ICLASS 2003, Sorento Italien

A SENSOR BASED TECHNIQUE FOR MULTI-PHASE SPRAY ANALSIS AT HIGH LOADS

Dipl. -Ing. Frank Landwehr*
Dr. -Ing. Helmut Wiggers*
Prof. Dr. techn. Peter Walzel**

Abstract

The analysis of complex multiphase flow is investigated for several years. Many different techniques are known for observing of the phase distribution, particle size, velocity distribution and the chemical composition of multiphase flows. The most common techniques are ultrasonic, conductance, tomography and for low particle loads, the laser based Doppler Aneometry (LDA) and Laser phase Doppler Aneometry (LPDA).

All techniques have some limitations in the maximum fluid load or spray density. Especially in the case of LDA or LPDA the data rely on to spherical particles or droplets, no phase recognition is possible and the resolution in time or space is low. To avoid these disadvantages we have developed a sensor array, based on glass or plastic (PMMA) fibres which are directly placed inside the multiphase flow. By using the FRESNEL effect it is possible to measure the refractive index at the surface of the sensor tip. An array of 400 sensors allows the calculation of the refractive index distribution in a two dimensional cut of the multiphase flow. As the refractive index depends on the chemical composition it is possible to visualize chemical reactions, in a pipe reactor or the temperature distribution for a single component.

Theory

The main concept of our new measuring technique is the use of a glass or plastic fibre for the sensor which is transmitter and receiver at the same time. A bending coupler is used for simultaneous incoupleing of a flat laser beam in up to 650 fibres. Moreover the bending coupler takes the part of a beam splitter (see fig. 1). The free tips of the fibres are polished under the Brewster angle for the given fibre material.

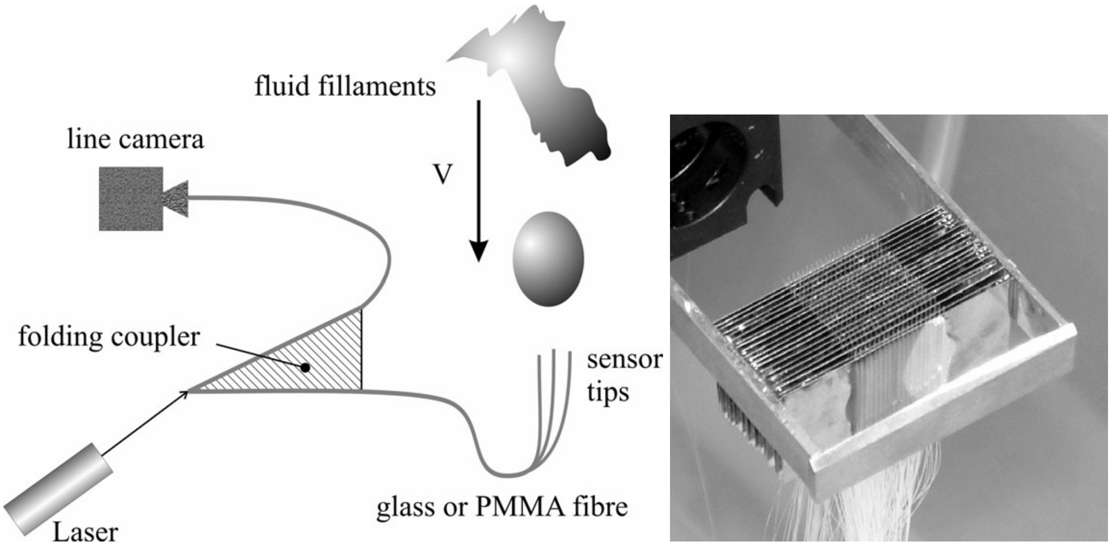

Fig.1: Sketch of a fibre sensor and a photo of an array with 400 sensors.

When a drop or fluid element impinge on the sensor, the outcoupleing efficiency in- or decrease in depending on the refractive index of the fluid in contact with the sensor tip. For a given refractive index of the fibre material the signal intensity can be calculated by the Fresnel equation.

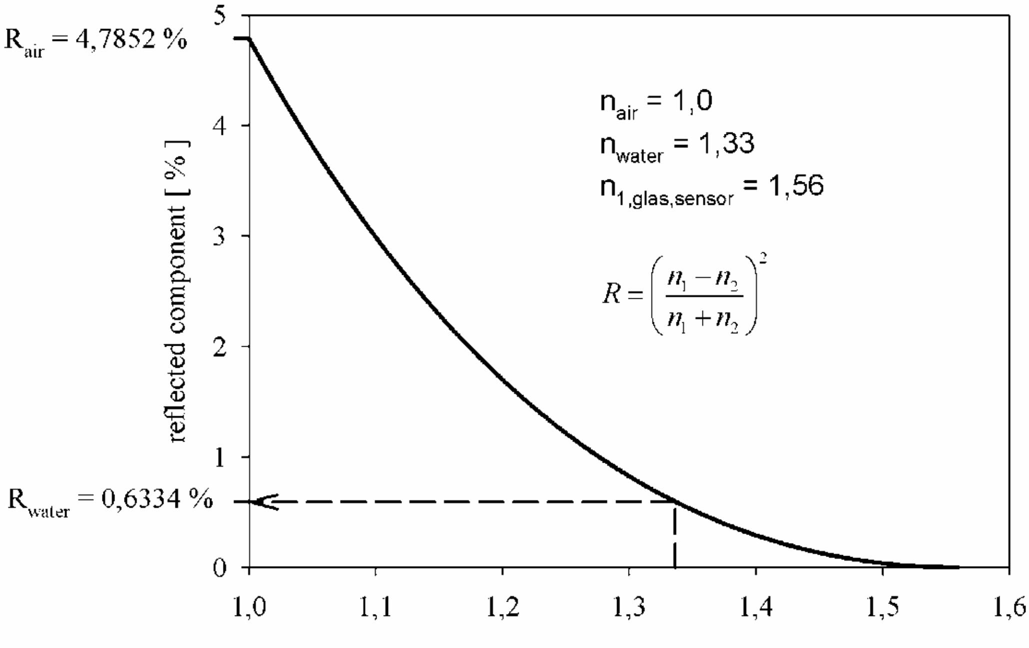

Fig.2: Theoretical signal intensity as a function of the surrounding refractive index at PMMA fibres.

Figure 2 shows the intensity distribution as a function of the refractive index of the medium touching the sensor tip. Each sensor of an array reads the absolute refractive index. To calibrate the sensor, it is necessary to measure the refractive index of two

standards, pure water (n = 1,33) and air (n = 1) at 20°C. After calibration the sensor array directly measures the refractive index distribution in a two dimensional sheet.
When the surface of the drop or a liquid filament oscillates, the reflected and recoupled laser light is modulated in its intensity. The modulation frequencies are the same as the oscillation frequency of the drop or filament and its harmonics.

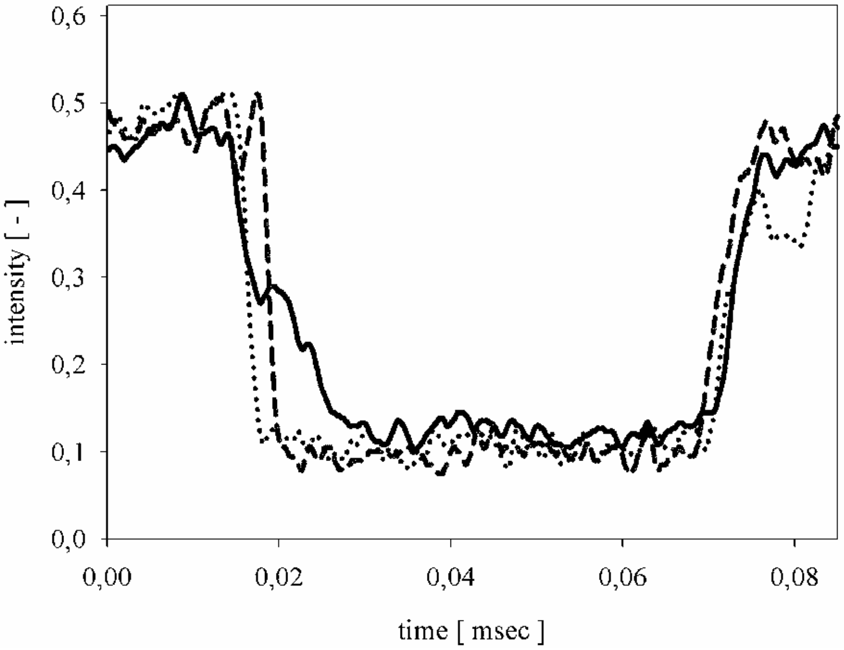

Fig.3: Signal of a crossing water jet.

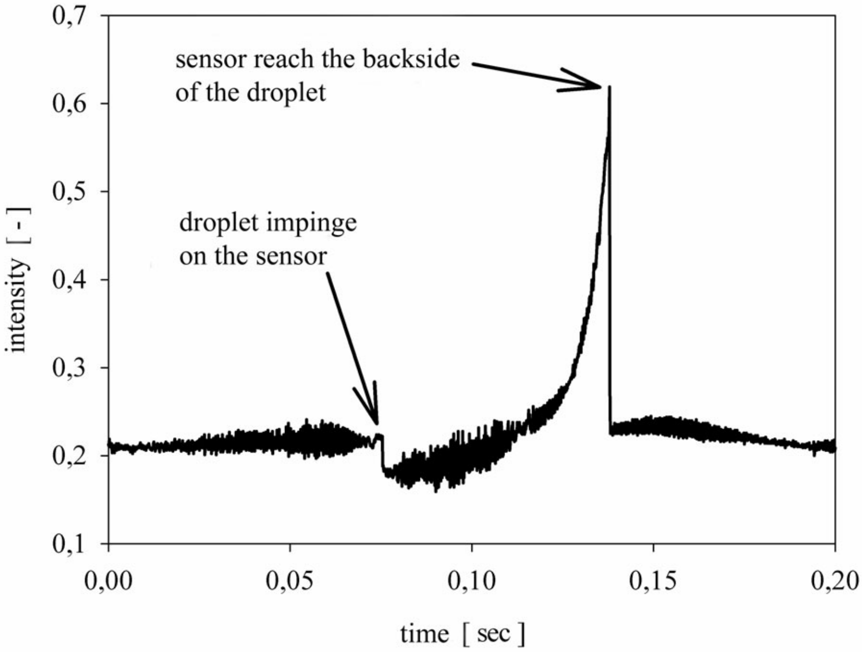

Fig.4: Signal of a droplet giving rise to an optical resonance field and an oscillating surface.

The frequency analysis of the intensity modulated drop or jet signal shows a characteristic spectrum for each filament diameter. In these cases it is possible to calculate the filament size by a comparison of the measured and the expected eigen frequency spectrum.

The theoretical spectra are calculated with a numerical simulation. This simulation is based on a given and known diameter and also known physical properties. For the mathematical description of the drop oscillation the theory of Becker is used. This model contains the viscous and surface tension effect on the oscillation frequency, amplitude and the decay of the drop oscillation. This complex and quite complete theory shows a good agreement with our measured frequency spectrum.

The simulation starts with an oscillating drop generated by a dripping process. At the beginning the optical sensor is near to the surface on the inner site of the drop. In the first time step a Gaussian laser beam is leaving the mathematically described glass fibre and produce an optical field inside the drop. By using a trace algorithm, the inner optical field is calculated by neglecting the interference.

The intensity of the reflected laser light is a function of the drop geometry, the position of the sensor inside the drop and the oscillation of the free surface. The mean intensity of the reflected light increases during its approximation to the back of the droplet. The intensity and the modulation - depth of the reflected laser light decreases, because of the decrease of the inner field. In the case of laminar water jets the Weber equation is used to calculate the frequency spectrum.

By this method not only the local refractive index can be detected but also the propagation velocity of refractive index gradients and of phase boundaries. The measurement of the phase surface propagation velocity of any geometry or of a concentration gradient is obtained by double sensors. These double sensors exist of two fibres with a distance between their tips of 1 mm in flow direction. The free surface propagation velocity can then calculated by the known distance between the fibre tips and the time offset of the sensor signals.

Evaluation

To examine this method the refractive index was measured with single sensors and an array. After calibration of each sensor within the array, it is possible to measure the real refractive index distribution which is necessary to obtain more accurate information on chemical reactions or temperature fields.

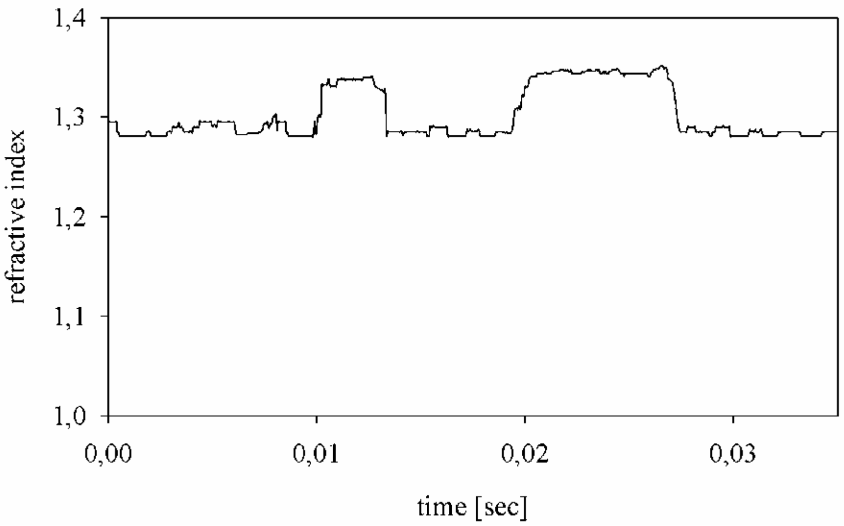

Fig.5. Refractive index distribution, measured with one sensor in the centre of the spray which is shown in Fig.6.

The refractive index is calculated by the Fresnel quotation and a correction factor for each sensor which is measured during the calibration. The results were compared by a reference measurement of an Abbe refractometer which shows a difference of 2% to the array measurement.

The visualisation of the phase distribution does not need any mathematical filter processes. The raw sensor data shows the refractive index distribution in a two-dimensional sheet. By using the calibration matrix on the raw data of an array measurement the real refractive index distribution can be visualized.

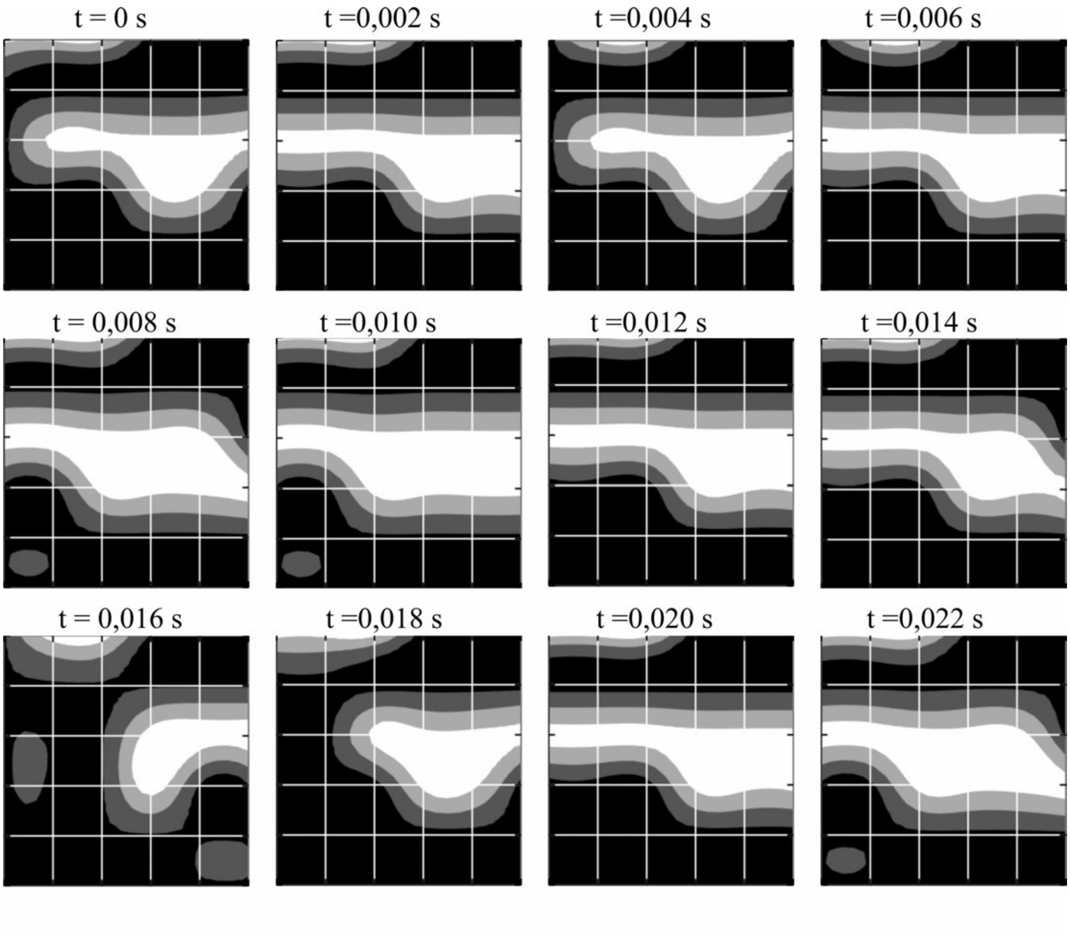

Fig.6. Phase distribution of a cut through a turbulent jet. White areas mean water (high refractive index) and black areas mean air or gas (low refractive index). The white matrix lines show the position of every fourth sensor.

The measurement of the surface frequency of a droplet or a liquid filament implies low signal intensities. To analyse these signals they have to be filtered computationally. The denoising of the signal is done by a combination of wavelet - filtering / wavelet - reconstruction combined with a kind of Finger Print algorithm. In the first step the complete measured signal is wavelet - reconstructed and wavelet - filtered. A result of the wavelet – reconstruction and filtering is a matrix of used wavelets, wavelet coefficients and validity intervals.

A Finger Print algorithm analyses a part of the signal which contains only a frequency analysis of the denoised signal shows the oscillation modes of the contacted fluid element. When the physical properties are known the drop diameter can be calculated. For this, relationships e.g. by Bauer and Becker [2,5,8] are used, which can be applied as long as surface amplitudes are small compared to the drop diameter. The drop diameter and mode of oscillation are results of a parameter fit between the two spectrums or of a cross correlation between theoretical and measured frequency spectrum.

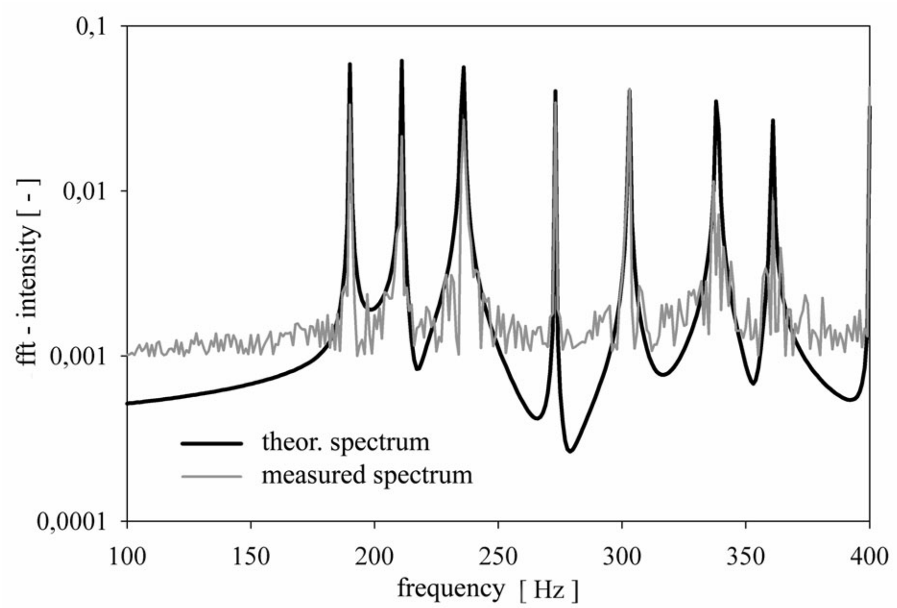

Fig.7. Frequency spectrums of theoretical and measured surface oscillation of drops.

Experiments were carried out with drops of a diameter from d=0.4mm up to d=3mm. A high speed CCD camera was used for direct optical control and comparison with our sensor reading. Because of the drop oscillation the diameter of 9 pictures of one drop were used to calculate the mean diameter.

Conclusion

A new measuring technique for phase detection was designed that has no limits in fluid concentration or load. Additional to the phase distribution the velocity and refractive index distribution can be measured. In the case of a single phase fluid it is possible to calculate the temperature of the fluids by measuring the refractive index. A sensor array of 400 fibre sensors was built with a fibre to fibre distance of 1 mm, a fibre diameter of 0.125 mm and a sampling frequency of 80 kHz. So a real time measurement of any multiphase flow is possible with a high resolution in place and time.

By using advanced filtering techniques its possible to resolve the surface oscillation of fluid filaments and especially of drops or bubbles. It was shown that this information and the knowledge of the chemical composition of both fluids are sufficient to calculate drop and fluid - jet diameters for a single drop at spraying jets with high load.

It is planed to integrate the fibre sensors in static mixers to measure the effectiveness of mixing. Another project is the measuring of the solid particle distribution in vibration conveyer.

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