Process Tomography for Multiphase Flow Analysis

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ABSTRACT

Besides NDT applications X-ray computed tomography can be applied to the analysis of multiphase flows which are common in process engineering as well as in the power industry. Two kind of process CT systems for multiphase flow analysis are described. 1. A 3D X-ray tomograph with high special resolution and low time resolution which is dedicated to analyzing the 3D gas distribution in vertical bubbly flow. This high resolution proved to be crucial to determine the detailed structure of wall-peaked gas distributions which occur in upward bubbly flow. 2. A 2D X-ray tomograph with high time resolution and low special resolution which is dedicated to visualize the dynamic motion of interfaces in multi-phase flow. It successfully quantified the transient multi-dimensional characteristics of interfaces in the flow.

Introduction

Multiphase flows are common in many applications of process engineering and the power industry. For such applications, the phase distribution plays a key role for many scientific and technological issues like heat transfer rate or mass transfer rate, pressure drop and process efficiency. Therefore, the knowledge of the distribution of the phases is the main interest in view of a safe and optimized operation of multiphase systems. Commonly used local probes measure the existence of liquid or gaseous phases at the tip of the probe. Such probes have an influence on the flow, i.e. the method is intrusive. Computed tomography is so far the only technique which provides phase distribution information without disturbing the flow.

For some applications the three dimensional phase distribution with a high spatial resolution is the main interest, whereas for other applications like in transient flow conditions a high time resolution is required. Both cases can be solved with x-ray computed tomography as will be shown in the article.

In the first section of this paper a high space resolution cone beam (3D) tomography system is introduced dedicated to analyzing the 3D gas distribution in vertically bubbly flow. Following an ultra fast scanning 2D X-ray CT system developed to visualize the dynamic motion of interfaces in multi-phase flow is described.

High-Resolution 3D Tomography System for Two-Phase Flow Diagnostics

Most CT systems which are now in operation make use of line detectors and therefore produce 2D results. However, if the evolution of the flow needs to be analysed 3D information is required. Therefore, a cone-beam X-ray tomograph was build and operated in Forschungszentrum Karlsruhe GmbH, Institut für Reaktorsicherheit [1]. The tomography system is dedicated to analyzing the 3D gas distribution in vertical bubbly flow. The aim of the experiments is to provide data for the development and improvement of two-phase flow models by investigation of dominant characteristics of adiabatic turbulent air/water bubbly flows in vertical pipes. These investigations are performed in a test facility consisting of a loop with two vertical test channels, for upward and downward directed flows, respectively. Besides other measurement techniques like hot-film anemometry, laser Doppler anemometry, and invasive local probes for the measurement of bubble data, X-ray CT system is used as a powerful non-intrusive method to determine the time-integrated phase distribution across the test section at arbitrary axial elevations.

Previous experiments in vertical upward bubbly flow showed rather sharp gradients in the phase distributions, for example a ”wall-peaked” gas distribution for high liquid superficial velocities [1]. In order to resolve such peaks which occur within the major velocity gradient patterns, sub-millimeter space resolution is required. Such a resolution performance has been achieved with the tomographic system, which makes use of a 2D detector array. This allows us to perform fully 3D tomography adding more versatility to the device, such as: the acquisition of much more data in the same time and the use of digital radiography as a method of flow imaging and more flexibility through correlation with other methods.

System description

In Figure 1 the principle scheme of the tomograph is shown.. The cone-beam tomograph is a third generation type, i.e. the complete system consisting of an 160 kV industrial X-ray tube, and a 2D detector array unit, is rotated around the vertical axis through the pipe center. During the rotation of the source-detector assembly the acquisition software detects several hundreds projections (frames) in about 2-10 min. Since this configuration involves a relatively slow mechanical rotation of the source-detector assembly its application is limited to the investigation of quasi-stationary, two-phase flow, like, for example, bubbly flow. A distinctive feature of this instrument is the relatively large (200x200 mm^2), flat, high resolution 2D detector array. The active sensor, formed by 512x512 squared pixels (0.4 mm pitch size), is based on amorphous silicon technology. It is coated with a Lanex scintillator layer sensitive to X-ray energies in the range 20-200 keV. Figure 2 shows a photograph of the system. For better visibility the pipe is removed to the right.

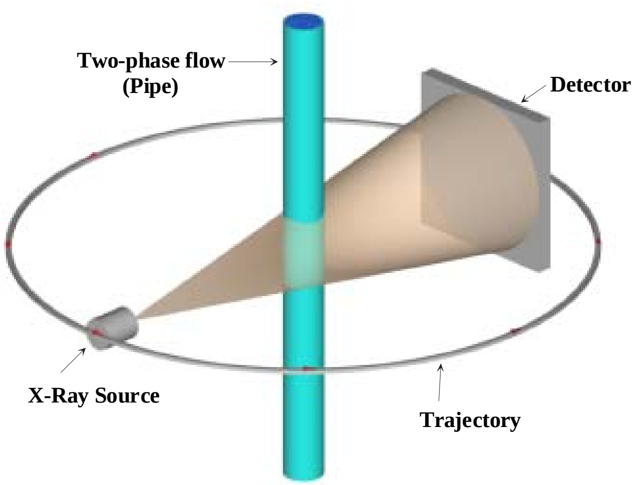


Figure 1: Principle of the cone beam tomography system

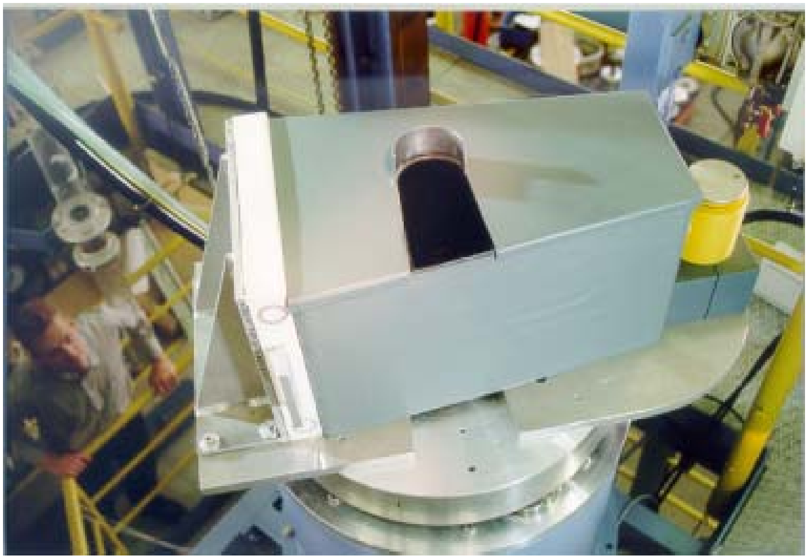


Figure 2: Cone-Beam X-ray tomograph applied to vertical bubbly flow. The pipe (which was removed) is located in the center between x-ray tube (right) and detector (left).

The comparison of different reconstruction algorithms as well as the simulation of the complete tomographic system allowed us to optimise the system for speed and accuracy to study the spatial development of air-water bubbly two-phase flow characteristics along vertical channels

Application to Two-Phase Flow

With the acquired knowledge of the geometrical and density accuracy, the cone beam tomograph was used to determine the gas distribution in actual bubbly flow. The main goal of these measurements was to analyze a few known patterns in comparison with previous X-ray tomography studies, e.g. [1].

Special attention has been paid to assessing the time averaging errors. In the mathematical formalism of the reconstruction from projections it is implicitly assumed that the gas distribution to be recovered is constant in time. That means it does not change from one projection angle to another. Actually, in tomographic measurements of two phase flow we performed a twofold time averaging. The first one is done over the integration time at every projection angle (usually a short time averaging, in our case an integration time of typically 200 ms). A second time averaging is performed over the duration necessary to collect the whole set of projections (i.e. relatively long time integration, in our case between 2 and 10 min).

Here we present three typical examples of upward bubbly flow. The main interest was to generate a wall-peaked gas distribution and to determine its characteristics with the improved geometrical resolution of the present instrument.

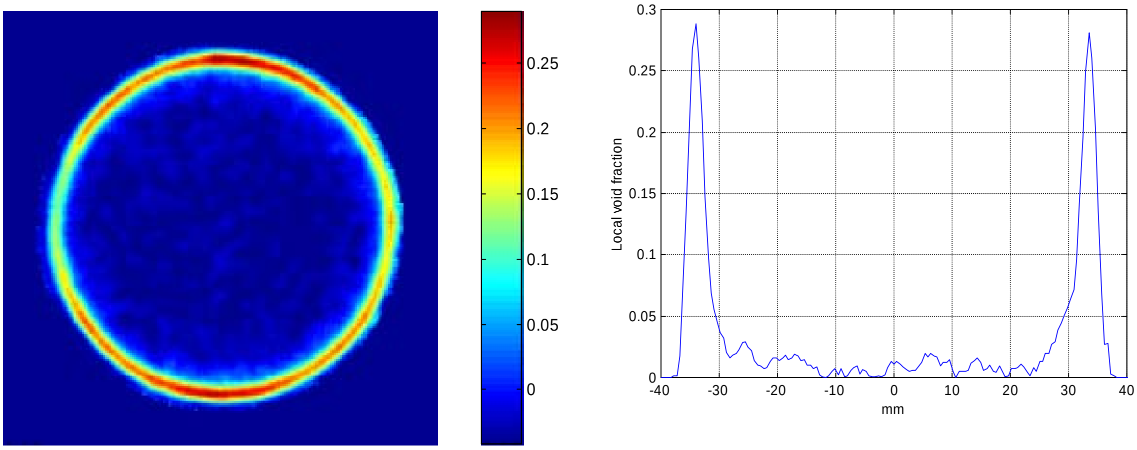
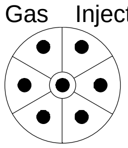


Figure 3: *Gas distribution in upward bubbly flow; β=3.25%, j_l=1.8 m/s, elevation 40D.*

Gas Injection: symmetrical through seven nozzles



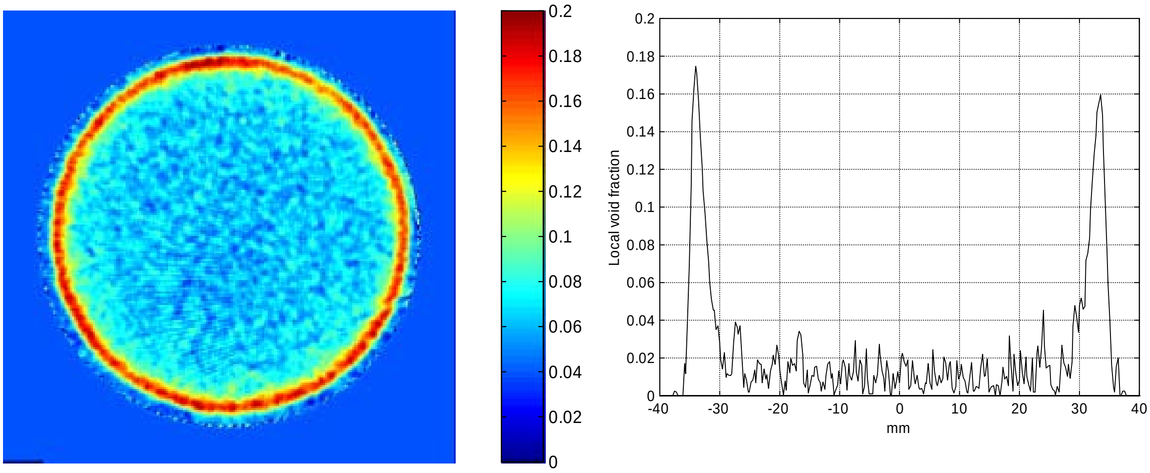
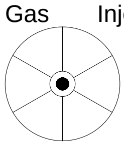


Figure 4: *Gas distribution in upward bubbly flow; β=3.25%, j_l=1.8 m/s, elevation 40D.*

Gas Injection: through one central nozzle



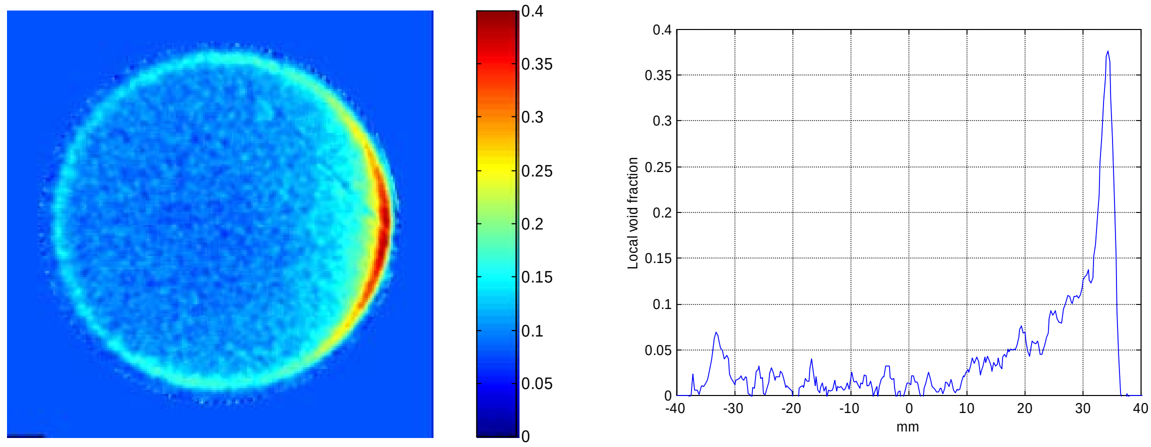
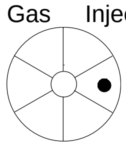


Figure 5: Gas distribution in upward bubbly flow; β=3.25%, j_l=1.8 m/s, elevation 40D.

Gas Injection: *asymmetrical through one nozzle*



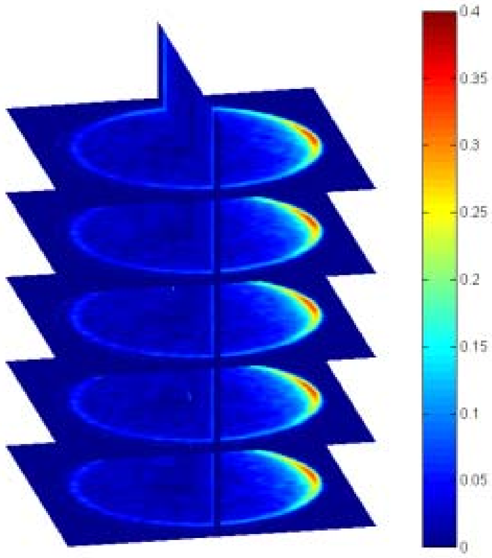


Figure 6: D slices for the gas distribution in Figure 5

For a gas injection through seven nozzles of a volumetric gas fraction β = 3.25 % and a superficial liquid velocity j_l= 1.8 m/s, one notices an unexpectedly sharp wall-peaked distribution, Figure 3. The measurement was performed at an elevation of about 40 inner diameters from the gas injection plane. It should be mentioned that the geometrical resolution of the present instrument ($\leq$ 0.4 mm) is well suited to describe such a detailed structure of the gas peak. This result demonstrates that both the use of local probes and/or of a medium resolution X-ray tomograph could be misleading in the absolute measurement of the local gas fraction in the region adjacent to the pipe walls.

In Figure 4 a result for the same flow parameters but an injection through only one central nozzle is shown. Although the gas distribution was center-peaked above the injection nozzles, the distribution is again wall-peaked in only 40 D distance.

Changing the gas injection scenario to a single off-center nozzle the measured gas distribution displays the same wall-peaked structure but with a clearly asymmetric pattern (Figure 5). It shows that there is a strong phase redistribution in the radial direction, but almost no redistribution in the circumferential direction.

Figure 6 shows several slices through the 3D gas distribution for the flow analyzed above. It is visible that, as expected, for an axial height of about one interior diameter the gas distribution does not change.

Ultra fast X-Ray Computed Tomography for Transient Phenomena

Highly deformed interface encountered in practical two-phase flow applications requires multi-dimensional measurement techniques with temporal resolution. A fast scanning X-ray CT system was developed to visualize the dynamic motion of interface in multi-phase flow at the Institute of Mechanical System Engineering, AIST, Tsukuba [3]. When the system was applied to an air-water two-phase flow and a simplified fluidized bed system, it successfully quantified the multi-dimensional characteristics of interface in flow.

System description

The key concept that realized faster scanning by two-orders of magnitude compared to medical CT systems is to use multiple X-ray sources and detector elements fixed to the system. Firing of each source is equivalent to the rotation of X-ray source in existing CTs.

18 sources turned on for 100 μs at every 3.8 ms, resulting in a maximum scan rate of 258 frames per second. With an improved source firing scheme a double sampling rate was achieved.

The CdTe detector module has 256 pixels. The sensor device technology is based on their prototypes previously assembled for high-resolution radiography and tomography imaging of electronic parts. About 60 pixels are to be irradiated by a single fan beam of 24 degree expansion angle. Equipped with the CdTe modules, the fast X-ray CT system was able to visualize 50 mm diameter cross section with a spatial resolution of around 2 mm.

Grid bias controls the pass of electron beam and thus of X-ray cycle. Pulsed X-ray and data acquisition are synchronized to capture instantaneous bubble interface. Figure 7 shows a simplified scheme of the principle of operation of the ultra fast X-ray CT.

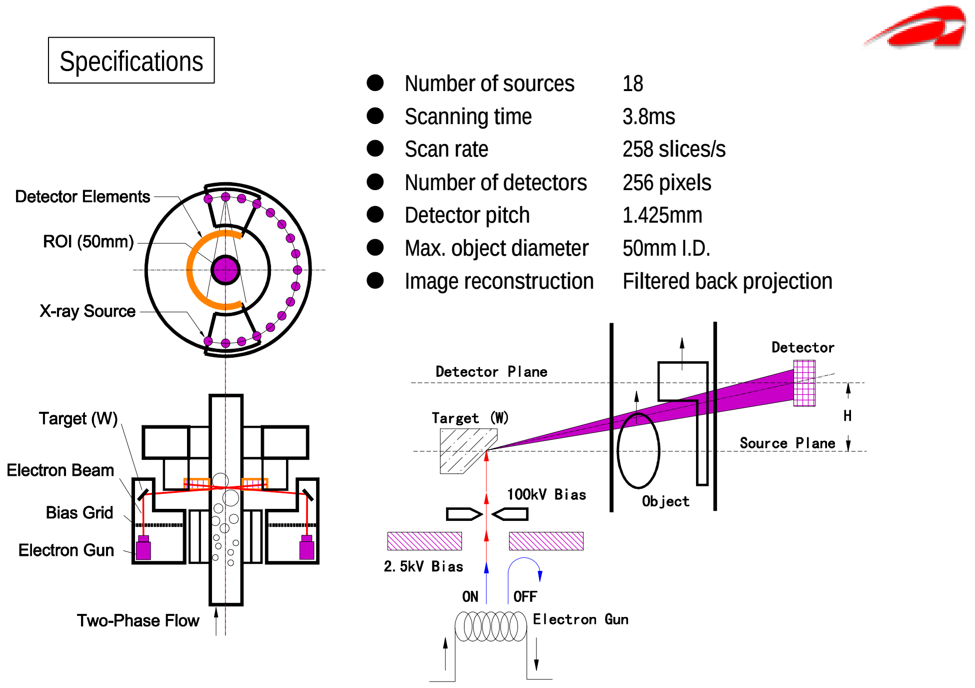


Figure 7: Ultra fast X-ray CT-system

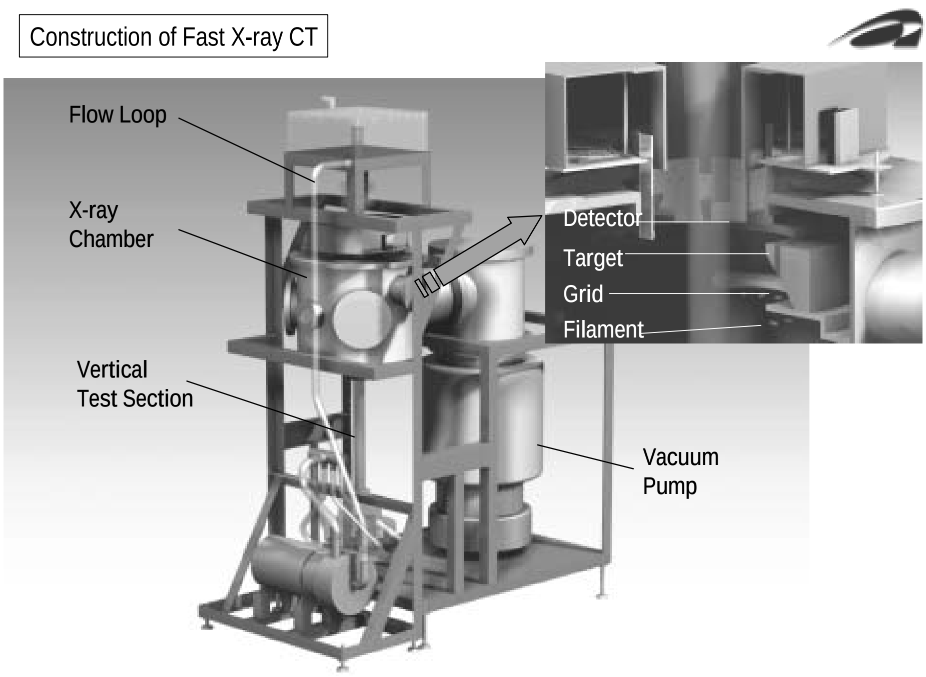


Figure 8: Ultra fast X-ray CT and two-phase flow loop

A two-phase flow loop is installed in the Fast X-ray CT (Figure 8). The vertical flow channel resides in the center of the cavity of the X-ray chamber. X-ray are emitted through a thin aluminum window which separates vacuum and atmosphere.

Measurements in Air-Water Two-Phase Flow

About 263 cross-section images of void distribution are stacked to visualize the overall interface distribution in bubbly flow and slug flow in a 42 mm diameter vertical pipe. 263 slices correspond to one second of flow.

The measuring plane was set at about 17 inner diameters above the air-water mixer exit. Bubbly flow was attained by injecting air through a sintered mesh plate with 100 microns pores, while air was introduced through four 5 mm diameter nozzles.

As the air flow rate increases the inner flow pattern becomes invisible. However, we detected a concentration of bubbles inside the bubble swarm as the air flow rate increases.

Using image processing techniques, area and perimeter of each bubble can be counted. (Figure 10). The area ratio of air and water in the cross section represents the void fraction, while the perimeter does the interface length. The perimeter determined here is normalized by the inner perimeter of the pipe. This parameter is an indicator of how much the bubble surface is deformed. The deformation of the slug bubble interface, especially in the wake region was significant under the present flow conditions and contributed to an increase in the interface area.

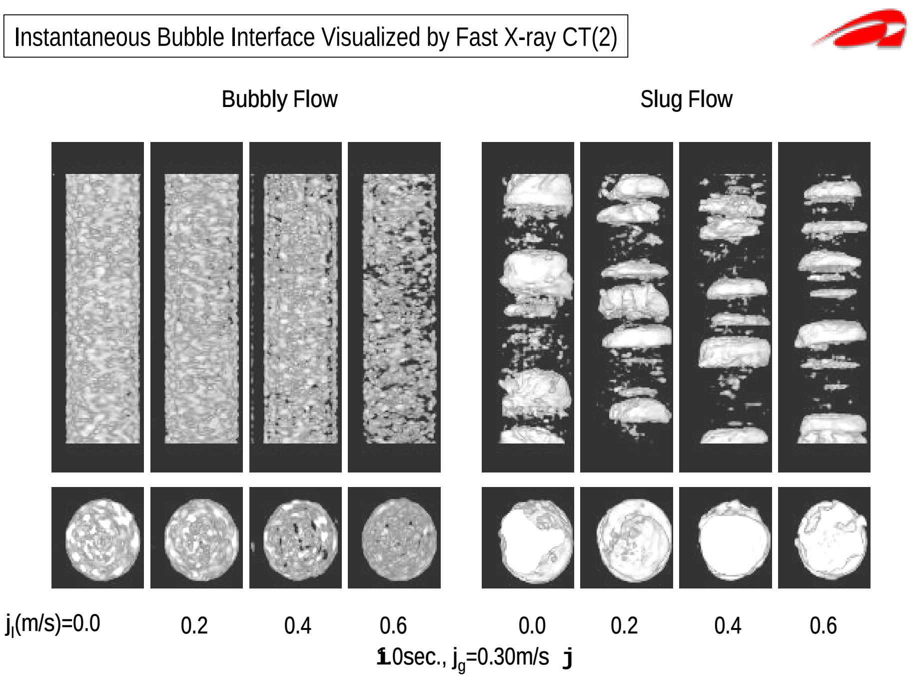


Figure 9: Instantaneous bubble interface visualized by ultra fast X-ray CT for different flow patterns corresponding to four combinations of liquid and gas superficial velocities.

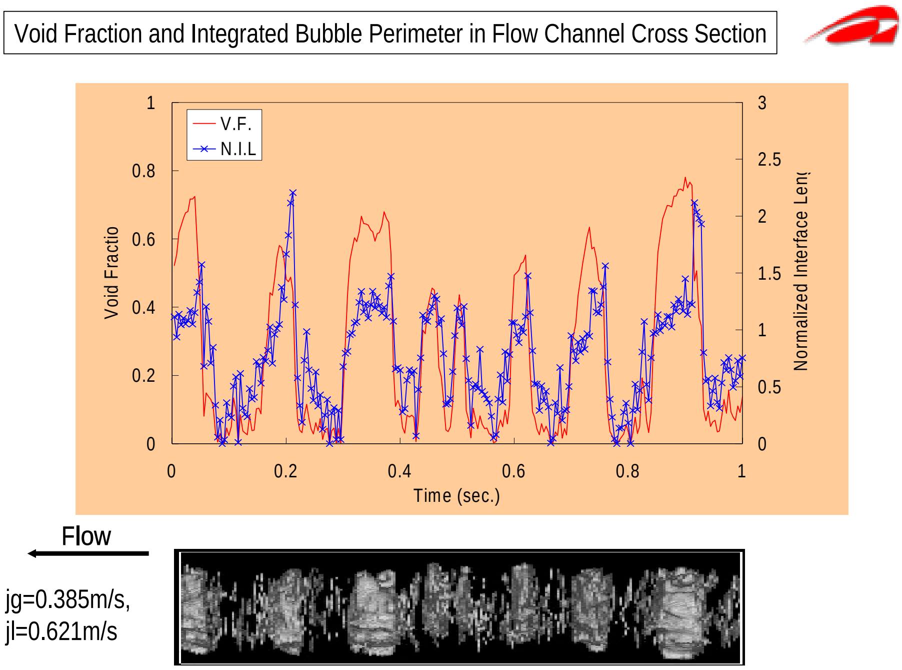


Figure 10: Time-resolved void fraction and normalized interface length for a slug flow pattern.

Measurements in Fluidized Bed System

Chemical plants often use a device called fluidized bed to augment the reaction rate with catalysts. Alumina powder serves a catalyst. When a reactant gas is introduced, it has been difficult see how the gas moves inside the powder. Fast X-ray CT is suitable for visualization of voids in the alumina powder since the effective density is lower than that of water. To obtain the interface area quantitatively, we used a fast-scanning X-ray CT that scans a cross-section of a flow channel in less than 4 ms and visualizes the instantaneous, two-dimensional phase distribution in a vertical upward slug flow.

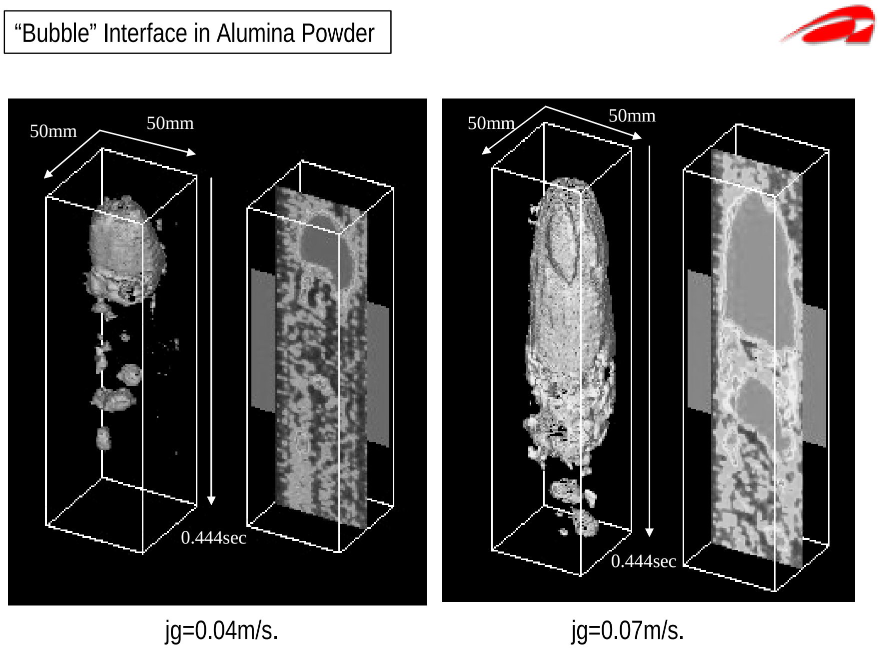


Figure 11: Pseudo-3D representation of gas flow in alumina powder

For large gas flow rates, the voids in the powder migrate upward. Jg is the average velocity of the gas introduced. The difference between this flow pattern and genuine two-phase flow is that the powder emulsion has intermediate densities, depending on the concentration of powder. Nevertheless, it is interesting to note that the interface is clearly defined as much as the air-water case.

Conclusions

Computerized Tomography (CT) is a non-intrusive measurement method that provides an ideal examination technique whenever the primary goal is to locate and size planar and volumetric details in three dimensions. The industrial applications where CT has proven most valuable are in the area of non destructive testing especially for material analysis. It was shown that CT can be successfully applied also to different kind of multiphase flow with either high spatial or time resolution.

The described 3D CT system was applied to study the evolution of vertical bubbly flow at different flow parameters and boundary conditions. It was shown that the 3D X-ray tomograph is a powerful non-intrusive measuring device for two-phase flow analysis that is able to determine highly resolved density profiles in 512 cross-sections in the flow direction with a single measurement, allowing new insights in two-phase flow phenomena. However, it can be only applied to quasi stationary flow conditions which show constant flow conditions within the measuring time of the CT scan.

As an example for the application of the CT technique to transient flow conditions an ultra fast scanning X-ray CT system developed to visualize dynamic motion of interfaces in multi-phase flow was described.

Highly deformed interfaces encountered in practical two-phase flow applications requires multi-dimensional measurement techniques with temporal resolution. When the system was applied to an air-water two-phase flow and a simplified fluidized bed system, it successfully quantified the multi-dimensional characteristics of interfaces in the flow.

Nomenclature

D	[m]	diameter
j_g	[m/s]	superficial gas velocity
j_l	[m/s]	superficial liquid velocity
β	[–]	volumetric gas fraction

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