

## Tomographic Imaging of the Void Distribution in Bubble Columns During Blowdown

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**Abstract** - Vessels filled with liquid mixtures are used in many chemical processes, under high pressure and at high temperatures. In the case of a process-breakdown, a sudden decrease of the pressure can occur. As a result, the liquid level inside the vessel swells and a blowdown of liquid and gas from the vessel occurs. For the operation of the plant, the design of the apparatus has to be safe and has to avoid similar states of operation. Therefore the hydrodynamic phenomena occurring inside the vessel during the blowdown have to be known. Using electrical tomography it is possible to measure the distribution of the void fraction in each cross section of the vessel during the blowdown operation.

**Keywords:** electrical tomography, bubble columns, pressure relief

### 1. INTRODUCTION

In recent years the standards for the chemical industry regarding safety, environmental protection, energy consumption, quality assurance and complexity of the products have increased significantly necessitating more complex and detailed measurement techniques for the design and control of chemical plants and transportation systems. During this development, the use of tomographic measurement techniques has become increasingly popular. The advantage of tomographic measurements in contrast to local measurements is the non intrusive imaging of the complete cross sectional area of the measured object once at a time. This is in contrast to local probes, which provide only local information. Since single probes, like one-point conductivity probes have been used by e.g. Menzel [1] or resistivity probes have been used by e.g. Idogawa et. al. [2] for the measurement of the radial void distribution in bubble columns.

The application of tomographic measurement techniques for process or chemical engineering applications is, in comparison to the medical sector, relatively new. Widely spread is the use

of electrical, x-ray or NMR tomographic techniques.

The advantage of x-ray tomography is its high spatial resolution. The time resolution varies depending on the used sensor system. Very fast and expensive systems can reach measurement times of 0.5 ms with a spatial resolution of 2 mm [3]. Most of the used systems have imaging times of several seconds or minutes and are therefore not applicable for investigations on instationary multiphase flows. Kumar et. al. [4] are doing measurements of the gas-hold up in bubble columns. Toye et. al. [5] investigate stationary flows in trickle bed reactors, measuring the liquid distribution on the packing. Sederman et. al [6] are using NMR for the imaging of the pore structure within packed beds. With the NMR technique the fields of density and velocity are measured simultaneously. The technique is restricted to non-metal materials due to the magnetic field used for the measurements. Hence this technique cannot be used for pressure vessels.

Electrical capacitance tomography (ECT) is used for the investigation of pulsing flow in trickle bed reactors by Reinecke et. al.[7]. Three phase flow was investigated by Johansen [8] using

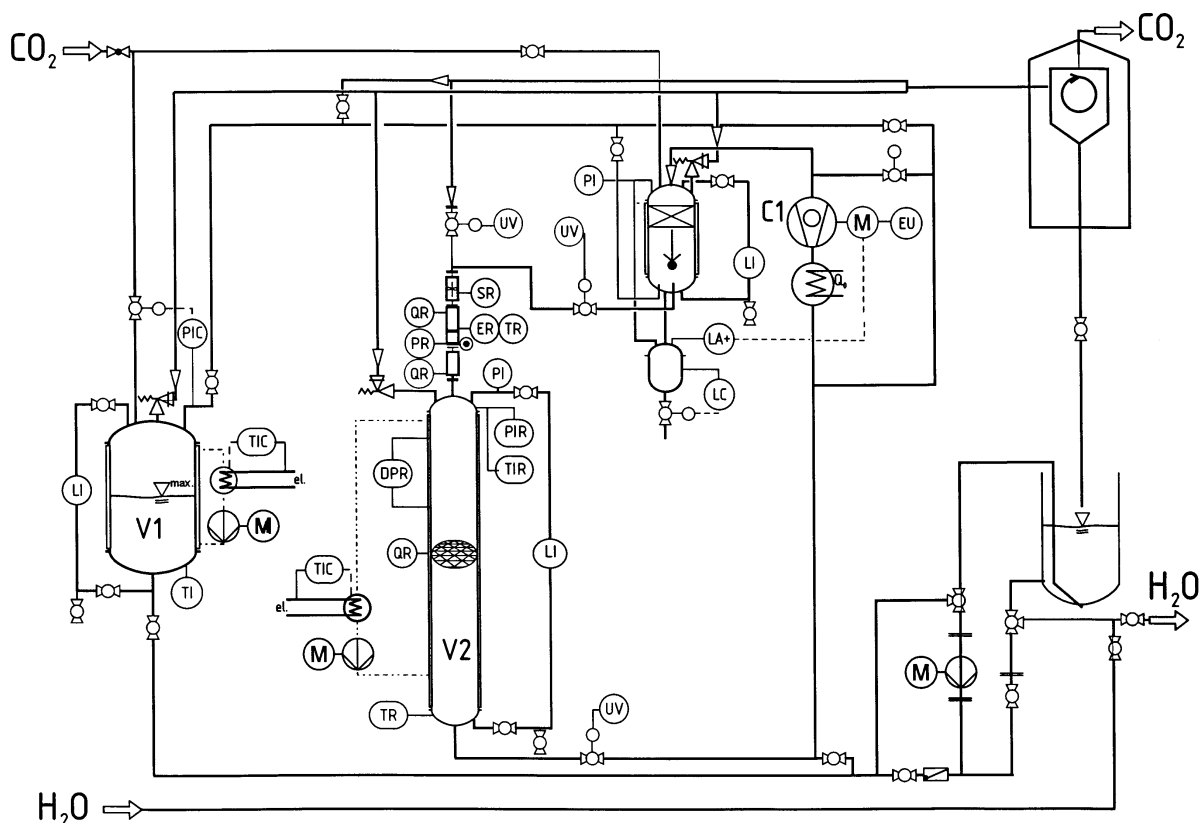


Figure 1: Flow sheet of the experimental set-up

mixtures of oil, water and gas. The results of Xie et. al. [9] are dealing with horizontal plug-flow. The time resolution for in these applications are in the range of 100 frames per second. The spatial resolution depending on the diameter of the pipe is about 10% of the cross sectional area. The tomographic measurement technique presented in this paper combines a high measurement frequency is with a high spatial resolution.

## 2. EXPERIMENTAL SET-UP

Figure 1 gives the flow sheet of experimental set up. It consists of two pressure vessels (V1,V2), which can be operated with pressures up to 1.6 MPa. They are built of stainless steel and are tempered by a double shell. For the experimental investigations the temperature is set to 10°C and the pressure to 0.9 MPa. In the first vessel V1, which has a volume of 300l, tap water is saturated with carbon-dioxide. This is done by the carbon-dioxide circulation. Carbon-dioxide is taken from the top of the vessel, separated from the liquid by a separator and

then compressed by the compressor C1. At the bottom of the vessel the gas is dispersed in the liquid phase. Due to the volume reduction the pressure inside the vessel is decreasing. To keep the pressure constant, carbon-dioxide is injected by a control loop. The liquid is saturated with carbon-dioxide. By weighing the carbon-dioxide supply bottle, the solved gas can be calculated.

In the next step the saturated liquid is pumped into the second vessel V2 which is shown in Figure 2. This vessel 2100 mm in height, and 315 mm in diameter has a volume of 160l. It is built from five cylindrical segments of different length. The tomographic sensor is built in the vessel at different heights.

In addition to the tomographic measurement of the void fraction, the axial profile of the gas holdup is measured by 10 differential pressure transducers mounted in equal distances from the bottom to the top of the column. The void fractions measured by the differential pressure transducers are compared to the void fractions measured by tomographic sensor.

The blowdown is started by opening the ball valve at the top of the vessel V2. The pressure in

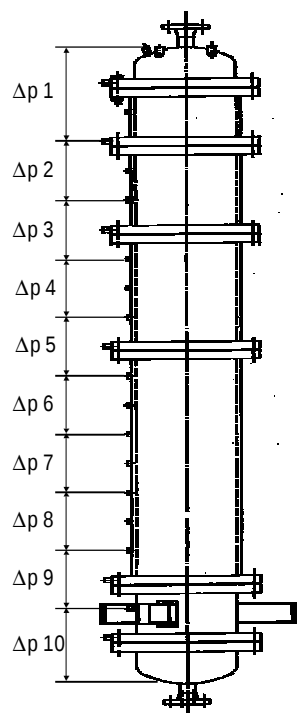


Figure 2: Technical drawing of vessel V2

the vessel V2 decreases rapidly and the liquid starts bubbling. The surface of the liquid rises and reaches the top of the vessel. A two phase flow through the blow-off pipe is established. It takes about one minute until the pressure reaches the ambient pressure. The time varies, depending on the viscosity and the level of the liquid at the beginning of the depressurization. The two phase flow is separated at the end of the blow-off pipe by a cyclone separator.

In addition to the void fractions the temperatures at the top and the bottom as well as the pressures at the top of the vessel are measured.

In a second experiment the ball valve at the top of the vessel is controlled by one of the differential pressure transducers to avoid the two phase flow in the vent-line. As a result the liquid remains in the vessel. The control-loop is given in Figure 3. If the two-phase flow reaches the maximum level in the vessel the ball valve is closed again. The pressure in the vessel increases again and the two phase flow mixture is collapsing. The ball valve is opened again when the two-phase flow mixture reaches the lower limit of the control mechanism. This is repeated until the pressure in the vessel reaches the ambient pressure.

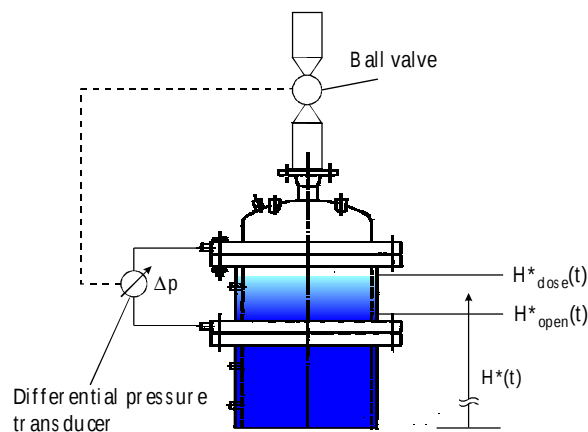


Figure 3: Control of the ball valve

### 3. TOMOGRAPHIC MEASUREMENT TECHNIQUE

For the measurement of the local void fractions a conductive tomographic measurement technique is used. The conductive tomographic measurement technique provides a spatial resolution of 5.3 mm and a time resolution of 100 measurements per second. The tomographic sensor consists, as depicted in Figure 4, of three planes of parallel wires with an axial distance of 7 mm. The inner diameter is set to 315 mm, which is equivalent to the vessel diameter. The sensor is made of stainless steel coated with plastics for electrical isolation. It is constructed for a maximum pressure of 1.6 MPa. The sensor elements are sealed with carbon gaskets. This allows a disassembly of the sensor in the case of any repair of the wires. The wires are made of stainless steel with a diameter of 0.18 mm and are spaced 5.3 mm to each other. In that way in every plane 59 wires are stretched across the sensor, resulting in 58 integral measurement values. The individual planes are rotated 120° to each other in such a way that 4722 isosceles triangles are obtained. Between two adjacent wires in one plane the conductance is measured, which is direct proportional to the void fraction in the area stretched by the wires.

From the measured conductance the void fraction of each triangle is calculated by using the ART-Algorithm. The computation is performed in an adapted coordinate system, as suggested by Reinecke et al. [10]. Details of the measurement technique are described by Reinecke et al. [11].

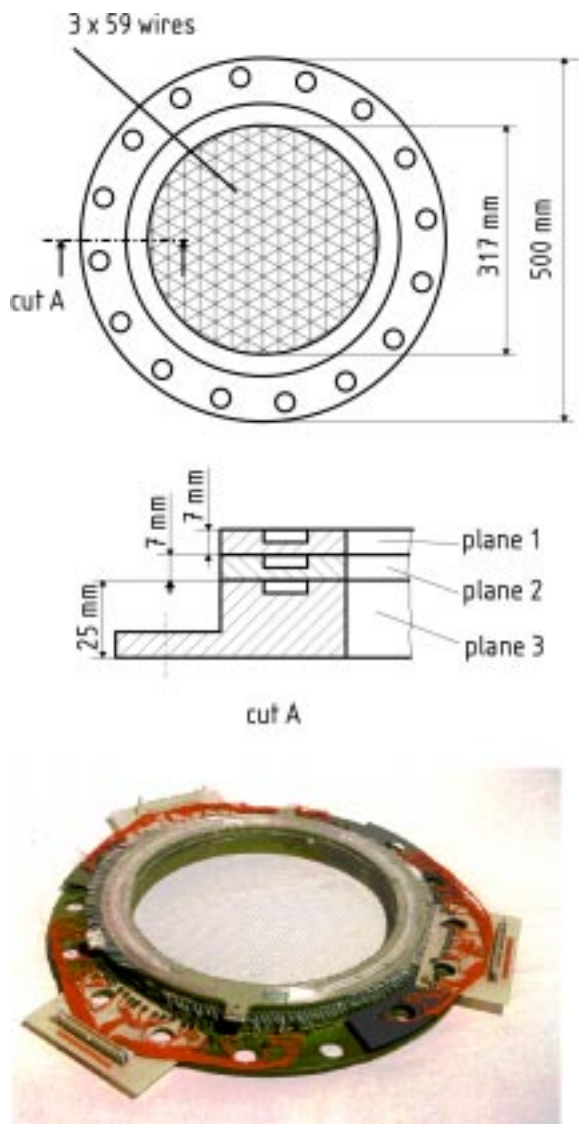


Figure 4: Technical drawing and depiction of the tomographic sensor

### 3.1 Measurement accuracy

The accuracy of the measurements taken by the tomographic sensor is verified in a separate test loop. It consists of a vertical acrylic pipe with an inner diameter of 123 mm and 2.5 m in length. A second tomographic sensor of the same construction regarding the distance of the wires is built into the test section at 1.3 m at height. This smaller sensor is built with 3x21 wires resulting in 60 integral measurement values and 522 reconstruction elements. The impact of the wires on the void distribution and the measurement accuracy is investigated in a

test loop by stationary bubbly flow. The gas flow rates are measured by a rotameter and are adjusted to a superficial gas velocities up to  $j_g = 0.3$  m/s to cover the flow regimes from bubble flow to churn turbulent flow.

| $j_g$ [m/s] | Tomographic sensor | Bed expansion |
|-------------|--------------------|---------------|
|             | $\epsilon_g$       | $\epsilon_g$  |
| 0.016       | 0.024              | 0.024         |
| 0.026       | 0.051              | 0.04          |
| 0.052       | 0.11               | 0.09          |
| 0.12        | 0.19               | 0.15          |
| 0.18        | 0.24               | 0.18          |
| 0.27        | 0.23               | 0.24          |

Table 1: Validation of the measured void fraction

The bubbles are generated by using a perforated plate distributor. The distributor is made out of a Perspex-plate with a thickness of 3 mm. In the plate 121 holes with a diameter of 1 mm are arranged on 6 concentric circles. In all investigations the static liquid height to diameter ratio was set above eight. Therefore so that the bed height was of negligible influence on the flow regimes. The void fractions and the bed expansion are measured by the tomographic sensors. In table 1 the obtained volumetric void fraction  $\epsilon_g = (V_c - V_l) / V_c$  for both measurements are given. The maximum deviation of the measured void fraction is about 25 %.

By visual observation it was recognized that the flow is not irrigated by the sensor. This has also been checked by comparing the volumetric void fraction of the three measurement planes. If bubbles are caught in any of the planes, the measured average gas holdups of the three planes would be different. This has not been observed during the experimental investigations.

## 4. EXPERIMENTAL RESULTS

In Figure 5 the pressure at the top of the vessel is plotted as a function of the time in dependence on the initial liquid level in the vessel. The pressure decreases faster if the liquid level is higher at the beginning of the depressurization. In all blowdown experiments a first minimum of the pressure occurs within the first five seconds. After the desolve retardation

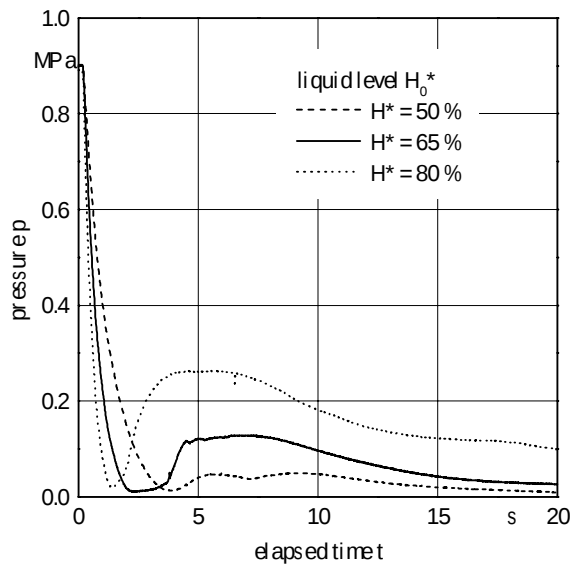


Figure 5: Pressure at the top of the column as a function of time

time of the carbon-dioxide the oversaturated liquid starts to swell. This results in an increase of the pressure in the vessel and finally in a two phase flow through the relief valve.

The tomographic sensor is located between the connections of the fifth differential pressure transducer connected to the vessel at 1052 mm.

In order to test the measurement accuracy of the tomographic sensor the measured void fractions are compared to the void fractions measured by the differential pressure transducers. In Figure 6 both measurements are plotted as a function of time. The measured values match each other qualitatively as well as quantitatively. The increase of the volumetric gas-holdup after 2 s corresponds with the minimum of the pressure inside the vessel. The

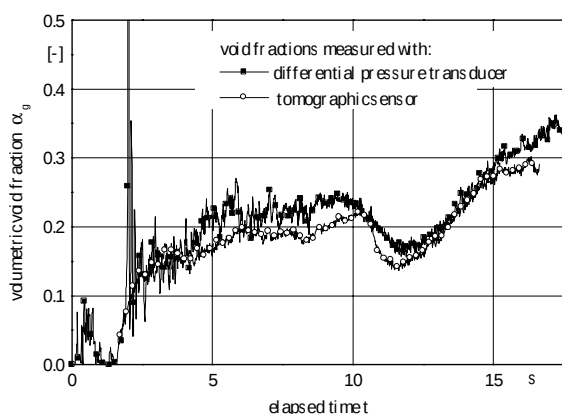


Figure 6: Comparison of the volumetric void fraction measured with the differential pressure transducer and the tomographic sensor

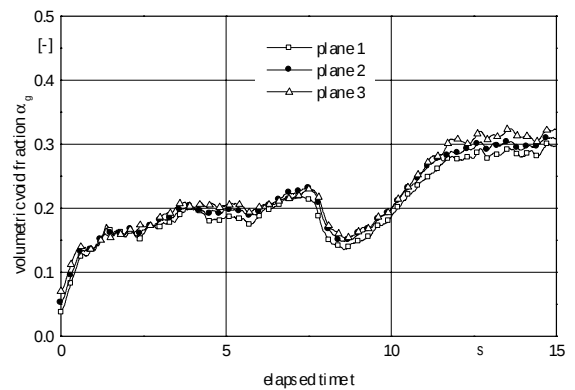


Figure 7: Comparison of the volumetric void fraction measure in three different measurement planes

gas holdup reaches approximately 20 % and is constant for the next 7 s. The maximum of the gas-holdup of 30 % is reached after 16 s.

In Figure 7 the integral volumetric void fraction for each of the three measured cross sections is given. The results for all void fractions measured agree quite well. This conforms with the assumption that the wires of the sensor are of no influence on the two phase flow.

The void fraction distribution in the cross sectional area of the column is given as a result of the tomographic measurements in Figure 8. On the left side the integral measurement value of each projection is shown. The void fraction is scaled according to the table on the right side. The time scale starts at the top. The measurement frequency is 100 frames per

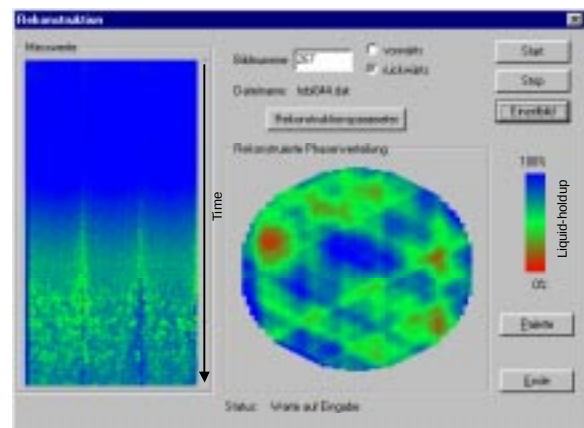


Figure 8: Result of the tomographic reconstruction

second. Beside the results from the integral measurements a tomogram is given at the right side. The tomogram is measured approximately 8 s after the starting of the blowdown. The level of the liquid is located at beginning of the blowdown at 65 % of the vessel height.

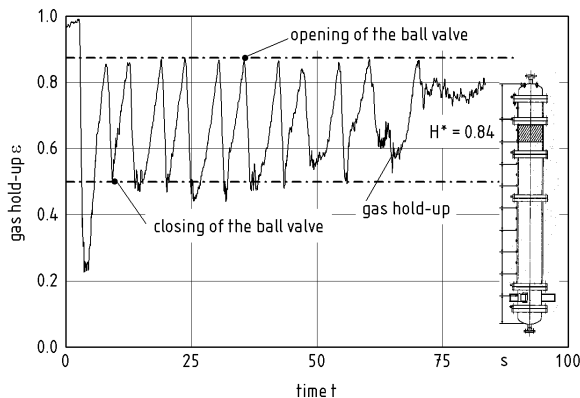


Figure 9: Gas holdup as function of time for the control loop of the ball valve

After 2.5 s the carbon-dioxide starts to desorb, as indicated by the change of the colors from blue to green. First the gas-holdup rises at the  $\omega$  wall of the vessel. The bubbles are generated merely at the wall due to the coarse

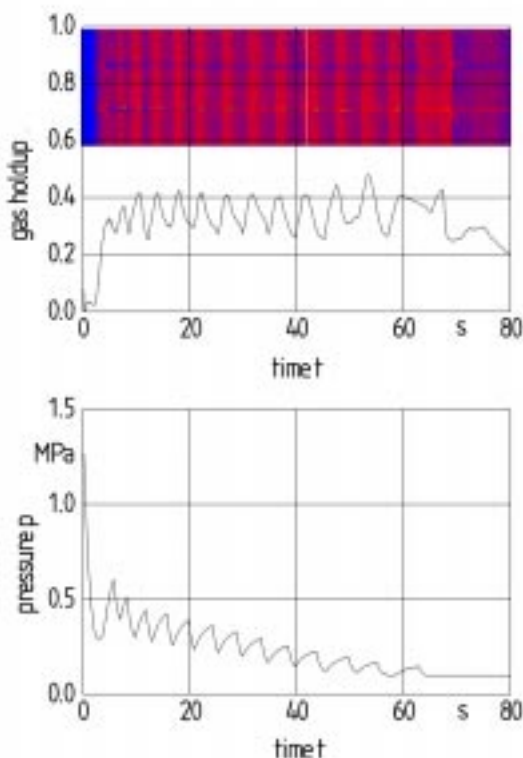


Figure 10: Gas holdup and pressure as a function of time

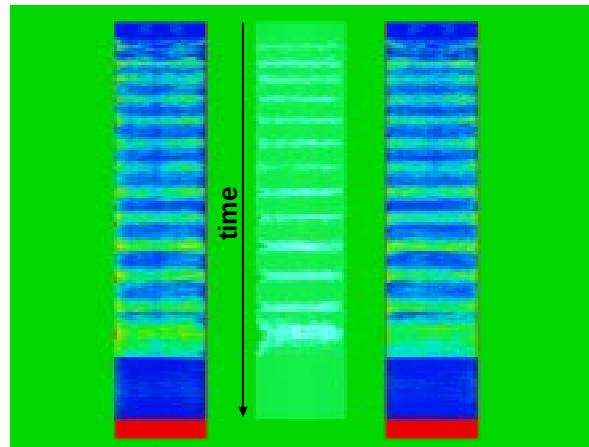


Figure 11: 3-dimensional representation of the tomographic measurement

surface. By selective undercooling of the wall section, the production of bubble nuclei can be reduced. More and more the void distribution becomes inhomogeneous. Areas with a high gas-holdup can be distinguished from others with a low gas-holdup.

To avoid the two-phase flow through the ventline a controlled pressure relief is conducted in addition. As described above the ball valve is controlled by one of the differential pressure transducers. In Figure 9 the gas holdup measured with the second pressure transducer is given. At the beginning of the measurement the ball valve is opened and the liquid level rises. As the gas hold holdup reaches the lower limit the ball valve is closed again. The gas holdup increases due to the rising pressure and the separating of the gas and the liquid in the column. With this control mechanism the liquid remains in the vessel. In figure 10 the gas holdup as well as the pressure in the vessel is given as a function of time. The gas holdup is measured with the tomographic sensor. During the experiment the ball valve is opened and closed sequentially which results in the given pressure curve. The ball valve is closed 13 times in total. The time of the controlled pressure relief is with approximately 70s equivalent to the time for the continuous pressure relief. The gas holdup during the experiment is oscillating between 25% and 40%.

In Figure 11 the result of the tomographic measurement is given as a 3-dimensional picture. The time starts at the top of the picture. In the middle of the picture a isosurface of the gas holdup is given. In addition two orthogonal

slicers are shown. In the slicer the changes of the gas holdup during the pressure relief are visible.

## 5. CONCLUSIONS

Electrical tomography is applicable for the measurement of the phase distribution during the blowdown of a pressurized vessel. Due to the high time resolution it is possible to measure the alteration of the void fraction during the pressure relief process. The sensor is mounted to different axial positions in the column in order to get the void fraction distribution in axial direction. The experimental data help to conduct further numerical modeling of the blowdown process.

## ACKNOWLEDGMENTS

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