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Velocity measurement for two-phase flows based on ultrafast X-ray tomography

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A B S T R A C T

The ultrafast electron beam X-ray tomography scanner ROFEX is used for the investigation of multiphase flows. Its functional principle allows us to obtain sequences of cross-sectional flow images, which shows local attenuation properties of the flow. Hence, the X-ray CT images mainly reveal the shape and interfaces of flow constituents, such as gas, liquid and solids via their X-ray contrast. It is, however, more difficult to obtain velocity information from multiphase flows. In this article we discuss different methods to extract information on the velocities of particles or interfaces as well as for continuous phase. For disperse phase velocity measurement, e.g. in gas–liquid or gas–solids flows, we employ cross-correlation based techniques using two imaging planes. Apart from the standard cross-correlation technique we developed a method and algorithm, which is capable to identify identical bubbles in the two planes giving us a unique Lagrangian particle-related velocity information. Eventually we give an example of velocity measurement in the continuous liquid phase using an X-ray contrast agent.

1. Introduction

Multiphase flows occur in many industrial processes and hence are an everlasting target of scientific investigation. Examples are multiphase flows in chemical reactors, thermal hydraulic circuits of nuclear power reactors or pipelines and equipment in the oil and gas industry. In all these applications the flow physics and interaction of phases with each other have to be understood. An important scientific objective is to develop mathematical models and numerical tools to describe and simulate such flows. Such multiphase CFD codes require closure relations for momentum, heat and mass transfer, which have to be obtained from experiments. Moreover such codes require constant evaluation, due to their complexity and potential problems with special simulation scenarios.

Two-phase flow of gas and liquid in a pipe or column is a simple but yet not fully tractable problem of computational fluid dynamics. High accuracy experimental data from such flows are needed for CFD benchmark exercises. One set of data that is required regards the gas phase parameters, such as gas hold-up profiles, and bubble sizes and shapes. Another set of parameters regards the interface dynamics, such as bubble deformation or interfacial waves. A third set of required parameters is velocity information, both from the continuous phase(s), like liquid mean velocities and fluctuations (turbulence), and the disperse phase(s), like bubble or droplet velocities and their trajectories.

Recently, advances have been made in fast imaging techniques for multiphase flows, which help to obtain phase distribution parameters [1]. One example is ultrafast X-ray tomography [2], another one is magnetic resonance imaging [3], a third one is electrical tomography [4] and a fourth one fast gamma ray tomography [5]. With the exception of MRI none of these techniques can readily measure continuous phase velocities, while all of these methods can to some degree measure disperse phase velocities. Continuous phase velocity measurements are well known from single phase flows. One method is Particle Image Velocimetry (PIV). It provides velocity information with high spatial and temporal resolution [6] but needs optical access to the flow, which is in some cases impracticable. In addition, seeding particles for scattering the laser light have to be added to the flow. Measurements in flow channels with internals are likewise difficult. For the latter, index-matched fluids may be used [7]. In two-phase flows total light reflection at gas–liquid interfaces, such as bubbles, pose problems both regarding coverage of the field of view as well as protection of the camera. In such cases, LIF techniques with fluorescent particles are helpful [8]. LDA acquires velocity information from Doppler shift between laser signal scattered on seeding particles in the flow and interfered reference laser beam [9]. It does not depend on flow parameters (e.g. temperature or density) and is therefore calibration free. However, all these

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velocity measurement techniques are clearly limited to gas fractions below 5%.

Another choice for velocity measurements in single phase flows is hot film anemometry [10]. It is a local and intrusive measurement technique. Hence it somewhat disturbs the flow and provides a single finite sampling volume only. Temporal resolution is, however, very high, with 1–100 kHz. It is therefore suited to measure continuous phase turbulence.

Measuring disperse phase velocities in two-phase flows can be done by applying cross-correlation techniques. The principle is to detect structural similarities in two measured time-series and determine a velocity from the given spatial displacement of the sensors and the correlated temporal displacement of the signal structures. This principle has been, e.g., applied by Kim et al. [11] together with double-tip and four-tip needle probes in gas/liquid flows. Wire mesh sensors, which are minimally intrusive imaging sensors, were also qualified for velocity measurements. For this purpose two wire mesh sensors are placed in sequence in the flow and images are then cross-correlated point-wise [12]. A similar approach is used with electrical tomography sensors.

Ultrafast X-ray tomography offers new capabilities for obtaining velocity information from single and two-phase flows. By virtue of its functional principle a non-intrusive flow capturing is possible and optical access to the flow is no longer needed. From image data based on X-ray attenuation velocities can be computed as time-averages as well as in a time-resolved way. A major advantage over sensor probe techniques is its applicability to flows with solid constituents, such as in fluidized beds or to flow channels with internals. However, some effort has to be spent on the computational analysis of thousands of CT images, as will be described below. In this paper, different analysis techniques are discussed. Based on the well-known cross-correlation technique, which gives the most probable velocity in a signal time series, a time-resolved approach is suggested and optimised for ultrafast X-ray tomography. It is able to reveal temporary flow field phenomena, like recirculation zones in the vicinity of bubbles. Further on, an algorithm for determination of single bubble velocities is described. The cross-correlation method is further demonstrated on a gas-particle flow. Eventually, we show how a contrast agent can be used to obtain continuous-phase velocity fields

2. Ultrafast X-ray CT Scanner ROFEX

The ultrafast electron beam X-ray tomography scanner ROFEX was developed at HZDR for non-invasive imaging of two-phase flows with very high temporal and spatial resolution. The system utilises a free electron beam, which is deflected by means of electron optics on a semi-circular target surrounding the investigated object. Thus, a very fast rotating X-ray source is generated. The radiation is attenuated while passing the object and recorded by a fast static multichannel detector. From the recorded projection data of each revolution of the beam one cross-sectional image is reconstructed by a filtered back projection algorithm [13]. For further details see Refs. [2] and [14]. The resulting image sequence may then be further analysed with respect to spatial phase distribution and secondary flow parameters. Recently, the scanner was extended for the investigation of larger objects up to 195 mm diameter and for dual-plane CT with two focal spot paths on the target and two corresponding detector rings. Thus, projection data sets from both imaging planes can be alternately acquired. The imaging planes have an axial distance of 13 mm. The static double ring detector comprises 432 pixels at each ring. In dual-plane imaging mode the maximum temporal resolution of the ROFEX scanner is thus halved to 4000 fps since the dual-plane scanning is time multiplexed. The spatial resolution is 1 mm under best conditions and depends somewhat on the X-ray attenuation of the object. X-ray energy is 150 keV with a maximum beam power of 10 kW. Fig. 1 shows the working principle and photographs of the ROFEX II set-up.

3. Velocity information extraction from fast X-ray CT image sequences

3.1. Dispersed phase velocity measurement in two-phase pipe flow using cross-correlation

3.1.1. Method

Very generally spoken, the cross-correlation method is based on the statistical analysis of the time-of-flight of markers in a flow or moving object. For us, that is for multiphase flow applications, these are similar interfacial structures in the flowing mixtures. Assume, two sensors arranged at axial distance L in flow direction are producing signal time series $S_1(t)$ and $S_2(t)$ the time-of-flight τ_m of a flow structure passing both sensors consecutively is a measure of velocity as

$$v = \frac{L}{\tau_m}. \quad (1)$$

In ultrafast X-ray CT the sensors are represented by the two CT planes A and B with axial offset L_{AB} and the signal may be any

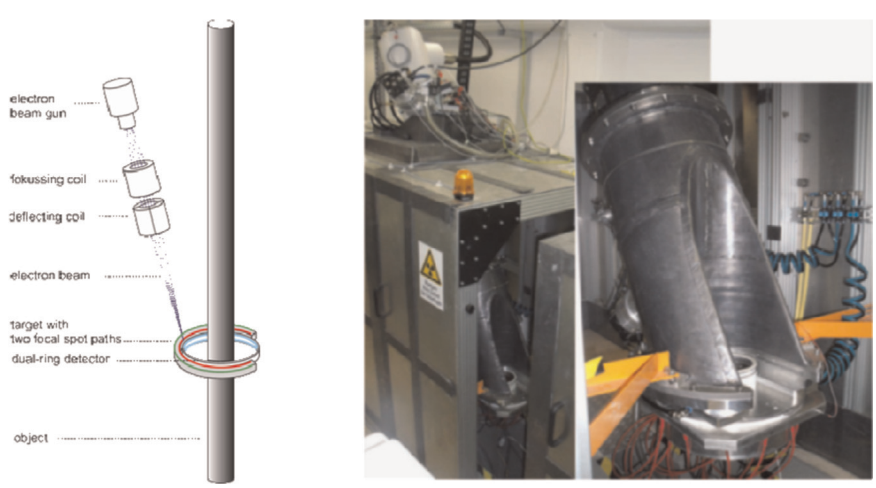

Fig. 1. ROFEX CT system. Principle (left) and photographs of ROFEX II scanner (right).

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