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Advanced tomographic imaging for multi-phase flow investigations in industrial apparatuses

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Abstract

Investigations on two- and multiphase flow phenomena inside technical apparatuses or feedings are of highest interest for designers and operators since the knowledge helps to understand the fundamental physics behind processes, e.g. in chemical and process engineering. It expedites the development of safer and more efficiently operated industrial facilities. Furthermore, measured data are used to validate new models developed for multiphase flow simulation, e.g. CFD. For non-intrusive two-phase flow investigations, two radiation-based computed tomography (CT) scanners are operated at the Helmholtz-Zentrum Dresden - Rossendorf (HZDR) at the department of Fluid Dynamics: a high-resolution gamma-ray computed tomography scanner (HireCT) and an ultrafast electron beam X-ray CT scanner (ROFEX). They are able to recover non-superimposed cross-sectional material distributions of the scanned plane or volume section within the flow as time averaged images or time resolved image sequences. The capabilities of both CT systems are demonstrated exemplarily at experiments on an industrial scale bubble column, a fluidized bed and a static mixer.

Introduction

Hydrodynamic investigations on two- and multiphase flows are of high interest, since they occur in many industrial branches such as chemical and power industry as well as mineral oil processing. The simulation of industrial scale multiphase flow behavior is still subject to ongoing research. Therefore, multiphase flow measurement techniques are needed to either generate validation data for computational fluid dynamics (CFD) models or to study certain flow phenomena, which cannot be simulated, directly in industrial plants or suitable experiments. In the last decades, tomographic measurement techniques gained increasing interest, because they are able to provide spatially resolved data of the object of investigation. Some modalities from medicine have been adapted for two- and multiphase flow investigations, such as X-ray CT, magnetic resonance imaging (MRI) or positron emission tomography (PET). Furthermore, new imaging techniques such as electrical impedance tomography (EIT) have been developed. Since none of the named methods fulfills all requirements of multi-

phase flow visualization, such as high penetration capability, high spatial and temporal resolution, new tomographic measurement systems have been developed and established at HZDR during the last 10 years.
The spatial high-resolution gamma-ray computed tomography scanner (HireCT) (Hampel et al 2007) offers detailed views inside industrial devices and vessels. It allows insights into processes operated in steady state and reveals stationary phase distributions. The system can be operated in conventional and rotation-resolved scanning mode. The later offers quantitative two-phase flow analysis in fast rotating objects, e.g. centrifugal pumps or fluid couplings, with sharply resolved structures.
The ultrafast electron beam X-ray CT scanner (ROFEX) (Fischer et al. 2010) is a tomography device, which reaches its high temporal resolution by fast electron beam deflection for generating a rapidly moving X-ray source. Thus it is able to recover the phase distribution of two- or multiphase flows with up to 8,000 frames per second. Due to its dual plane modality, also information about the axial velocities of bubbles or other objects can be retrieved. Various studies have been performed revealing the dynamic structure of gas-liquid two-phase flow in e.g. vertical pipes, (slurry) bubble columns (Rabha et al. 2013), monolith reactors, static mixers (Rabha et al. 2015), separators, and ceramic foam structures. Furthermore, gas-solid distributions in fluidized beds have been under investigation (Bieberle et al. 2012).

High-resolution gamma-ray Computed Tomography (HireCT)

Gamma-ray computed tomography with high gamma photon energies offers views inside technical devices and vessels consisting of thick walls of high density, e.g. steel or aluminum. Simultaneously, a sufficient contrast between different phases is achieved, e.g. liquid and gas. One drawback is the low gamma photon flux that limits the process diagnostic application to scenarios operating in steady state. To counteract the low gamma photon flux single detector elements must be operated in gamma photon counting mode and must have a huge active area which leads to in-plane resolution of about 10 mm for most conventional gamma-ray CT systems (Chaouki et al 1997, de Vuono et al. 1980, Johansen et al. 2010). Thus, a spatial high-resolution gamma-ray CT (HireCT) measurement system was developed at the Helmholtz-Zentrum Dresden - Rossendorf during the last decade. The CT system has already been successfully applied to many industrial applications (e.g. Bieberle et al 2009, Leon et al. 2013, Rollbusch et al. 2015). The spatial in-plane resolution is approximately 2 mm. The main components are a collimated isotopic source, a radiation detector arc, an external signal processing unit, a thermal stabilization system and a commercial computer. To perform CT scans, the components are placed onto a rotational-lift unit (see Figure 1). As isotopic source Cs-137 with an activity of 185 GBq and a gamma photon energy of 662 keV is used. The collimated radiation fan beam is directed to an in-house developed radiation detector arc that consists of 320 seamlessly arranged scintillation detector elements each with an active area of 2 mm in plane by 8 mm in height. The detector elements converts interacted gamma photons into electric voltage pulses whose amplitudes are proportional to the energy of the detected gamma photons. A pre-defined pulse height window allows counting of those photons passing the object of interest without interaction (scattering). Furthermore, the radiation detector arc is designed modularly (see Figure 1b), which permits an easy adaption to various applications and establishes an efficient heat exchange of lost heat from the active electrical components.

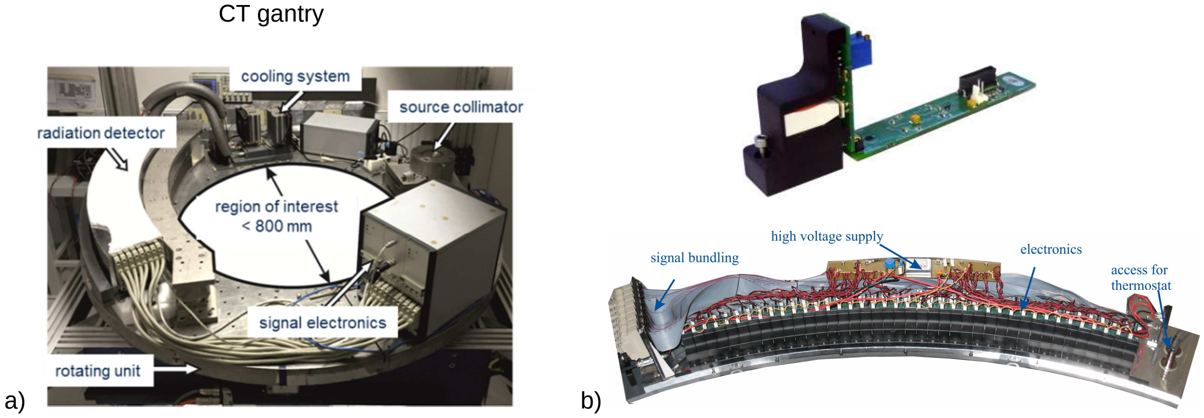


Figure 1: a) gantry to perform gamma-ray CT scans with the b) spatial high-resolution gamma-ray detector arc (opened view on the analogue electronics) composed of 40 detector module comprising analogue electronic processing stages for eight detector channels.

The HireCT measuring system can be operated in conventional and time-averaged rotation synchronized CT scanning mode. For conventional CT scanning mode (Figure 2a) radiographic projections are taken from different angular positions by either a rotation of the CT system or of the object. The calculated attenuation projection data set is then used as input for computed tomography reconstruction algorithms to calculate the non-superimposed cross-sectional material distribution. That CT scanning mode produces slice images in which all static components of the object are sharply visualized.

For time-averaged rotation-synchronized computed tomography (Bieberle et al. 2007) HireCT stays in a fix position. The rotation of the object is, thereby, used to acquire projection data from different angular positions. Therefore, the data read-out of the detector is synchronized with an angular transmitter delivering the current angular position of the rotating object. Scans over many rotations have to be taken so that projections from the same angular position can be summed up to achieve adequate statistics. In the reconstructed cross-sectional image, components rotating with the same rotational speed as the object, such as gas fields in stirred chemical reactors or centrifugal pumps, can be sharply visualized.

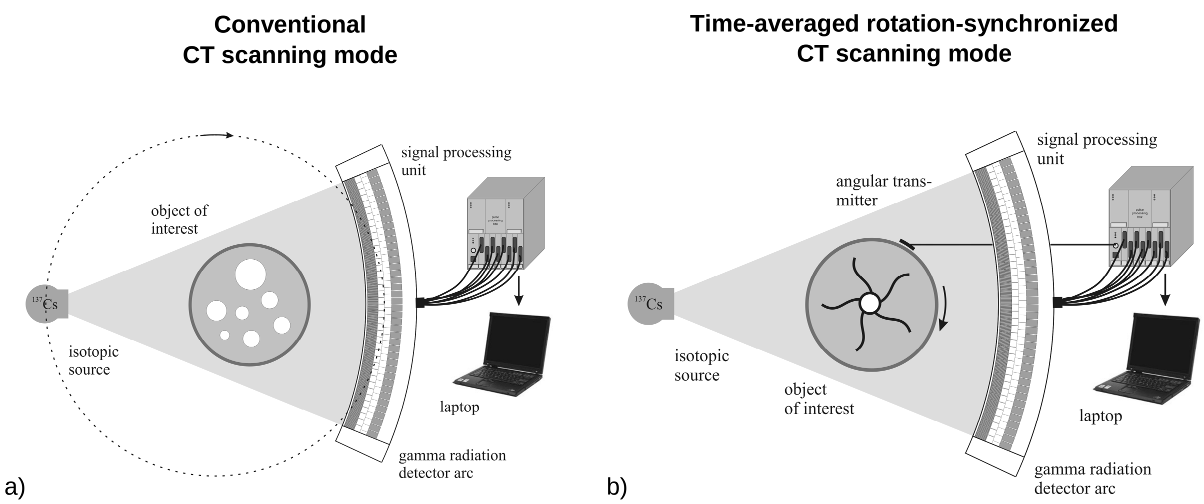


Figure 2: Principle sketch of a) conventional and b) time-averaged rotation-synchronized CT scanning mode.

Ultrafast electron beam X-ray Computed Tomography (ROFEX)

Conventional X-ray CT systems on the basis of rotating source-detector-compound as described in section 2.1 are not able to reach a temporal resolution required for imaging of transient multiphase flows. In order to speed up the data acquisition, the principle of electron beam X-ray tomography is exploited in this ultrafast X-ray CT system, which is called ROFEX (Rossendorf fast electron beam X-ray CT). There, an electron beam is focused onto a heavy metal target, where it induces the generation of X-ray radiation (see Figure 3). By electromagnetically deflecting the electron beam along the ring-shaped target a rapidly moving X-ray source spot is generated. One revolution of the electron beam results later on in one reconstructed image. In our system the frame rate can be chosen between 500 s^{-1} and 8000s^{-1}. The detector elements are arranged on a static ring around the object of interest. Thus, no mechanically moving components are required for this measurement technique. With the fast read-out capability of the detector of 1 MHz, the ROFEX CT system is able to acquire projection data from multiple positions per electron beam revolution. In practical applications, a compromise between temporal and spatial resolution must be found, since the frame rate is inversely proportional to the number of projections per image.
Furthermore, the ROFEX system comprises a dual plane option. The combination of X-ray source target and detector ring is installed twice with a defined distance in axial direction. The electron beam can be guided along one target or alternately along both targets to achieve quasi simultaneous imaging in both planes. Thus, also information about the axial velocity of moving structures within the object of interest can be retrieved in addition to the evolution of the in-plane material distribution (Bieberle et al. 2010). For multiphase flow analysis this is especially important, since the true dimensions in axial direction can only be retrieved from the image sequence, if the velocity of the current object is known.

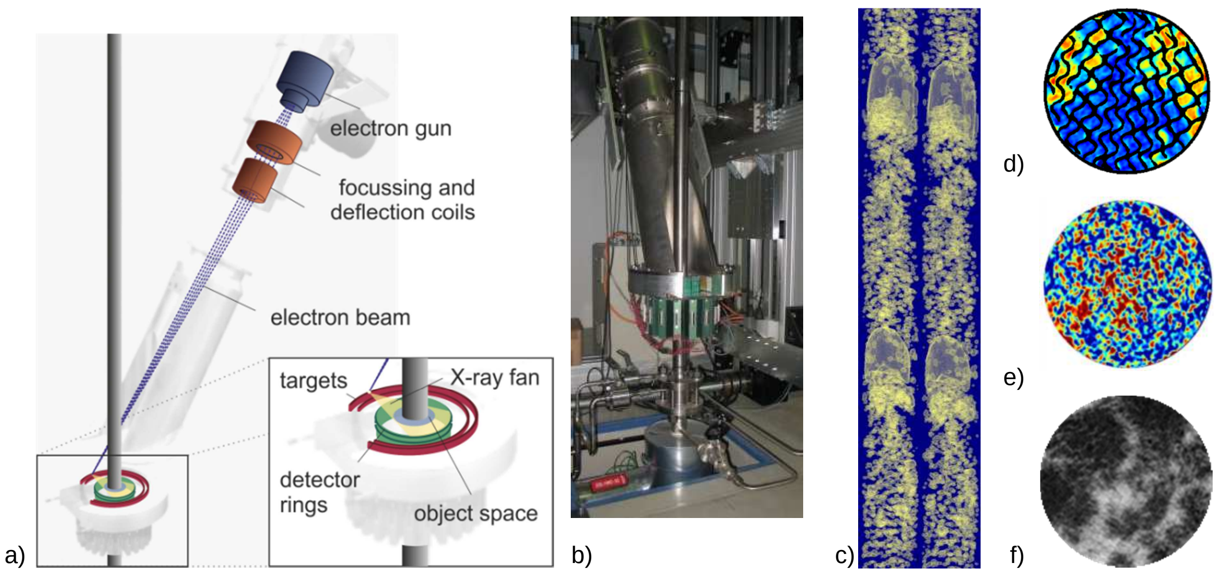


Figure 3: Principle of ultrafast X-ray CT (a), setup (b) 3D view of recovered phase boundaries in image sequences of vertical pipe flow from both CT planes (c), cross sectional images of gas-liquid flow within a structured packing (d), within a ceramic foam (e), and gas-solid distribution in a fluidized bed (f).

HireCT measurements within a bubble column

Bubble column reactors are widely applied in the chemical process industry for a large number of two-phase and three-phase flow systems. They have been extensively studied in the last decades. Gas holdup is considered as one of the crucial hydrodynamic parameters as it affects the liquid recirculation and back mixing, which in turn influence the space-time-yield and selectivity of the process (Deckwer et al. 1991, Rollbusch 2015). Most bubble columns are operated at elevated pressure conditions in order to increase the solubility of the gaseous components and to prevent evaporation of the liquid phase at high temperatures. However, gas holdup studies have mainly been limited to aqueous bubble columns operated at atmospheric conditions, which results in poor predictions for industrial bubble columns. Thus, the development of improved predictive design tools for bubble column reactors requires reliable process data at industrial operating conditions, in particular at elevated temperature and pressure for organic liquids. To access gas-liquid flow characteristics, high-resolution gamma-ray computed tomography (HireCT) was exemplarily applied on a laboratory bubble column to provide insights into the phase distributions and flow pattern at different gas superficial velocities and gas sparger geometries (Figure 4). As operating fluids tap water and compressed air (de-oiled) at 23°C are used. The gas sparger contains of 352 × 1 mm holes homogeneously distributes on a circular area of 0.045 m² (Figure 4 middle). In Figure 4 right the determined gas fraction distribution of three differently modified gas sparger areas are shown for different bubble column heights and a constant gas superficial velocity of 4.0 cm/s. It proves very clearly, that a non-equalized gas distribution inlet is equalized in our bubble column configuration after a height H to diameter D ratio of approximately H/D = 1.5. These data can now be used to validate simulation results using simplified flow models.

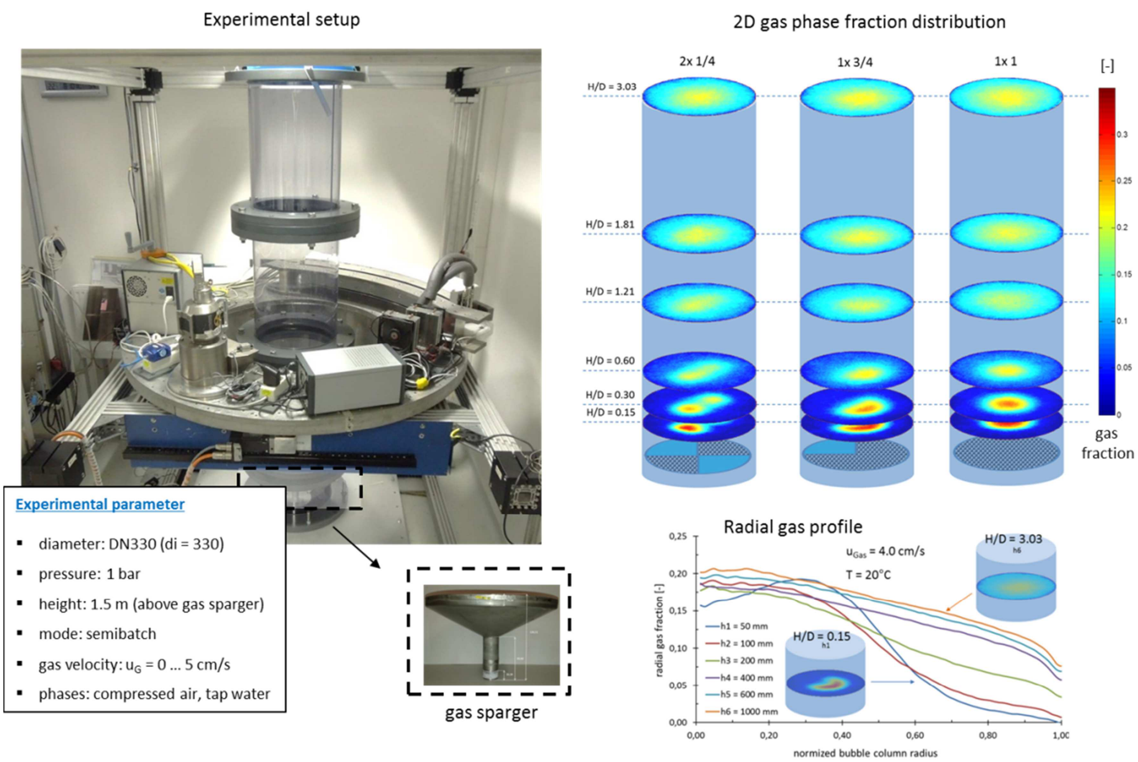
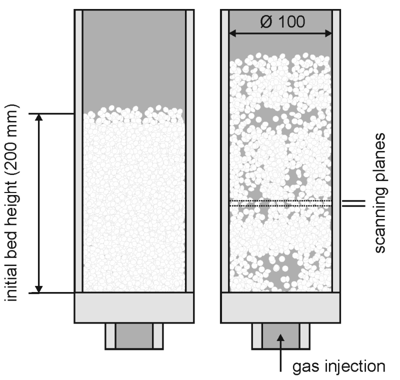


Figure 4: HireCT applied on a laboratory bubble column for gas phase fraction determination in different heights (left) and measured cross-sections as well as calculated radial profiles of the gas phase fraction distribution for three different (symmetric and asymmetric) gas sparger inlet distributions.

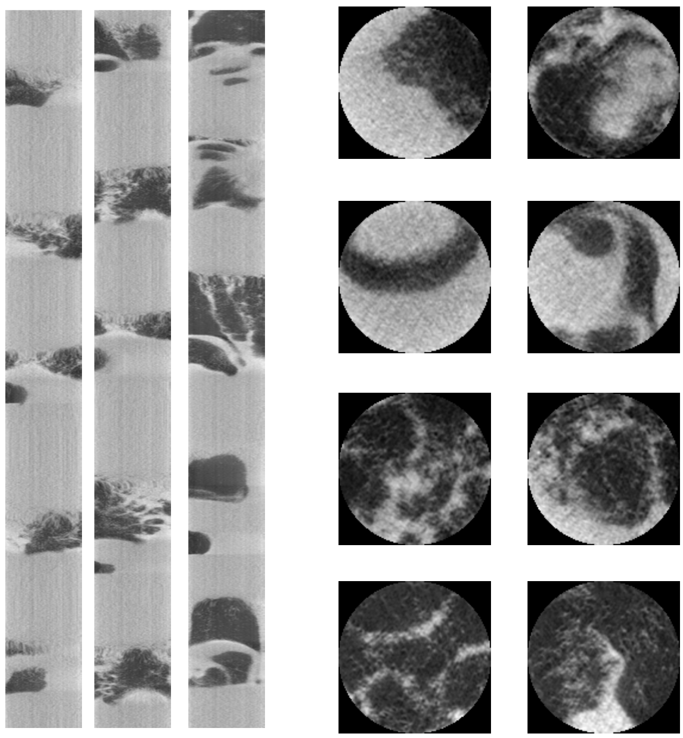
ROFEX measurements within a fluidized bed

The processing of granular media occurs in different forms in several industrial branches. The fluidized bed is one type of device, which is widely used for processing solid particles by injecting gas from the bottom to achieve good mixing as well as heat and mass transfer conditions through a large interfacial area. It has for example applications in chemical reaction, combustion, drying, granulation and coating. Although there exists quite a lot of experience on the operation of fluidized beds, the complete physics is not jet understood in the detail, which would be necessary to simulate the whole dynamics of fluidized beds for different conditions. Therefore, great effort is spent on studying its behavior in experiments. However, due to the mostly dense distribution of opaque media in fluidized beds, measuring the particle distribution is a challenging task. Here, ultrafast X-ray CT was applied to an experimental fluidized bed of 1 mm diameter glass beads with an initial height of 200 mm within a 100 mm diameter column. The phase distribution within the measuring planes was recovered at a frame rate of 1000 images per plane per second for gas inlet velocities u_{G} in the range of $1.25\,u_{\mathrm{mf}} \leq u_{\mathrm{G}} \leq 2.0\,u_{\mathrm{mf}}$ with u_{mf} being the minimum fluidization velocity. A sketch of the principle setup and resulting X-ray images are shown in Figure 5. The cross-sectional as well as virtual axial slice images show the material distribution for the different gas inlet velocities. It is obvious, that the revealed structures are more complex than in gas-liquid systems, where a clear phase boundary defines bubbles, droplets or at the very most streaks. Here, dense, dilute and void regions merge into one another without a defined boundary in between and form structures, which could be described as bubbles, streaks, curtains or other forms of dense or dilute regions. Taking only the large bubble structures into account, the X-ray CT results have been compared with simulations based on the two-fluid model (Verma et al. 2014). More detailed analysis of the X-ray CT data is subject to ongoing research.



Experiment parameters:

- particle diameter: 1 mm
- particle material: glass
- column diameter: 100 mm
- bed height: 200 mm
- imaging plane height: 100 mm (upper plane)



a) b) 1.25 Jmf 1.50 u_{mf} 2.00 u_{mf} c)

Figure 5: X-ray CT results of an experimental fluidized bed: Experimental conditions (a), resulting virtual axial slice images for different u_{G} (b), and exemplary images of the cross-sectional solid distribution.

ROFEX measurements within a static mixer

Static mixers are an attractive alternative to bubble columns or stirred tank reactors for the dispersion of a gaseous phase within a liquid, which is a typical processing step in many industrial applications. Besides being operated directly in feed lines, static mixers also comprise the advantage of not needing any additional motor. Low shear rates, self-cleaning capability, sharp residence time distributions, and high interfacial area production are further beneficial features of this component. From the different designs proposed, the helical static mixer is one of two preferable versions. However, the reciprocal effects of either mixing or separation due to the centrifugal forces induced by the helical structure require careful design of the mixer elements. Therefore, the internal phase distribution within a typical helical static mixer structure has been analyzed for representative flow parameters by using ultrafast X-ray CT. The generated data can be used to validate multiphase CFD codes, which in turn can serve as a tool for optimizing the mixer structure. For the experiments, three helical static mixer elements with diameter and height of 80 mm have been arranged within a column of 80 mm inner diameter and 3.45 m length as shown in Figure 6a. Air was fed into the water flow through a nozzle of 12.5 mm diameter, whose orifice was located in the center of the pipe. X-ray CT scanning was performed at 6 different heights, 4 of which are located within the static mixer elements, and the other two were located below and above the static mixer. In each position, the experiment was scanned for 10 s at 1000 fps per tomography plane.

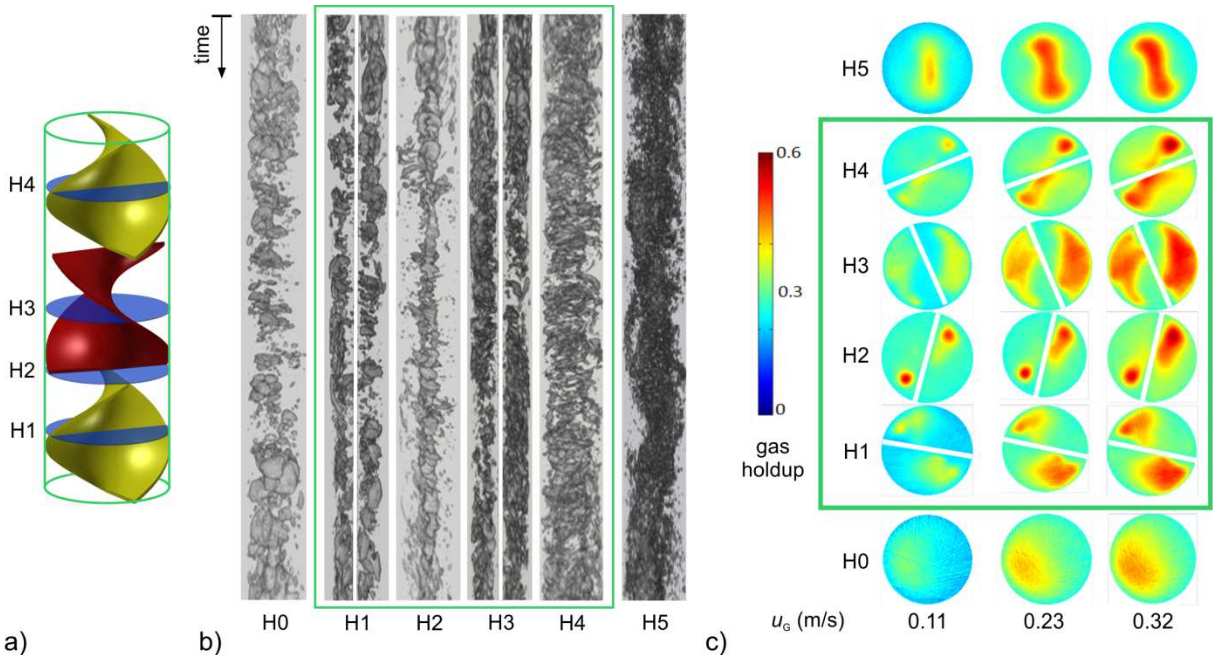


Figure 6: X-ray CT results of an experimental helical static mixer: structure of helical static mixer with indicated measurement heights (a), 3D representation of the extracted phase boundary for the experiment with superficial gas velocity $u_\mathrm{G} = 0.11\ \mathrm{m/s}$ and superficial liquid velocity $u_\mathrm{L} = 0.6\ \mathrm{m/s}$ (b), and time averaged cross-sectional gas holdup distributions for different u_G at $u_\mathrm{L} = 0.6\ \mathrm{m/s}$.

In Figure 6b, the 3D representation of the extracted phase boundary of one of the performed flow experiments is shown. The time averaged gas hold-up is depicted in Figure 6c for three different gas superficial velocities. It could be shown in this study that the helical static mixer decreases the mean bubble size and thus increases the interfacial area. A shifting of the gas fraction towards the center of the pipe has been measured, but at the same time a reduction of this effect with further increasing the number of static mixer elements could be observed.

Conclusions

It has been demonstrated through different examples of multiphase flow scenarios that radiation based tomographic imaging can contribute substantially to the understanding of complex flow phenomena by providing insight into flows in opaque structures. The high-resolution gamma-ray CT reveals stationary phase distributions within large vessels with thick walls while the ultrafast X-ray CT is able to resolve the dynamic behavior of the phase distribution with up to 8,000 fps in smaller scale vessels.

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