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PIV IN MULTIPHASE FLOW

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ABSTRACT

PIV can be a useful tool for the investigation of multiphase flow problems. Different from single-phase flow applications, a number of technical problems arise, e.g. due to high concentrations of the dispersed phases and the need of separating the signals originating from different phases. Specific techniques providing solutions for these problems are reported in this paper.

INTRODUCTION

Particle image velocimetry (PIV) is an ideal tool for measuring the velocity distribution of dispersed particles in multiphase flow systems. Applications reported in the literature include the measurement of droplets in a spray jet (Brandt and Merzkirch, 1994), bubbles transported in water (Hassan et al., 1992), cavitation phenomena (Tassin et al., 1995), fluid mechanics of multiphase mixing (Torii and Yang, 1992; Song et al., 1996), flotation of hardcoal (Zachos et al., 1993), entrainment of bubbles by a vortex (Sridhar and Katz, 1995). For determining the velocity of the continuous phase it is necessary to seed this phase by tracer particles. The question has been raised many times on how accurately the tracers will follow the motion of the fluid, here: the continuous phase, and a number of quantitative answers have been given for this problem (see, e.g., Mei, 1996). This question is not relevant for particles dispersed in a continuous phase, if the intention is to measure the velocity of the dispersed phases.

In applying PIV to multiphase flow systems one might encounter special problems that do not exist in single phase flow. Two of such problems that may occur and technical means for their solution are discussed in this paper. We always refer here to 2D PIV with the illumination provided in form of a thin laser light sheet. One problem arises at high values of the concentration of the dispersed phase. This can cause a strong attenuation of the laser light, so that the penetration length of the light sheet into the flow system is limited. Lowering the dispersed phase concentration might lead to concentration values which are not realistic for the prolem to be investigated.

The second problem to be discussed originates from a difference in the velocity distributions of the continuous and dispersed phase. If we evaluate the PIV recording in a conventional way, e.g. with a correlation technique, then the resulting velocity value will be affected by the signals from the two (or more) different phases, i.e., it is some average of two (or more) different velocities. We shall therefore discuss possibilities of separating the signals arising from the individual phases, so that phase-separated velocity distributions can be determined. In this context we also present a method that allows particle tracking even in the case of high particle concentrations.

PIV MEASUREMENTS AT HIGH CONCENTRATION OF THE SOLID PHASE

The particles present in the light sheet scatter light that is recorded by the camera of the PIV system. The intensity in the sheet decreases in the direction of laser light propagation according to the amount of light scattered by the particles. This extinction effect often is negligible at low seeding rates and with very small tracer particles. But with higher concentration of the solid phase in a multiple phase flow, the extinction can cause an undesired inhomogeneous intensity of the light sheet, or even limit the penetration depth of the laser sheet into the flow.

Zachos et al. (1996) report on a technique based on refractive index matching with which it was possible to perform PIV measurements in studying coal flotation processes at realistic values of the solid phase concentration. Instead of using coal and mineral, the solid phase was modelled by glass spheres whose mass density is not much different from that of the minerals usually present in flotation processes. For the liquid phase, in the real case water, tetraline (C_{10} H_{12}) was chosen as the main component; is only disadvantage is ist bad smell. The refractive index of tetraline, n_{te} = 1.540,, n_{te} = 1.540, is slightly higher than that of glass, n_{gl} = 1.513 and for adjusting this value, tetraline was mixed with „coal oil“ (n_{co} = 1.480) for making the refractive indices of the two phases equal. It turned out that, though the refractive indices were equal, light from the laser sheet was still scattered in sideward direction, most probably due to surface imperfections of the glass spheres. This residual scattered intensity was sufficient to allow PIV measurements of the solid phase velocity distribution.

A similar refractive index matching technique for matching the solid phase in PIV studies has been described by Cui and Adrian (1997), and it should be mentioned that the same approach is also known for LDA experiments (see, e.g., Liu et al. (1990).

TRACKING ENSEMBLES OF PARTICLE IMAGES AT HIGH PARTICLE CONCENTRATION

It is knowm that evaluation of PIV recordings by tracking single particles is limited to low or moderate particle concentrations (see, e.g. Adrian 1991). Gui and Merzkirch (1996a) describe a method with which the evaluation by tracking is extended to higher values of the particle concentration as it may occur in multiphase flow. Instead of sigle particles, ensembles of particles or „patterns“ are tracked. This method („minimum quadratic difference“ (MQD) technique) is a least-squares algorithm that determines the degree of similarity of two matrices whose elements are the digital gray values $g_1(i,j)$, $g_2(i,j)$ of the pixels in a „pattern“ or interrogation window of size M x N pixels. It is necessary to determine the minimum of the quadratic difference

$$D(m,n) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left[g_1(i,j) - g_2(i+m,j+n)\right]^2 \qquad (1)$$

in varying (m,n); see Fig. 1. If the minimum $D_{min}(m^*,n^*)$ is found, then (m*,n*) is the displacement experienced by the considered ensemble of particle images during the time interval Δt. The respective velocity vector is assigned to the center (or center of gravity) of the „pattern“, as it is usually done with correlation methods when applied to interrogation windows.

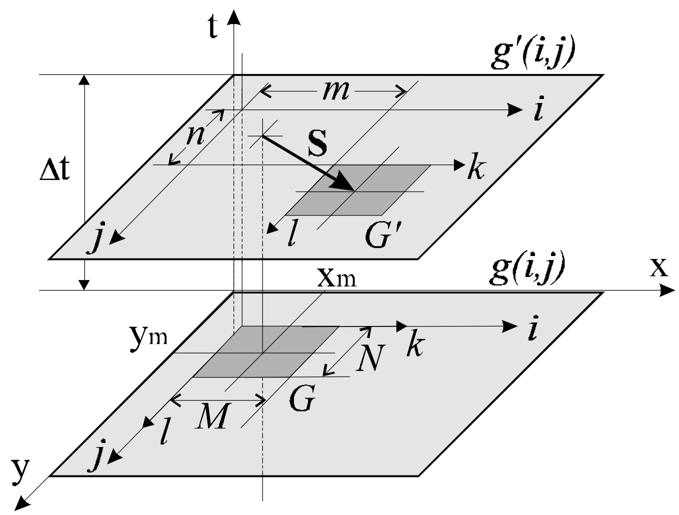

Fig. 1: Interrogation windows or „patterns“ used for the MQD method.

This method can be applied to both PIV double exposures and consecutive singlel exposures which are traditionally evaluated by autocorrelation or cross-correlation techniques, respectively. It can be shown (Gui and Merzkirch, 1996a) that the accuracy is at least equal to that attained with correlation methods when the particles are uniformly illuminated and evenly distributed in the flow, and even better if these conditions are not fulfilled, like it is the case in many experimental situations. Examples reported in the paper by Gui and Merzkirch give evidence of the obtainable measurement accuracy.

Separation of signals originating from different phases

If one takes PIV recordings in a two-phase flow, e.g. liquid/solid with the liquid (continuous) phase seeded with small tracer particles, the measured velocity is an average of the signals originating from the two phases, provided that both solid (dispersed) and tracer particle images are present in the interrogation window. This averaging is of not a problem if the two phases have the same velocity; but it can result in irrelevant values if there is a velocity difference between the two phases. A technique for distinguishing between the two different signals by using fluorescent tracer particles has been described extensively in the literature (Hassan et al., 1993; Sridhar and Katz 1995; Hilgers et al., 1995). The fluorescent tracers, in our example, scatter the light at a wavelength different from that scattered by the „neutral“ solid particles. The technique requires either the use of a recording in color with subsequent differentiation of the signals by image processing, or the application of optical filters, chosen according to the wavelength of fluorescence, in front of a black-and-white camera.

A different way for separating the signals has been described by Gui and Merzkirch (1996b). This procedure based on the use of a digital mask technique is applicable when the particles of the two phases exhibit a significant difference in their size distribution. The mass Δ(i,j) superimposed to the M x N pixels of an interrogation window (or „pattern“) is defined such that

$$\Delta(i,j) = \begin{cases} 0 & \text{if pixel } (i,j) \text{ belongs to phase A} \\ 1 & \text{if pixel } (i,j) \text{ belongs to phase B} \end{cases}$$

A threshold must be chosen for separating the two size classes of phases A and B. The mask technique is described here in combination with the MQD evaluation algorithm (see above) and with the assumption that two consecutive PIV single exposures are to be evaluated.

The gray values of the pixels in the interrogation windows („patterns“) of the first and second exposure are designated as g_1 and g_2, respectively. In order to determine only the velocity distribution of phase A (here assumed as the dispersed phase) a mask Δ_1(i,j) is superimposed to the pattern in the first exposure, in combination with eq. (1) resulting in

$$D_A(m,n) = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left[g_1(i,j)-g_2(i+m,j+n)\right]^2\left[1-\Delta_1(i,j)\right]}{\sum_{i=1}^{M}\sum_{j=1}^{N}\left[1-\Delta_1(i,j)\right]} \qquad (2)$$

The denominator on the right side is the sum of all pixels assigned to phase A. According to eq. (2) only the „pattern“ belonging to phase A is tracked, while the images of particles representing the continuous phase B in the first exposure are masked, i.e. removed from the investigated pattern.

This procedure is exemplified with the simulated PIV recordings shown in Fig. 2. The two recordings on the left and right side of Fig. 2a are two consecutive exposures taken at times t and t+Δt. The recordings include images of a great number of small tracer particles and the images of two big dispersed particles that move at a velocity different from that of the continuous phase. A pattern or window g_1(i, j) of quadratic shape is chosen. The evaluation of the unmasked patterns in Fig. 2a is dominated by the influence of the very big particles; the small tracer particle images only contribute a certain „noise“ so that the resulting velocity, as an average of the whole pattern, is slightly different from the velocity of the big particles. The phase mask is shown in Fig. 2b. The „noisy“ influence is removed in the masked patterns shown in Fig.2c, except for a few tracer particle images that partly overlap with the images of the big particles and thus are taken as being part of the big particle images.

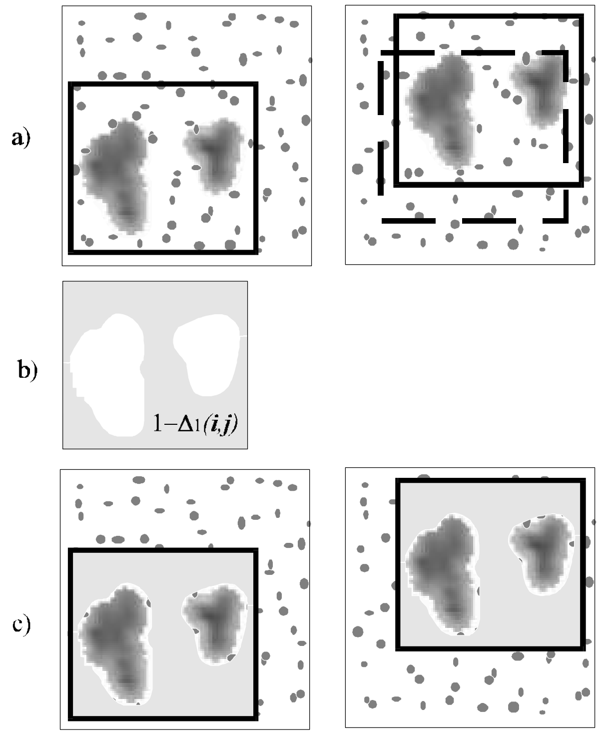

Fig. 2:Simulated PIV recordings of a two-phase flow with small tracer particle images and images of the big dispersed particles. Application of phase mask to the seeded continuous phase.

A modified form of the mask technique is used for determining the velocity of the continuous phase B. This is explained with the aid of Fig. 3 that presents the same simulated particle image patterns as shown in Fig. 2. Determining the minimum of the difference D_B for the continuous phase and simultaneously masking the dispersed particle images is done in several steps: First, a pattern (or window) g_1(i, j) is selected in the first exposure (Fig. 3a, left). The dispersed particle images included in this exposure are masked; this is described by Δ_1(i, j) which is only one portion of the total mask. The position of the pattern in the second exposure, g_2(i+m, j+n), is then varied (Fig. 3a, right), and a variable mask Δ_2(i+m, j+n) masking the dispersed particle images in the second exposure is defined for each position (m, n). The total mask Δ is composed of the two portions Δ_1, Δ_2: Δ = Δ_1(i, j) ·Δ_2(i+m, j+n) (Fig. 3b).

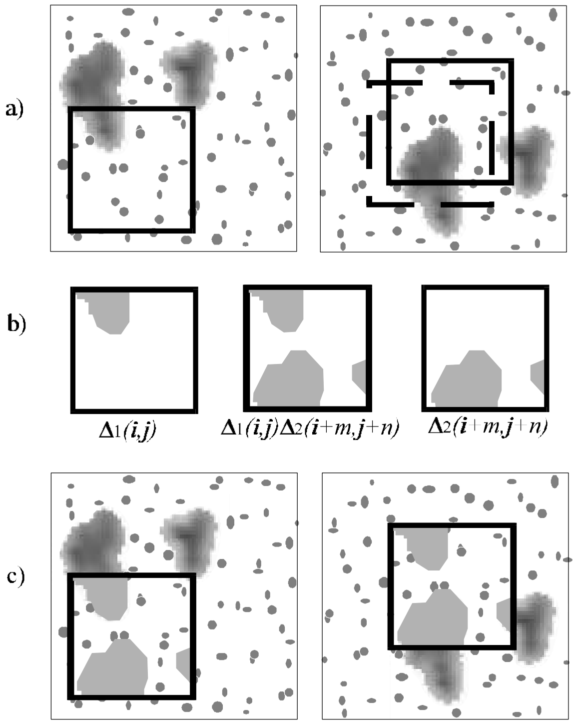

Fig. 3: The same simulated recordings as in Fig. 2. Application of the phase mask to the dispersed phase.

In this way, tracer particle images appearing in the first exposure that are obscured by the big particles in the second exposure (and vice versa) do not contribute to the formation of the difference D_B. The minimum of D_B is determined for the tracer particle image patterns in the unmasked areas as shown in Fig. 3c. The difference is thus described by

$$D_B(m,n) = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left[g_1(i,j)-g_2(i+m,j+n)\right]^2 \Delta_1(i,j)\Delta_2(i+m,j+n)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\Delta_1(i,j)\Delta_2(i+m,j+n)} \qquad (3)$$

From eqs. (2) and (3) follow the displacements (m^*_A, n^*_A) and (m^*_B, n^*_B) experienced by the particles of the dispersed and continuous phase, respectively, during the time interval Δt and at the position of the interrogation „pattern“ or window. This position assigned to the displacement or velocity must be determined separately for the two phases as the center of gravity of the particle images referring to phase A and phase B according to their distribution in the interrogation pattern.

The threshold value must be found from experience and knowldge of the individual experimental situation. I should be emphasized that this mask technique is more than just a size clasification by applying the threshold. In combination with the MQD technique, as here described, it is a phase-separation scheme of „higher order“.

Examples

Three examples for the application of PIV to multiphase flow situations are presented. The first example is a simulated case for which it is assumed that a number of big dispersed particles move in the seeded continuous phase with a significant difference in the velocity of the two phases, by both magnitude and direction. The two simulated successive PIV recordings are shown in Fig. 4. Evaluation of these two recordings by the conventional cross-correlation algorithm and without distinction of the phase signals must result in

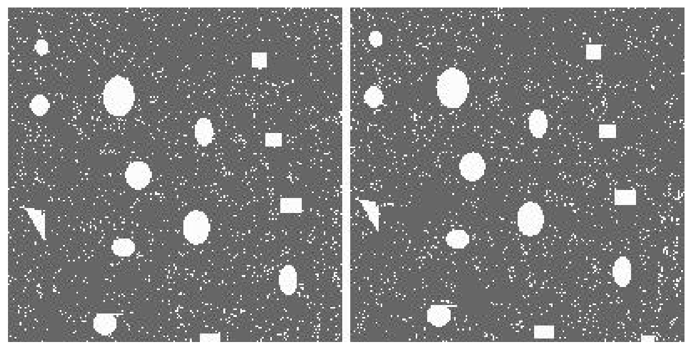

Fig. 4: Simulated two-phase PIV recordings

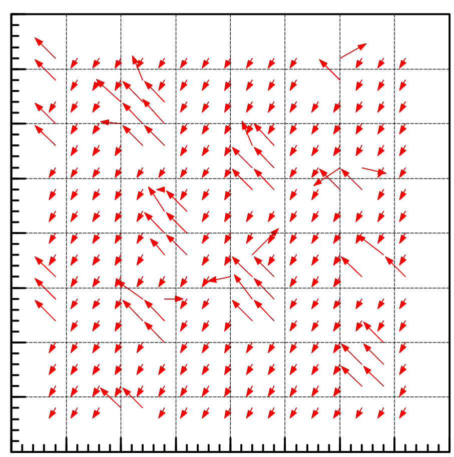

Fig. 5: Evaluation of Fig. 4 by cross-correlation without phase separation

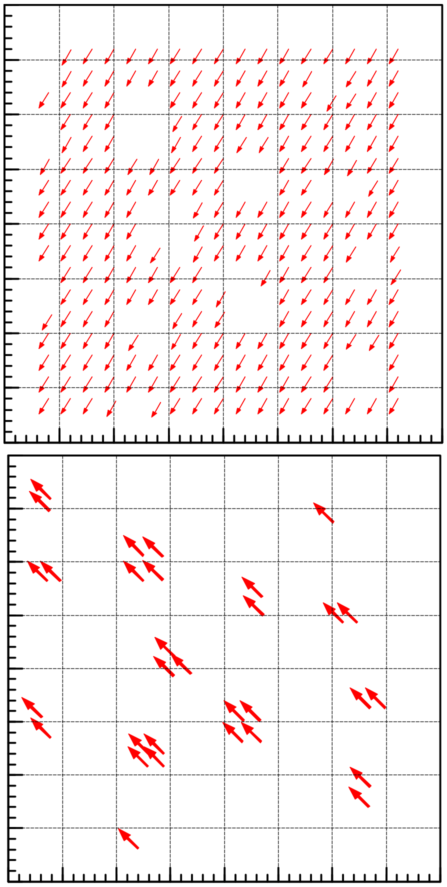

Fig. 6: Phase-separated evaluation of Fig. 4 by means of the digital phase mask

erroneous velocity vectors, particularly in the close neighbourhood of the big particles, as it is evident in Fig. 5. A more accurate result is obtained with the digital mask techniqe; the phase-separated velocity distribution for the simulated test case of Fig. 4 is given in Fig. 6.

The second example applies to the flow induced in a water tank by big solid particles whose specific weight is lower than that of water and which are released at the bottom of the tank. The solid particles are covered with a fluorescent coating, while the seed particles in the water are optically inactive. Phase-separation of the signals is realized here by an optical filter in front of the CCD black-and-white camera. Fig. 7 shows two successive optically flitered recordings carrying only the information of the fluorescent dispersed particles. The superimposed velocity distributions of the two phases is given in Fig. 8. Each of the longer vectors represents the velocity of one of the big particles whose rise velocities are significantly higher than the velocity induced in the water.

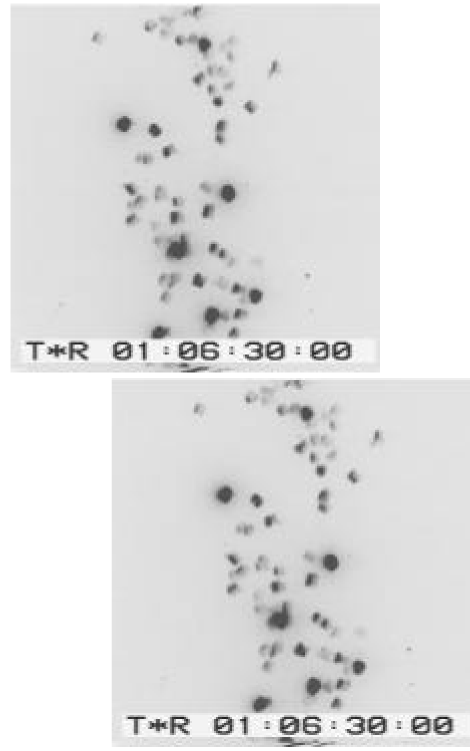

Fig. 7: Color-filtered PIVrecordings of fluorescent dispersed solid particles.

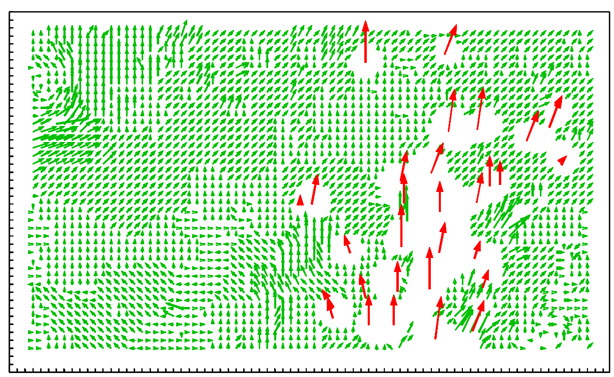

Fig. 8: Velocity distribution of liquid (continuous) and solid (dispersed) phase.

If such a prominent difference in the velocities of the two phases exists, this difference itself can be taken for distinguishing between the two phases. An example is given in Fig. 9 where a stream of air bubbles is rising in water, thereby entraining water into the bubble flow and inducing secondary, vortical flow in the water.

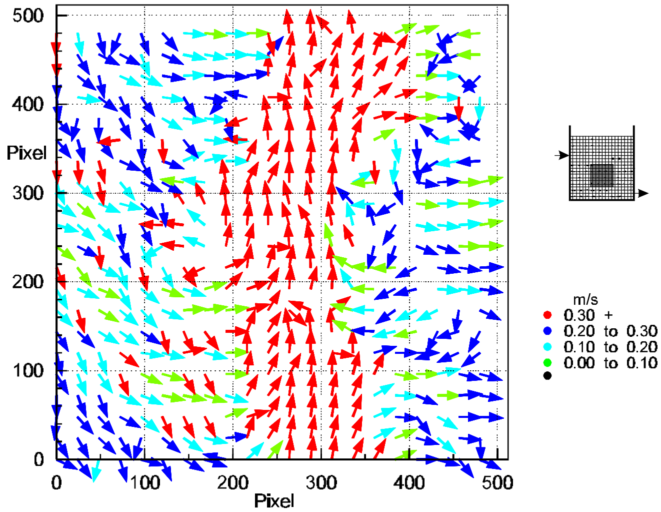

Fig. 9: Flow distribution induced in water by stream of upwards flowing air bubbles (center). The sketch on the right indicates position of measured plane in the tank with throughflow of water.

This flow configuration is of interest because the stream of gas bubbles may enhance the mixing of the liquid with a possible third, solid phase that was not present in this experiment (see,e.g., Torii and Yang, 1992). it appears that the governing mechanism for the mixing are the induced vortical structures which move through the liquid before they disappear due to dissipation. A convenient way for identifying these structures is to determine from the PIV data the component of the vorticity normal to the plane of the light sheet as it is shown for a particular section of the flow field in Fig. 10. Problems in determining the vorticity from PIV data have been discussed by Abrahamson and Lonnes (1995).

Details of the experiments used here as examples and further examples are reported in the dissertation of Hilgers (1996).

SUMMARY

PIV is a useful tool for investigating two-phase or multiphase flow fields. In contrast to single-phase applications a number of technical problems require specific solutions, particularly when high concentrations of the dispersed phase are present and for separating the velocity information of the different phases. Possible ways for solving these problems and examples of their applications have been reported here.

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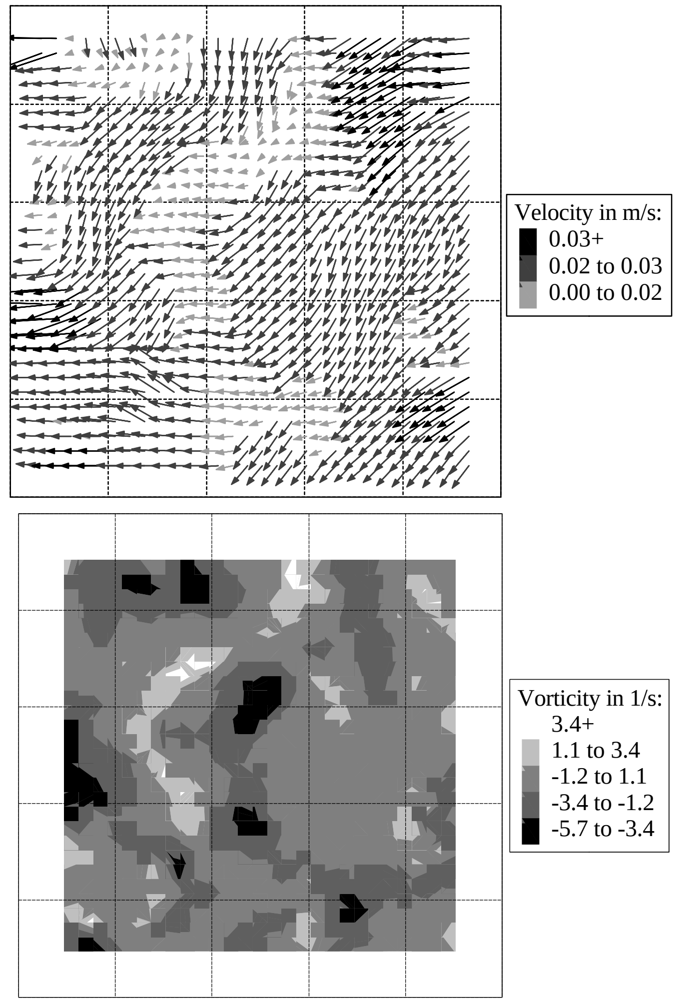

Fig. 10: Velocity and vorticity distributions of the continuous phase in a mixing tank. Ranges of measured values are indicated by different gray levels.

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