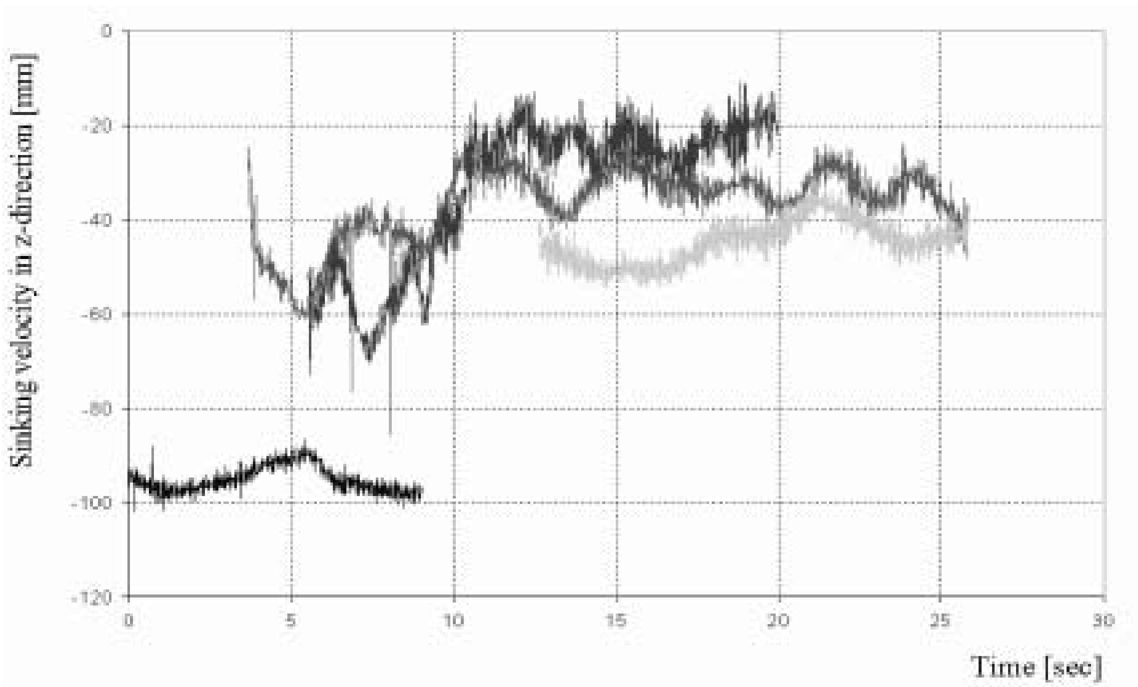
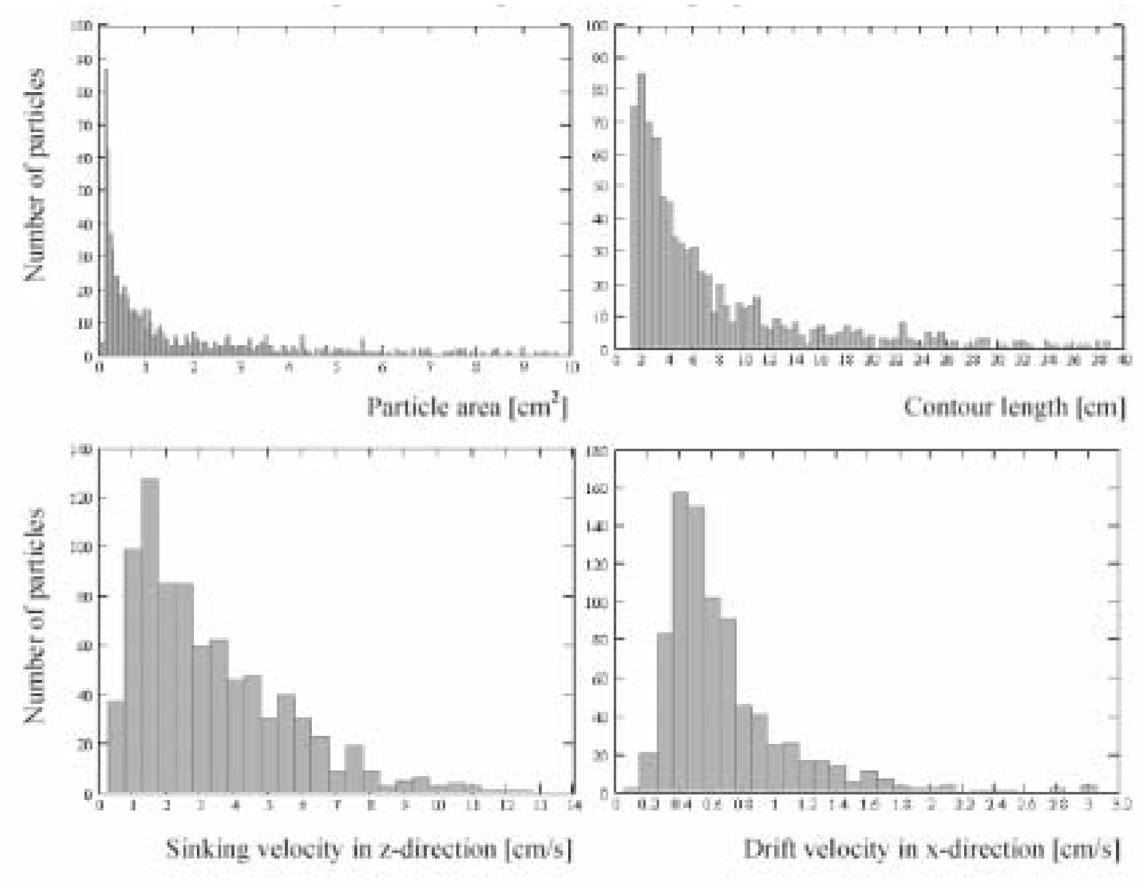


Figure 13. Vectorial velocity in z-direction



A lot of sinking experiments were realised. The vectorial velocities of several hundreds particles were determined. The histograms for particle areas, contour lengths and vectorial velocities of first MD2-sinking experiments at the "Column"-rig are shown below in Figure 14. Next steps of data evaluation will include the data interpretation with methods of cluster analyses to generate dependencies of vectorial velocities on the detected parameters.

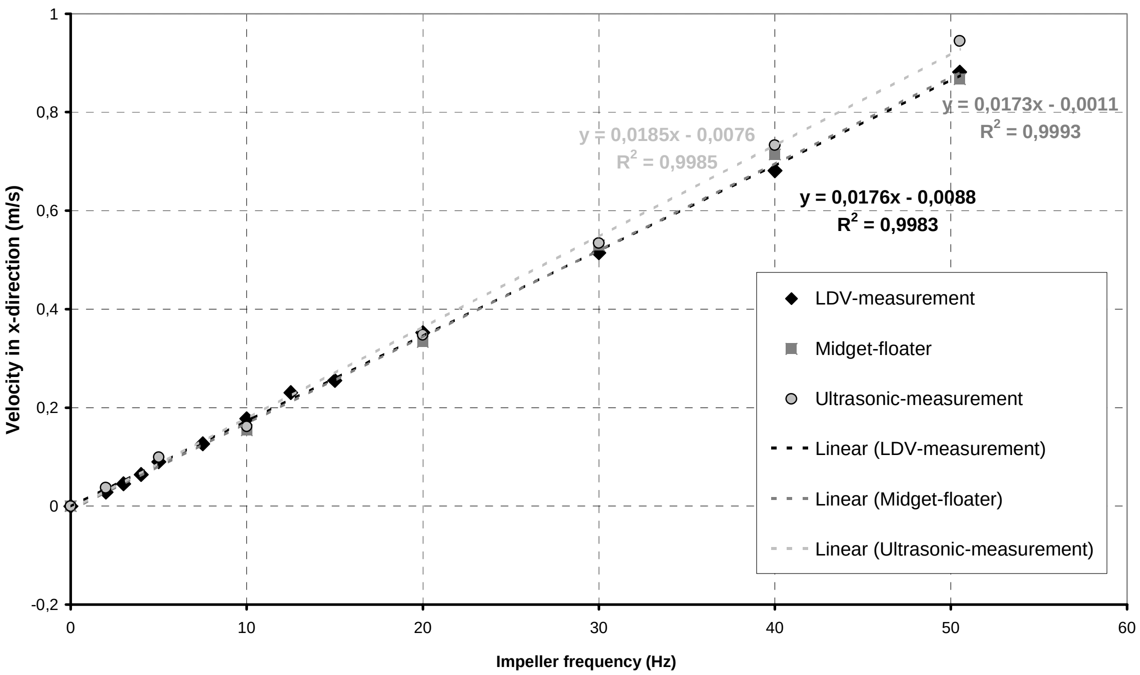
Figure 14. Histograms for sinking experiments



4.2 Water basis flow and particle movement at facility "Ring Channel"

At first it was necessary to detect the dependence between impeller rotation speeds and average water basis flow velocities. The characteristic curves which were measured by different measuring systems are very closed, how it is shown in Figure 15. However, it is possible to control the average water velocities in the "Ring Channel" between 0 and 0.90 m/s.

Figure 15. Characteristic diagram of average water velocity over impeller frequency



Secondly the vertical and horizontal profiles of the water basis flow were determined in the segments. Figure 16 includes the vertical profile of the average velocity in segment 3 measured by the ultrasonic system. This segment 3 is arranged two segments in direction to the impeller segment. The impellers were positioned in 250 mm and 625 mm height and rotated with equal frequencies. Characteristic vertical velocity profiles with two maxima at 100 mm and 500 mm height were observed up a speed of 5 cm/s. Quite uniform profiles could be determined for lower impeller rotation speeds. The profiles have been approved by local LDV-measuring. The LDV measured data are shown in Figure 17. The absolute LDV values are larger than the ultrasonic data because the LDV data were determined in the centre of the “Ring Channel’s” breadth and the US data represents average velocities.

Horizontal profiles at different elevations are shown in Figure 18 with the lowest impeller rotation speed at 2 Hz. The results clarify quite good turbulent profiles. So, it was possible to accept that the image measurement system could observe a 2D-flow behaviour of insulation particles.

Figure 16. Vertical average velocity profile of the basis water flow in segment 3

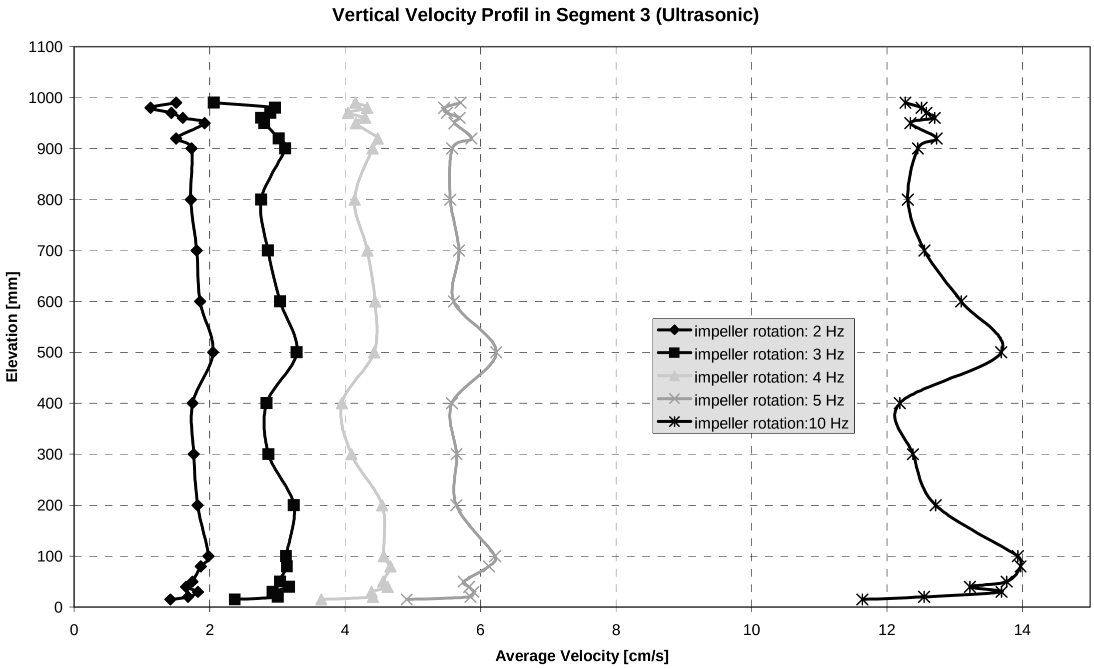


Figure 17. Vertical local velocity profile of the basis water flow in the centre of segment 3

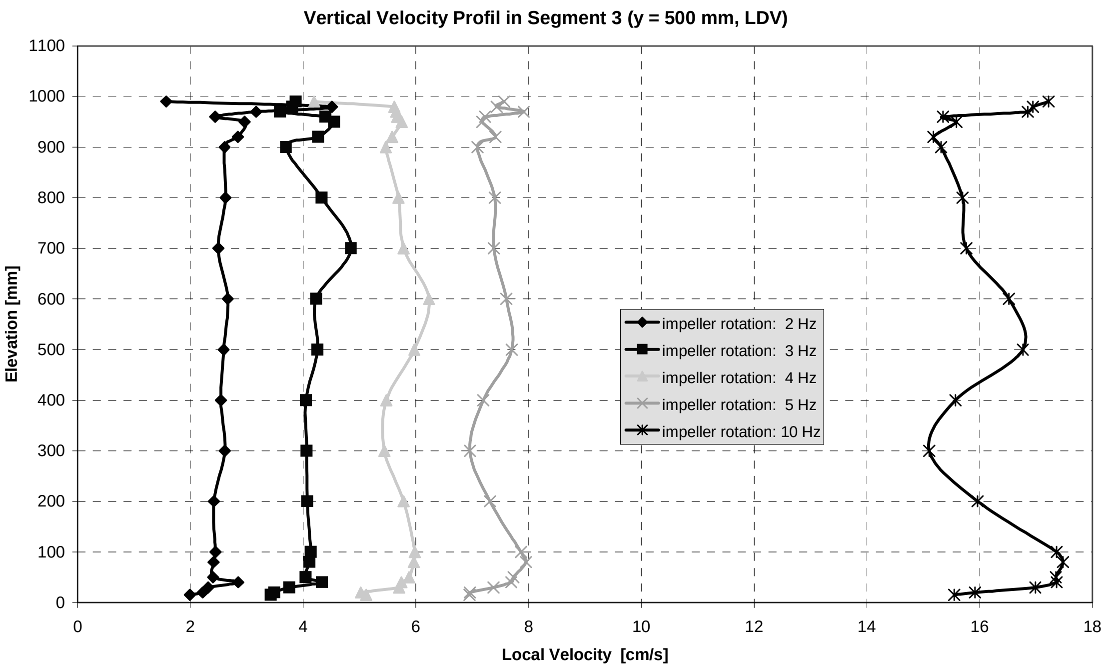
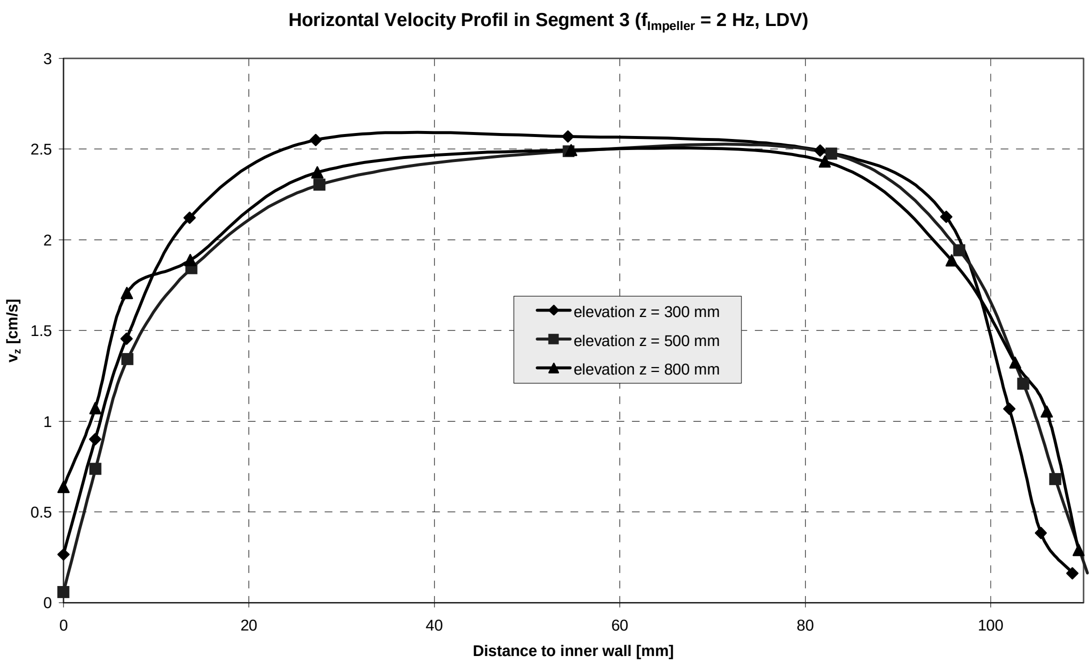


Figure 18. Horizontal velocity profiles of the basis water flow in segment 3



After the determination of the basis water flow, experiments with particle fragments were realised.

Figure 19 shows an screenshot of a sequence generated at segment 3 with a MD3 insulation particle solution and impeller frequencies of 5 Hz.

The coloured lines of each particle illustrate the trajectories. The blue lines surround the ambient dimension of the particles. This is a size for the cross section area of the particles. So, it is possible to determine some important parameters for CFD-modelling, how the velocity vectors of each particle, the drift in the 2D-water basis flow field, the 2D-area (3D-volume) fraction of solid-water flow, the sedimentation rate, etc.

The next steps will include statistic analyses of the very large data basis for 2D-solid-water flow. The experiments will be going on with different insulation materials as well as with barriers, grids and varied cross section areas (e.g. stairs) inside the “Ring Channel” test facility.

Figure 19. Screenshot of a sequence observed with the image measurement system at segment 3

5. Outlook

Statistic analyses will permit a classification of flow relevant parameters in clusters which depend on typical optical parameters, geometrical dimensions and on shape factors of different particle sizes. The analyses also allow the formulation of general rules concerning the behaviour of insulation particles under various ancillary conditions.

The data basis for CFD-Code will be extended by additional data to the 2D-flow concerning the behaviour of insulation particles in a 3D-flow field under consideration of turbulences. According experiments will be realised at the test facility “Tank”. It permits the observation of any influences of waterfall effects on a two-phase mixture of insulation particles and water.

Furthermore, the developed modelling for CFD-Codes will be validated by supplemental experiments on large scaled integral test facilities.

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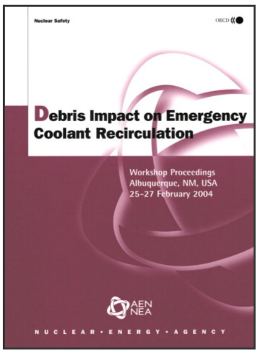

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