PIV measurements in environmental flows: Recent experiences at the Institute for Hydromechanics in Karlsruhe

Volker Weitbrecht ^{a,e,*}, Dong-Guan Seol ^{b,e}, Eletta Negretti ^{c,e}, Martin Detert ^{a,e}, Gregor Kühn ^{d,e},
Gerhard H. Jirka ^e

^a *Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, 8092 Zurich, Switzerland*

^b *Ocean Dynamics LLC, Houston, TX 77084, USA*

^c *Laboratoire des Ecoulements Géophysiques et Industriels (LEGI), UMR 5519, CNRS, Grenoble Cedex 9, France*

^d *WALD + CORBE GbR, 76549 Hügelsheim, Germany*

^e *Institute for Hydromechanics, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*

Abstract

Particle-Image-Velocimetry (PIV) has been applied to many different environmental flows in the last twelve years at the Institute for Hydromechanics, Karlsruhe Institute of Technology. The present paper gives an overview about the most important results gained with PIV during this period and summarizes the advantages and disadvantages of this measurement technique. PIV applications to determine velocities at the water surface as well as internal flows characteristics are discussed with respect to physical and technical aspects. It can be concluded that PIV is still not a standard tool, every application needs adaptation and comprises certain limitations. Every element of the measurement system (window size, camera, spatial and temporal resolution, etc.) has to fit exactly the physical problem to be examined.

Keywords: PIV; Surface PIV; Groin field; Groyne field; Internal waves; Shallow vortex dynamics; Incipient motion; Gravel bed; Flocculation

1. Introduction

Particle-Image-Velocimetry (PIV) has been applied to many different hydraulic-engineered and environmental flows with various spatial and temporal resolutions at the Institute for Hydromechanics, Karlsruhe Institute of Technology, Germany. PIV as a non-intrusive measurement technique has been widely used to measure instantaneous velocity fields in experimental fluid mechanics based on the drastic development of digital image capturing and processing techniques and computers.

The basic concept of PIV is to determine the translation of particle groups or, generally speaking, the translation of any kind of intensity pattern in certain areas of the measurement field or the so called *Field of View* (FOV) via cross-correlation of two images (Raffel et al., 1998). Therefore, PIV is not only restricted to the analysis of fluid motion but can be applied for every kind of motion as for example for the translation of dunes in rivers. The main assumption of PIV is that the movement of seeding particles or the movement of the intensity pattern of the images exactly reflects the local velocity of the observed medium. While there are many different PIV applications, the common procedures of this technique include the following steps: seeding the flow with tracers for visualization, illuminating the measurement area, photographing the seeded flow or video-recording digitally the flow, and finally processing the recorded images to obtain the velocity information. A complementary and relatively similar technique to measure flow fields non-intrusively is called

* Corresponding author. Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, 8092 Zurich, Switzerland. Tel.: +41 44 632 68 23.

E-mail addresses: vv@ethz.ch (V. Weitbrecht), seoldg@gmail.com (D.-G. Seol), maria-eletta.negretti@legi.grenoble-inp.fr (E. Negretti), detert@vaw.baug.ethz.ch (M. Detert), g.kuehn@wald-corbe.de (G. Kühn).

Particle Tracking Velocimetry (PTV). Generally, the same digital image can be used to determine the translation of single particles with PTV resulting in a number of vectors corresponding to each particle pair. Each vector of PTV analysis represents the exact movement of a single particle. Meanwhile, each vector of PIV analysis represents the mean movement of many particles in a certain area. The decision on which technique to use (PTV or PIV) is influenced by many parameters. The most important one is probably the number of particles distributed in the measurement area. A very high number of particles would lead to ambiguity problems and long computing time in case of PTV. In some applications the advantages of both techniques are combined. If the dynamic range is high, it can make sense to first perform a PIV analysis and then to do PTV with improved efficiency on searching matching particles (Brevis et al., 2007).

Many environmental flows have much larger scales in the horizontal dimension than in the vertical direction. Typically, these flows are characterized by large-scale predominantly *Two-Dimensional Coherent Structures* (2DCS) generated by different types of disturbances (Jirka, 2001). The studies on 2DCS using PIV measurements at the Institute for Hydromechanics in Karlsruhe include the formation of quasi-two-dimensional coherent structures from grid turbulence (Uijttewaall and Jirka, 2003), the flow around groin fields (Weitbrecht, 2004; Weitbrecht et al., 2008), shallow wake flows generated behind a cylindrical structure (von Carmer, 2005, von Carmer et al., 2009), diffusion induced by grid turbulence in shallow flows (Rummel et al., 2005), the stabilization of cylinder wakes in shallow flows (Negretti et al., 2005), and single shallow vortex dynamics (Seol and Jirka, 2010). In these specific PIV applications, the flow structures are visualized and analyzed with so called surface PIV by seeding the water surface with appropriate tracers such as plastic beads or other types of floating material (Fujita et al., 1998; Weitbrecht et al., 2002). The FOV in typical laboratory studies with surface PIV is in the order of 1–10 m² and illuminated with normal lighting system. This technique can be very useful when the underlying flow problem is dominated by two-dimensional horizontal flow phenomena as in the case of shallow flows. Of course, three-dimensional flow characteristics, for instance upwelling in the center of a horizontal *Large Coherent Structure* (LCS) (von Carmer et al., 2009), cannot be measured directly. However, in many cases the determination of the surface flow field in combination with structural analysis of the 2DCS can give very useful insights and lead to improved understanding of the flow.

PIV-systems using high-frequency and high-power laser systems are applied to studies on internal, turbulent flow phenomena typically with much smaller FOV size (order of 10⁻² m²). Technically, the major differences from surface PIV lie in the illumination of the FOV and the size of the tracer particles used. To visualize flow structures inside the water-body, a planar light sheet is generated, using the combination of optics and laser systems (pulsed or continuous), which are synchronized with a digital camera. The mixing layer of a two-layered stratified shear flow (e.g. Negretti, 2007; Negretti et al., 2007, 2008), flow in a turbulence column to

determine particle interaction (e.g. Kühn, 2008) and turbulence properties at the bottom boundary of the open channel flow with gravel bed (e.g. Detert et al., 2010a; Detert et al., 2010b) are PIV applications presented in this article. Furthermore, by combining PIV with *Laser-Induced Fluorescence* (LIF), PIV-LIF can be used to analyze various kinds of environmental flows with respect to momentum and mass transport process as for example in case of gas exchange problems at the air–water interface (Herlina and Jirka, 2008).

This paper presents summaries of recent PIV applications in environmental flows at the Institute for Hydromechanics at the Karlsruhe Institute of Technology (KIT). In the following Section 2, surface PIV results are presented from the fundamental studies on vortex dynamics in shallow-water conditions. In Section 3, the measurements of the flow field around river groins are presented. As an example of internal PIV, two-layered density-stratified flows over a submerged sill are discussed in Section 4. Results on turbulence properties in a water column and on top of a gravel bed in application to open channel flow are described in Sections 5 and 6, respectively. Finally, a summary and recommendations for further application are presented in Section 7.

2. Shallow vortex dynamics

Shallow-water flows are very common in many hydraulic, environmental, and geophysical flows, where the horizontal length scale of the flow is much larger than the flow depth. For flow scale much below the Rossby radius (free from the Coriolis acceleration), the “geometrical confinement” is the only limiting condition toward two-dimensionality. Due to the vertical confinement of the flow, the flow instabilities grow in the horizontal dimension and lead to the generation of large-scale predominantly *Two-Dimensional Coherent Structures* (2DCS) through the inverse energy cascade (Jirka, 2001). The 2DCSs frequently appear in form of a single vortex (monopole), dipole, tripole, or further multiple vortices based on the distribution of vortex patches (e.g. McWilliams, 1984; van Heijst and Kloosterziel, 1989; Kloosterziel & van Heijst, 1992). After their generation, these structures continuously interact with ambient flows and neighboring vortices until dissipated by the viscosity. The studies on dynamics of individual 2DCS can provide physical insight into turbulent flows, which can be regarded as a superposition of large numbers of single vortices with various scales (Seol and Jirka, 2010). The present study is to investigate the correlation between the flow instabilities and the flow conditions with a single large-scale vortex as a precursor to more complex multiple vortex system.

2.1. Experimental setups and procedure

The laboratory experiments were conducted in a Plexiglas shallow-water tank with a dimension of 1.6 × 1.6 × 0.20 m³ without background rotation (Fig. 1). Prior to the experiment, the tank is filled with a water depth of H . A single axisymmetric vortex is created with a vortex generator consisting of a bottomless Plexiglas cylinder with a diameter of D and 4–8

Fig. 1. Schematic view of the experimental setup (not scaled). Plan view (a) and side view (b) of the shallow-vortex generation system.

internal sectors driven by a stepper motor. After a short spin-up time of 4 s, the vortex generator is rapidly lifted up from the water and manually moved outside of the tank. The time origin $t = 0$ s is defined as the moment when the vortex generator is removed from the water. To avoid flow disturbances on removing the cylinder, the measurements for the first 2 s are not considered for the analysis. Two non-dimensional parameters, shallowness and Reynolds number, are varied for the experiments. The shallowness (S) is defined as the ratio of the cylinder diameter $D = 10$ or 20 cm) to the flow depth $H = 2$ – 6 cm). The considered shallowness ranges from 2 to 10. The Reynolds number is defined as $Re = \Omega_0 r_o^2 / \nu$, where Ω_0 is the initial angular velocity of the rotating cylinder (3.14 – 12.56 s $^{-1}$), r_o is the cylinder radius, and ν is the kinematic viscosity of water. The Reynolds numbers for the study are estimated in the range of 7850 – 56000 .

To obtain quantitative velocity field measurement, surface PIV was applied. The flow field is homogeneously illuminated with 4 white-light photo floodlights with 1000 W each and seeded with buoyant polyester glitter particles (Sigmund Lindner GmbH) with size distribution of 0.5 – 1.5 mm and a density of 0.4 g/cm 3 . The images of the tracer particles are recorded using a CCD camera (Imager Compact, La Vision GmbH, 1024×1024 pixels with 12-bit grayscale intensity) with a -Nikkor 15 mm lens from 285 cm directly above the water surface. The covered measurement area was about 130×130 cm 2 with maximum 2.5% of image distortion at the image edge. The tracer particle images are taken in a single-frame mode with a frequency of 10 Hz with the exposure time of 50 ms. Contrary to a typical PIV image of individual tracer particles, the recorded image appears as a brightness pattern image of groups of moving particles in the flow (Fujita et al., 1998). In this type of image, the measurement error was estimated about 5% for the seeding density (the percentage ratio of seeded to total image area) of 33% (Meselhe et al., 2004). Note that the measurement error here is a bias error relative to the surface velocities, estimated from the cross-sectional average velocities based on the logarithmic vertical velocity profile. Using a commercial PIV software (DaVis 6.2, LaVision GmbH), the captured images are processed to obtain velocity vector fields. The adaptive

multi-pass cross-correlation algorithm is applied to the raw image with decreasingly smaller interrogation window sizes from 128×128 to 32×32 pixels with 50% overlap. The resultant data resolution is 64×64 vectors, which result in about 2 cm of the vector spacing between two consecutive vectors.

2.2. Shallowness effects on a single vortex: instability analysis

The vorticity maps are estimated from the measured velocity fields for different shallowness with high Reynolds number cases $Re \geq 14000$ at $t = 5$ s (Fig. 2a, d, g). A bar in the right-hand top corner in the figures indicates the water depth. Positive vorticity (represented by red color) is created around the cylinder (gray circle represents the initial position) and surrounded by negative vorticity (represented by blue color). Note that the vorticity contour maps are normalized with the observed maximum vorticity and the scale bar is presented in Fig. 2b. For the strongest shallowness $S = 10$), the flow shows the tripole system (subplot a), where the horizontal vortex size greatly exceeds the water depth. On the other extreme, the weakest shallowness case $S = 2$) show a distinctly different flow behavior: The annulus of the negative vorticity originated from the initial shear boundary layer around the central vortex is stagnating and gradually diffuses with time. This horizontal diffusion, evidently in form of three-dimensional vortex, whose length scale is below of the order of the water depth, leads finally to an irregular turbulent region. The estimated vorticity fields show that the vortex system for strong shallowness and high Re converges to a tripolar system due to the development of flow instability around the generated single vortex.

The dominant flow instability modes associated with the final form of shallow-water vortices are identified using harmonic analysis on the vorticity fields. Firstly, a vorticity field is transformed into polar-coordinate system based on the initial assumption of pure azimuthal flow about the vortex center (Fig. 2 b, e, h). In the figures, the horizontal and vertical axes represent the azimuthal direction (θ) and radial distance (r) from the vortex center, respectively. The vortex center is defined by calculating

Fig. 2. Estimated vorticity maps (subplots a, d, g), polar-coordinate transformed vorticity maps (subplots b, e, h), and spectra of instability wave amplitudes (subplots c, f, i) for different shallowness. The gray circles in (a), (d), and (g) represent the initial cylinder contour. The vorticity contour maps are normalized with the observed maximum vorticity as shown in the scale bar in subplot (b).

the center of mass of the positive vortex patch defined by the vorticity contours satisfying $\omega = \delta \omega_{\max}$, where δ is a constant varying 0.5–0.7 and $\omega_{\max}$ is the measured maximum vorticity. Secondly, the complex vorticity field is decomposed into the sum of harmonic functions with different wave number (k) as $\omega = \sum_k \omega_k$ (Kloosterziel and Carnevale, 1999). The influence of azimuthal deviation $k \neq 0$ on the axisymmetric component $k = 0$ can be measured with the wave amplitude (A_k). Fig. 2(c), (f), and (i) show the spectra of instability wave amplitude normalized with the axisymmetric component (A_0). For the strongest shallowness case (subplot c), the most unstable mode wavenumber $k = 2$ shows the largest magnitude. Amplitude of perturbation wavenumber $k = 4$ is also relatively large, but stays smaller than A_2 by around 40%. For the deep-water case (subplot i), the magnitude of A_2 is much smaller than other modes (e.g. $k = 3$ and 4), which means that the tripole formation is much less pronounced than for a shallow-water vortex.

2.3. Pros and cons of the surface PIV measurements of shallow vortices

An application of PIV to a surface flow field measurement requires low-cost and simple setup compared to a conventional internal PIV-setup. Simple combination of photo floodlights and camera system has been used for this study without complex laser system. One of the difficulties in this application is associated with the sensitivity of floating tracer particles to the water surface motion. Upon the removal of the vortex-generating cylinder from the water, the tracer

particles are subject to the surface waves in radial direction. To minimize this effect, the maximum deflection of the water surface is kept small less than 1 cm. In addition, due to the agglomeration of particles, it is difficult to resolve small scale flow structures (e.g. about 0.1 cm of shear boundary layer thickness). However, the large-scale flow structures were captured well as presented in the previous result section.

3. Groin field flows

The goal of this more applied project was, to determine the influence of dead-water zones, as for example river groin fields, on the mass transport characteristics in rivers (Weitbrecht, 2004). With the help of Surface PIV, the driving mechanism for mass exchange, large-scale, predominantly *Two-Dimensional Coherent Structures* (2DCS) in the shear layer between the main stream and the dead-water zone, could be identified. By analyzing the transverse velocity component in the shear layer between dead-water zone and main stream the characteristic residence times in the dead-water zone as defined by (Altai and Chu, 1997) could be determined and compared to results from tracer experiments (Weitbrecht et al., 2008).

3.1. Experimental setups and procedure

The experiments were performed in a laboratory flume 20 m long and 1.8 m wide, and having an adjustable bottom slope (Fig. 3). The channel bottom was painted white with a bottom roughness < 0.2 mm. Groins were placed on one side of the

Fig. 3. Schematic top view of the laboratory flume. The field of view (FOV) of the PIV-setup is indicated by a typical raw image taken with the PIV camera from above the flume. The black dots indicate seeding particles at the water surface.

flume with the opposite smooth flume wall assumed to be the channel midpoint. Each groin consisted of a cuboid box ($0.05 \times 0.05 \times 0.5$ m) with a half cylinder attached at the end of the groin protruding into the main channel (Fig. 3). In order to cover a wide range of groin field designs, groins were positioned with different spacing, length, and inclination angle.

The acquisition and analyzing system is very much the same as presented in Section 2. To capture large measurement planes while the space above the experiment is limited to a maximum of 3 m, a 15 mm wide angle lens (NIKON) leading to negligible distortion errors was used. To get a proper seeding of the water surface, polypropylene particles with additional matt black lacquer finish have been used. Compared to other particles they showed the lowest tendency to conglomerate (Weitbrecht et al., 2002). A homogeneous distribution of particles within the measuring field has been achieved by using a particle dispenser where a roller brush with adjustable rotation speed is connected to a vibrating container filled with particles (Weitbrecht et al., 2002).

The illumination of the water surface was achieved with continuously operating floodlights. The measurement field of 1.5×1.2 m was captured with a frame rate of 7 Hz by a CCD camera with a 12-bit, 1280×1024 pixel chip (LaVision Imager 3, PCO Sensicam). Thus, one pixel on the camera chip represented an area of 1.2 mm^2 , about half the size of the PIV particles. The surface velocity vectors were calculated using the DaVis software package from LaVision. To realize an acceptable dynamic range, an adaptive multi-pass algorithm was used beginning with an interrogation window of 64×64 pixels and a final window size of 32×32 pixels with 50% overlap. Each of the 60×84 vectors represents the average movement in an area of approximately 13 cm^2 . The overlap of 50% leads to a reduced distance between each vector of 1.9 cm.

3.2. Measured flow characteristics in groin fields

Fig. 4 shows an instantaneous flow field generated from two successive pictures similar to the raw image shown in Fig. 3. The vectors in Fig. 4 indicate the deviation from the time averaged mean flow that has been deduced from a series of 600 images. The vorticity distribution shown in Fig. 4 is indicated by light color for clockwise rotation and dark color for anticlockwise rotation. 2DCS are clearly visible in the

shear layer between dead-water zone and main stream, generated by topographic forcing (Jirka, 2001).

In many rivers the groins are built with a certain inclination angle in upstream direction. Only in very few cases where increased bank erosion is wanted, for example as an ecological measure, groins can be inclined in downstream direction. Fig. 5a shows resulting streamlines to visualize the mean flow pattern in the case of upstream inclined groins. In case of downstream inclined groins the secondary gyre in the upstream corner is much larger (Fig. 5c). As the secondary gyre is rotating much slower, mass exchange in this region of the dead-water zone is also much slower. Hence, the retention time in groin fields with an inclination angle larger than 90° is expected to be longer than in the other case.

Fig. 5b and d show the transverse component of the turbulence intensity v'/u_* (v' = standard deviation of the transverse velocity component, u_* = shear velocity) in groin fields with up- and downstream inclined groins. The lower values of v'/u_* in the case of downstream inclined groins also indicate lower values of mass exchange with corresponding higher values of residence times.

3.3. Pros and cons of the surface PIV measurements of groin fields

Similar conclusions can be drawn as these in the shallow vortex dynamics section. The setup is easy and no laser is

Fig. 4. Vorticity distribution in the mixing layer between dead-water zone and main stream. Light color indicates clockwise rotation and dark color anticlockwise rotation (Weitbrecht et al., 2008).

Fig. 5. Flow characteristics in groin fields with backward and forward inclined groins: a, c) mean flow properties visualized with streamlines; b, d) transverse component of the turbulence intensity v'/u_* . Dark regions indicate low values and bright regions indicate the maximum values. The maximum value in b) is 1.7 and in d) it is 1.5.

needed. The field information can be used to detect the driving mechanisms of the underlying flow phenomena.

One of the disadvantages of the used surface PIV-system is revealed in Fig. 5b. Hinterberger et al. (2007) showed with the help of detailed Large-Eddy-Simulations that the highest values of the transverse component of turbulence intensities, are located close to the upstream groin tip. However, the PIV results in this study show the highest value in the middle, between up- and downstream groin in the mixing layer (Fig. 5b and d). Close to the groin tip the PIV results show lower values. The reason for this discrepancy compared to the LES simulations is the limited spatial resolution of the used PIV-system and the expected small scale turbulence close to the groin tip. Simultaneous LDV measurements close to the water surface show that the RMS values of the instantaneous velocities are captured with very high accuracy in the center of the mixing layer where the velocity is dominated by large turbulent structures (Weitbrecht et al., 2002).

Another problem in the case of surface PIV is the homogeneity of the seeding particles and the tendency to form conglomerates, especially under low turbulence conditions. To achieve homogeneous seeding inside the groin field additional manual seeding is needed.

4. Internal waves

Adjacent water bodies, connected by a narrow pass or channel, often have density differences caused by different salt or sediment concentrations or different temperatures. These density differences lead to pronounced exchange flows by which large water masses containing various water quality properties (e.g. chemical, physical and biological constituents and species) can be carried from one water-body to the other. Numerous examples in the oceanographic context (e.g. Straits

of Gibraltar (Farmer and Armi, 1988) and Bosporus, Baltic/North Sea exchange) and in hydraulic/environmental applications (e.g. lakes and reservoirs with interconnections and side arms) exist (Arita and Jirka, 1987). At the interface of such exchange flows, flow instabilities, like Kelvin-Helmholtz-billows develop, which lead to mixing between upper and lower layers. These flow phenomena strongly affect the water quality as well as the flow circulation of both water bodies (Lawrence, 1993; Zhu et al., 2002).

The main objectives of this study concerned the investigation of the effect of large Reynolds numbers, of locally enhanced bottom roughness and the influence of the bottom topography on the interfacial waves and instabilities and the related entrainment and mixing processes. A quantification of these phenomena has been achieved through laboratory experiments using advanced synoptic measurement techniques (PIV and PLIF). In particular, the PIV technique enabled to estimate the hydraulic parameters of the flow, like the flow rates and the instantaneous velocity profiles, and the turbulent transport. Especially, velocity fluctuations enabled to estimate the time and spatial correlation functions and so the length scales of internal large-scale instabilities and finally, to relate these structures to the hydraulic features of the flow. Also, we could estimate the entrainment rates under different flow conditions between the two-layers.

4.1. Experimental setups and procedure

To perform the experiments of a two-layer density-stratified flow over a submerged sill, a 12 m long and 0.6 m wide basin was used, which was divided in the middle into two basins, and connected by a channel of reduced width (14.5 cm). The tank had a volume of 6 m³. A bottom sill made of foam plastic was placed in the middle of the channel (Fig. 6). The tank was

Fig. 6. Sketch of the experimental set-up; a) Plan view; b) Side view.

first filled with fresh water to a desired depth. A Plexiglas barrier was then placed at the sill crest to divide the tank in 2 reservoirs. A buoyant acceleration of g' was produced by adding NaCl to the water in the left reservoir (Negretti et al., 2007). The density of each reservoir was determined based on the water temperature (measured to a precision of 0.1 °C) and salt concentration (weighted to a precision 0.1g) with a high-precision densimeter (Anton Paar, DMA 5000). Therefore, the error in the reduced gravity g' was estimated to be less than 1%.

The PIV set-up, consisted of a light source, light sheet optics, seeding particles, a camera, and a PC equipped with a frame grabber and image acquisition software. Polyamide-particles (PA12, Vestosint 2157) with diameters ranging from 100 to 300 μm with a specific density of 1.016 g/cm^3 , were added in both reservoirs as tracer material for the PIV measurements. It turned out that an appropriate particle density in the water-body could be achieved by adding 0.04 g particles per liter. Because of the small density difference between the two reservoirs and the given density distribution of these specific particles they could be used as seeding material for both, the fresh water and the salty water reservoir. A 10 W Argon-Ion laser (Stabilite, 2016; Spectra-Physics lasers) operating in multimode ($\lambda_1 = 488 \text{ nm}$, $\lambda_2 = 514 \text{ nm}$) has been used as continuous light source. The beam was transmitted through a fiber optic cable to a line generator with spherical lenses (OZ Optics Ltd., Nepean, Ontario) (Morin et al., 2004). The generated lasersheet at the sill crest had a length of approximately 2 m and a width of 5 mm and was positioned in the middle of the channel. Images of $70 \times 70 \text{ cm}$ were captured with a CCD camera (1024×1024 pixels) at a frame rate ranging from 16 to 24 Hz. A wide angle lense (SIGMA AF EX 1.8/24 DG Macro AF for Nikon) was used along with a low-pass filter (DT Cyan, Linos Photonics GmbH, Goettingen) at a distance of 2.1 m to the FOV, leading to a spatial resolution of 0.0625 cm/pixel. Time series of 625 s leading to 15,000 raw images were stored in real time on a raid system. Including the resulting vector fields each experiment led to approximately 20 GB of data, which have to be stored,

backed up and archived. The raw images were then processed using a PIV-algorithm to compute the velocity fields, each from two consecutive raw images. With the software package DaVis (LaVision) the velocity fields were computed using a cross-correlation PIV-algorithm. For this purpose an adaptive multi-pass routine was used, starting with an interrogation window of 32×32 pixels and a final window size of 16×16 pixels with 50% overlap. Each vector of the resulting vector field represents an area of $0.6 \times 0.6 \text{ cm}$. The velocity vectors were post-processed using a local median filter and checked by the distinctiveness of the highest correlation peak.

4.2. Mean flow characteristics in a two-layer stratified exchange flow

The chosen PIV particles described above, were not leading to a sufficiently uniform particle distribution in both layers. Fig. 7a shows the particle distribution without seeding. It can be observed that particles are lacking in the high sheared regions in the middle of the picture and in the upper fresh water layer near the water surface, where particles are distributed with a different density at different heights. To achieve homogeneous seeding, a grading of the particles was necessary to be performed in the following steps. A high concentrated particle solution was stirred for 1–2 h (fresh water and salt water solution of appropriate density). After the mixing we waited for 24 h, and eliminated all the particles at the surface and at the bottom from each solution. The particles remaining in the water column were used for the experiment (Fig. 7b).

A field of view (FOV) of $70 \text{ cm} \times 70 \text{ cm}$ with a particle diameters of 100 to 300 μm led to a non-dimensional particle diameter of 0.4 pixels/pixel. Particles smaller than one pixel always occupy one pixel in a digital image and generally the true position of the particle cannot be resolved within a pixel reducing the accuracy from the sub-pixel range to the pixel range and the corresponding peak locking effect (Raffel et al., 1998). A small ratio of particle size to pixel size was inevitable in this experimental set-up due to the large field of view required for this study. This problem was partly reduced by

Fig. 7. Raw image (a) with a non-uniform particle distribution and raw image after grading of the particles (b) resulting in a uniform particle distribution.

slightly defocusing the camera lens, leading to a 3 times larger particle size on the camera chip than the true value of the non-dimensional particle diameter. Fig. 7b shows a typical instantaneous PIV raw image and a zoomed area of it is presented in Fig. 8a to evidence the true particle size relative to the pixels size. The corresponding velocity vector field obtained is shown in Fig. 8b. Despite this small true particle diameter and by defocusing slightly the camera lens, the used PIV-algorithm was able to calculate accurate velocity fields.

The presence of a recirculation zone and of relatively small velocity values in the left bottom corner of the image, on the left side of the sill, made it difficult to resolve the velocities in this region, as shown in Fig. 8b. The same problem was encountered as well when bottom roughness elements were placed on the sill to study the influence of a rough bottom (Negretti et al., 2008). The velocities were difficult to determine in the dead-water zone because of very low velocities and reduced contrast between bottom roughness (Fig. 9). Clearly, the spatial resolution was not sufficient to resolve well these regions. These regions were neglected in the further analysis of the flow.

This experimental set-up permitted thus, to calculate with a good accuracy the velocity fields and the velocity fluctuations (a quantification of the error is given in the next

paragraph). These quantities were used in a second step for further processing the data to calculate flow rates, spatial and temporal correlation functions, shear layer thickness, spectral distributions and entrainment rates. Averaged velocity fields and Reynolds stresses, total kinetic energy and vorticity are shown in Fig. 10.

The velocity measurements are influenced by the following possible source of errors: high velocity gradients, variable particle density, low particle diameter, out-of-plane-motion and peak locking (Cowen and Monismith, 1997). Peak locking refers to the bias that occurs when the estimated location of the correlated peak is shifted toward the next integer value. Applying the Cowen and Monismith, 1997 approach to estimate these errors shows that 2% of the streamwise velocity vectors and 18% of the vertical velocity vectors were affected by peak locking, to give a mean value of 10% for the total velocity. The averaged Q-factor represents the ratio of signal-to-noise peaks in the correlation map. An average Q-factor above two, indicates that strong correlations were found. The averaged Q-factor in the experiments was 2.4. This is a surprisingly good value considering that despite the slight defocusing, the size of the particles was still below the pixel size, which accounts for peak locking. Part of this problem has been solved considering that the software LaVision identified

Fig. 8. Raw image (left) showing the real particle size relative to the pixel size. A slight defocusing of the camera lens triplicated the size of the particles on the camera chip, leading to a typical non-dimensional diameter of 1.2 pixels/pixel. The red circles mark regions of possible particle groups, which are recognized as single intensity patches by the DaVis Software; Instantaneous velocities (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. Averaged vertical velocity profiles of a two-layer flow over smooth (top) and rough topography (bottom). The velocities were difficult to determine in the dead-water zone in the left lower corner of the FOV because of very low velocities and reduced contrast (a) and in the zone between bottom roughness elements when enhanced bottom roughness was employed (zone between the continuous and dashed lines in b).

patches of high intensity zones larger than one pixel which might be generated by more than one single particle (see red circles in Fig. 7a). However, there was no possibility of determining the percentage of the particles affected by this effect. The mean values of the largest velocity gradients in the streamwise and vertical directions were computed from the unprocessed vector fields and evaluated to be approximately 2%. The total error due to a 2% gradient of a particle diameter of 1 pixel was estimated to be 0.08 pixels (Fig. 8a Cowen and Monismith, 1997). Out-of-plane motion has been neglected, as the flow can be treated as two-dimensional. The total error can be then estimated as the error of the particle size and velocity gradients to 0.08 pixels, which corresponds to a value, in the worst scenario, of

$$STR \times E \times f = 0.0625 \text{ cm/px} \times 0.08 \text{ px} \times 24 \text{ Hz} = 0.12 \text{ cm/s}$$

expressed in velocity units, where STR represents the spatial true resolution, E is the error due to the velocity gradients and f is the acquisition frequency. Given the velocities encountered

in the experiments, the experimental error in the instantaneous velocity was estimated to be approximately 3%.

4.3. Pros and cons of the PIV measurements in a two-layer stratified exchange flow

A two-layer density-stratified flow over topography has been studied by means of PIV measurements. With a set-up, made of a continuous laser light source and a CCD camera of La Vision with a resolution of 1024 x 1024, it was possible to determine velocity fields with appropriate accuracy. The particularity of these experiments was the large size of the PIV images (70 x 70 cm) due to the large experimental set-up to study high Reynolds numbers exchange flows. The most remarkable difficulties were the choice of the particles, and in particular to obtain in both layers (fresh and salty water), a uniform particle distribution. This was achieved by sorting the particles by their density (see results).

Another problem was the non-dimensional particle size relative to the pixel size, which was approximately half the

Fig. 10. Averaged quantities of the resulting velocity fields. Velocity field (a), Reynolds stresses (b, c, d), total turbulent kinetic energy (TKE, e) and y-vorticity field (f).

size of the pixel. By slightly defocusing the lens, it was possible to eliminate this effect.

5. Particle interaction in open channel turbulence

Water quality in natural rivers is strongly related to the appearance of fine sediment particles in the water-body. Fine sediment particles offer large surface areas and a high adsorption potential leading to electrostatic agglomeration of contaminants at the particle surface. To investigate fine sediment particle interaction (aggregation and segregation), under the influence of open channel turbulence, an experimental tank called “*Differential-Turbulence-Column*” (DTC) has been developed (Fig. 11). In contrast to the turbulence column described by Brunk et al. (1996), the turbulence is not produced by single grids but with five pairs of oscillating grids driven by 10 individually controlled motors, respectively. The main difference to laboratory flumes or field studies is the possibility to produce turbulence without the action of shear, created by the mean flow. Due to the absence of the advective mean flow, it is possible to investigate the influence of the turbulence on the behavior of fine sediments over a long time without moving the measurement window.

To determine, optimize and validate the turbulence characteristics in the DTC, different measurement techniques were used. PIV was mainly employed to determine the remaining mean flow field and the distribution of the turbulent kinetic energy. Additional Laser-Doppler-Velocimetry (LDV)

measurements were used to validate the PIV-data and to determine small scale dominated properties of the turbulence.

5.1. Experimental setups and procedure

For the measurements of the mean flow field a commercial PIV-System purchased from LaVision was adapted to the experimental setup. The system consists of a FlowMaster 3 CCD camera with 1280×1024 pixels with double-frame technique. For illumination a Continuum Minilite II PIV Laser ($I_{\max} = 25$ mJ) emitting on $\lambda = 532$ nm was used. The

Fig. 11. Photo of the Differential-Turbulence-Column (DTC).

timing and synchronization of the system was managed by a Programmable Timing Unit (PTU). The analysis of the images and calculation of the vector field were done with LaVision software DaVis 6. The same system was used for the investigations described in Section 6.

The camera was mounted on a 2D traversing system for fully automated measurements. The complete experimental set-up is shown in Fig. 12.

The laser-sheet with a thickness of about 1 mm was produced with a top-hat beam shaper that is specially shaped to fit the intensity distribution of the laser beam, leading to a uniform light intensity distribution in the laser-sheet. The laser-sheet was introduced into the water-body by a glass plate placed on the water surface. Surface floats were used to dampen occurring waves at the water surface.

White polyamide-particles were added as tracer material to the water-body (Vestosint[®], type 1101, $d \cong 80\text{--}200\text{ }\mu\text{m}$, density $\rho = 1.06\text{ kg/m}^3$). Similar to the grading process described in Section 4, low and high density particles were eliminated before use.

The laser-sheet was adjusted in the middle of the tank in the $x\text{--}z$ plane. To capture the complete vertical profile, the measurement window was divided in 14 sections at a size of $8.7 \times 6.9\text{ cm}$. This led to a spatial resolution of $68\text{ }\mu\text{m/pixel}$. In each measurement section, 900 double frames were recorded with frequency of 4 Hz.

5.2. Results of PIV measurements in the Differential-Turbulence-Column

The PIV measurements were conducted for different experimental conditions, by changing the frequency of the

Fig. 12. Sketch of the front-view of the experimental set-up for PIV measurements in the differential-turbulence-column.

oscillating grids. The conditions were characterized by the mean frequency of the bottom grids, while the upper grids run with a lower frequency to reproduce a vertical turbulence profile of an open channel flow in terms of turbulent kinetic energy described by Nezu and Nakagawa (1993).

In a first step the images were inverted and the background illumination was eliminated by a low-pass filter, mainly to reduce the amount of data without using lossy image compression. The flow field was then calculated with an adaptive multi-pass procedure to a resulting window size of 32×32 pixels, leading to a spatial resolution of 2.1 mm per vector.

The resulting vector fields were used to visualize the remaining mean flow field in the center of DTC. Fig. 13a shows the mean flow with a bottom grid frequency f_0 of 4 Hz. As explained above, the oscillating grids should produce turbulence, free of advective mean flow. However, the results show that steady 3D flow structures develop. The size of these observed structures clearly scale with the grid size.

Assuming isotropic turbulent conditions it was possible to calculate the turbulent kinetic energy defined by Pope (2000) as

$$k = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (1)$$

where u' , v' and w' are the fluctuating components of the velocities in x -, y - and z -direction. w' has been calculated by the mean of u' and v' assuming isotropic turbulent conditions. In Fig. 13b the vertical turbulent kinetic energy profile averaged in x -direction is shown for different grid frequencies. By scaling the turbulent kinetic energy with the adapted bottom shear stress velocity, the distribution of the turbulent kinetic energy shows a similar behavior as the measured distribution by Nezu and Nakagawa (1993).

The results show as well, that the ratio between velocity fluctuation and mean velocity is greater than 1. On that basis, we assume that the flow is dominated by the velocity fluctuations with relatively low influence of the mean flow, which is an important precondition for the following investigations of the particle behavior. Further details on this study can be found in Kühn (2008).

5.3. Pros and cons of PIV measurements in the Differential-Turbulence-Column

The main advantage of PIV measurements is the acquisition of field compared to point measurements. Therefore, spatial information is captured much faster. Due to hardware limitations, like camera frame rate and storing capacity the advantage in gaining spatial information causes a low dynamic resolution of the velocity information. In the present study LDV measurements were additionally used to capture the small scale fraction of the turbulence.

It is difficult to use PIV with reflective interfaces, where the laser light is reflected leading to images with low contrast. Another problem is laser safety that has to be handled. Especially when high energy lasers are used and the reflecting interfaces are moving like the water surface in the present

Fig. 13. a) Mean flow field in the center of the of the Differential-Turbulence-Column (DTC) with an oscillating bottom frequency $f_0 = 4$ Hz; b) distribution of the turbulent kinetic energy k_x scaled with the bottom shear stress velocity u_* in the center of the differential-turbulence-column in comparison to the results of Nezu and Nakagawa (1993).

study. Finally, PIV measurements are limited by the capacity of the PC RAM and of the used hard drives. Storage of the raw data and backup has to be taken into account. Nevertheless, PIV provided an effective way to analyze the entire flow field in the DTC with respect to mean and turbulent flow characteristics, which was not possible with other techniques.

6. Turbulence in gravel bed rivers

This project focused on the hydrodynamical processes that occur in open channel flow, above and within rough porous gravel beds. The main results were recently published in Detert (2008), Detert et al. (2010a, 2010b). As the Kolmogorov length scale η is hardly resolved by PIV measurements, turbulent fluctuations with scales smaller than the spatial resolution will cause noise in the calculation of the vector fields. Peak locking effects combined with sub-pixel displacements also lead to inaccurate velocity vectors, especially if they are combined with strong velocity gradients — as is typical in the near-bed region of open channel flows. The present section addresses the question to what extent sources of errors influence the turbulence statistics of the PIV measurements. To this end, two PIV recordings in a centerline plane perpendicular to and near the bed are analyzed exemplarily next.

6.1. Experimental setups and procedure

The experiments were carried out in a rectangular laboratory flume at the Institute for Hydromechanics (IfH), with an effective length of 17.0 m and a width of 0.9 m. Two different types of bed material were laid and investigated underlying turbulent open channel flow so that natural streambed conditions were simulated in full-scale: At run #sph1 the bed was

roughened by spheres (mean diameter $d = 25$ mm), and at #rhi9 the bed was formed by gravel from an armoring layer of the river Rhine ($d = 26$ mm, $d_{85}/d_{15} = 2.8$). For #sph1, the chosen water depth was $h = 0.129$ m, the bulk velocity was $U = 0.16$ m/s, and the Reynolds number $Re_h = 20.6 \times 10^3$. For #rhi9, the conditions were $h = 0.215$ m and $U = 0.93$ m/s, resulting in a ten times higher $Re_h = 200 \times 10^3$. Thus, the examined flow conditions cover the broad diversity of hydrodynamic loads and roughness parameters as can be found in non-moving gravel beds. Detailed information is given in Detert (2008). In the following, a coordinate system is used, where x is orientated in streamwise flow direction and y in upwards vertical direction. $y = 0$ denotes the wall level, where a linearly extrapolated log-fit of the spatiotemporally averaged streamwise velocity profile is zero. The velocity components u and v correspond to x and y .

A commercial 2D PIV LaVision-system was used for measuring velocities in a centerline plane perpendicular to the bed (xy). The PIV package included camera, laser-illumination, frame grabber, controlling and evaluation software. Digital images could be recorded by a 1280×1024 pixel² 12-bit PCO camera with a CCD-sensor (Flowmaster 3S). To get a satisfying spatio-temporal resolution, a double frame mode was used. In this mode, two images are captured within a very short time. The first image is not read out directly (as in a simple single-frame mode), but shifted to the storage position on the camera chip and then the second frame is taken. According to the flow velocities an interval time of 8 ms was used to acquire one double frame at #sph1, and an interval time of 2 ms was used for #rhi9. However, during the transfer of this double frame to the RAID system a relatively long read out time of 250 ms is necessary for a full double frame of $2 \times (1280 \times 1024)$ pixel². Consequently, vectors are only able to compute between one

image-pair of one double frame, but not between different double frames. Special adoptions to the laboratory problem were made. Measurements were based upon seeding the flow with neutrally buoyant tracer particles (polyamide powder Vestosint[®], type 1101, $d \cong 80\text{--}200\text{ }\mu\text{m}$, density $\rho = 1.06\text{ kg/m}^3$). The flow field was illuminated by a dual-cavity Q-switched Nd:Yag laser with a pulse energy of up to 25 mJ per pulse. The emitted green light had a wavelength of 532 nm. The laser-sheet was enlarged by a top-hat beam shaper leading to a linear energy distribution with a thickness of the laser light sheet of about 1 mm. For measurements in the xy -plane, the laser-sheet was guided into the water through a glass bottom of a streamlined hull construction of 15 mm breadth and 300 mm length. In this, no free surface was present where the sheet entered the water and, in turn, the sheet remained undistorted. Typically, the hull was immersed by 5 mm and caused small surface waves in the wake, but did not affect the flow in the near-bed region. In this, a plane perpendicular to the bed was illuminated in the center-line of the flume. The size of the camera frames was vertically reduced to $1280 \times 384\text{ pixel}^2$ to decrease the read out duration of the camera chip. Thus, constant double frame rates of $f = 8.5\text{ Hz}$ were reached, leading to 1740 double frames within 205 s. The camera was adjusted to a streamwise vertical xy -plane of $202.0 \times 60.5\text{ mm}^2$ directly above the bed, incurring a loss for the observation of the outer flow. Fig. 14 gives an example of a single PIV inverted raw image of this size.

6.2. Results of the near-bed turbulence measurements

The 2D velocity field was gained by a multipass cross-correlation method with discrete window offset, where the intermediate vector fields were smoothed by a 3×3 Gaussian filter. For the spectral analysis a final window size of $16 \times 16\text{ pixel}^2$ without overlap was chosen. Thus, the vector spacing of 2.52 mm was the same as the spatial resolution. The resulting vectors were checked by a median filter, an absolute allowed vector range and the distinctiveness of the highest correlation peak. In general, 75–95% of all vectors within one double frame were validated, depending on the density and homogeneity of the seeding. Fig. 15 shows a resulting vector field where a constant mean flow velocity has been subtracted.

Fig. 14. PIV frame from #sph1 as raw picture (negative print). The seeding and the spherical bed becomes visible. The field of view (FOV), accords to the observed near-bed area, i.e. the lower half of the full water column. The roughness crest, indicated by the black line, is located at $y = 4.5\text{ mm}$ and $y = 18\text{ pixel}$, resp.

Fig. 15. Instantaneous velocity field for #sph1. Flow direction is from left to right. For visualization, in x (1) the vectors are presented with a constant convection velocity $0.85 U$ removed, and (2) only every fifth vector in x and y is plotted. Contours of swirling strength highlight the location of vortex cores (e.g., Adrian et al., 2000). The background shading indicates $(u^2 + v^2)^{0.5} > U$.

As an example, the spatial spectra S_{uu} of the velocity signal u measured on a horizontal line at a vertical bed distance of $y/\delta_h = 0.2$ are given in Fig. 16, where $\delta_h = y(\partial\bar{u}/\partial y) = 0$ refers to the dip strength phenomenon with $\delta_h/h = 0.97$ (#sph1) and 0.72 (#rhi9). The spectra are estimated by Welch's method with a window length of $n = 2^6$ using rectangular and non overlapping windows. The spectra are based on PIV vector fields that were processed without overlap. Thus, spatial resolution and vector spacing is the same. All spectra given in Fig. 16 follow the expected tendency within the inertial subrange, where a decrease of the wave number by $k^{-5/3}$ can be observed. At larger scales, this slope shifts — at least in tendency — toward k^{-1} , indicating a stronger interaction between the mean flow and its fluctuating part (Nikora, 1999). However, this characteristic is not well-pronounced here. Estimated wavelengths larger than $L = 161.2\text{ mm}$ or smaller than twice the spatial

Fig. 16. One-sided spectra $S_{uu}(y/\delta_h = 0.2)$. The bold lines denote the spectra from PIV recordings calculated using Welch's method with a window length of $n = 2^6$ (rectangular and no overlapping). Symbols indicate wavelengths of $L = n \cdot 2.52\text{ mm}$ with $n = 2^{[6,5,\dots,21]}$. The lines declining by $k/(2\pi)^{-5/3}$ give an extrapolation down to 3η , where η is approximated by Nezu and Nakagawa (1993), p. 30. The dashed lines denote spectra estimated using Welch's method with a maximum window length of $n = 2^6 + 16$. The apparent maxima of the spectra are due to the limited streamwise length of the PIV frame, the real maximum is expected to be larger.

resolution, $L = 2 \cdot 2.52$ mm, are not resolved, thus the production range and the viscous range are not displayed correctly.

At scales smaller than $L = 4 \cdot 2.52$ mm, irregularities become prominent in the appendix of the curve progressions. The spectra trend toward a horizontal line indicating the level of (subgridscale or white) noise and aliased spectral components. Here, sub-pixel displacements, i.e. small scale fluctuations, are not resolved adequately.

The spatial resolution of turbulent fluctuations is evaluated by spectral analysis in the following. Let $\sigma_{u,\text{tot}}^2$ be the total variance of the velocity signal u , consisting of $\sigma_{u,\text{PIV}}^2$ and the residual $\sigma_{u,r}^2$. Then, the variances are related by:

$$\sigma_{u,\text{tot}}^2 = \sigma_{\text{PIV}}^2 + \sigma_r^2 \quad (2)$$

The total variance can also be expressed by its one-sided spectrum as:

$$\sigma_{u,\text{tot}}^2 = \int_0^\infty S_{uu} dk \quad (3)$$

In other words, if S_{uu} is plotted against the wave number k , the area below the curve equals the variance $\sigma_{u,\text{tot}}^2$. As the velocities gained from the PIV-data represent the larger scales, an extrapolation of the $k^{-5/3}$ cascade can be used to estimate the residual $\sigma_{u,r}^2$. This approach reads:

$$\begin{aligned} \sigma_r^2 &= \int_{2\pi/L_N}^{2\pi/\eta_k} \frac{S_{uu}(k_N)}{k_N^{-5/3}} k^{-5/3} dk \\ &= -3/2 \frac{S_{uu}(k_N)}{k_N^{-5/3}} \frac{1}{(2\pi)^{2/3}} \left(\eta^{2/3} - L_N^{2/3} \right) \end{aligned} \quad (4)$$

where L_N is twice the final window size applied in vector processing, $k_N = 2\pi/L_N$ is the corresponding wave number, and the smallest relevant scale is denoted by $\eta_k (>\eta)$. If $\sigma_{u,r}^2$ is known, the quality of the PIV vector fields can be rated by the quotient of the resolved turbulence intensities, $\sigma_{u,\text{PIV}}^2/\sigma_{u,\text{tot}}^2$, i.e.:

$$\frac{\sigma_{\text{PIV}}}{\sigma_{u,\text{tot}}} = \sqrt{\frac{\sigma_{\text{PIV}}^2}{\sigma_{\text{PIV}}^2 + \sigma_r^2}} \quad (5)$$

Eqs. (4) and (5) are applied to the PIV-data. The smallest relevant scale is approximated by $\eta_k = 3\eta$. The lines declining as $k/(2\pi)^{-5/3}$ give the extrapolation to 3η (see Fig. 16), for which $S_{uu}(2L_N)$ was chosen as starting point instead of $S_{uu}(L_N)$ to exclude noise and aliasing effects at smaller scales. The spectral analysis shows an excellent quality of $\sigma_{u,\text{PIV}}^2/\sigma_{u,\text{tot}}^2 > 0.95$ for the low Reynolds number experiments of #sph1, and $\sigma_{u,\text{PIV}}/\sigma_{u,\text{tot}} > 0.95$ holds for run #rhi9. Further analysis reveals that these lower limits estimations are also valid for the vertical fluctuations σ_v .

For a further spectral analysis of the signal the modulation transfer function (MTF) has to be considered as well. However, a sound description of the MTF for the actual

measurements cannot be found due to the complexity of a global MTF that considers the PIV-algorithm and the PIV-setup including effects of the camera, laser thickness, and further geometries of the setup. Instead of a detailed consideration, a rough estimate following approaches of Foucaut et al. (2004) and Giordano et al. (2008) shows that $\text{MTF} = \sim 1.0$ for the present PIV conditions, i.e. the influence of the MTF is of minor importance. Thus we conclude that within the PIV vector fields obtained here at least 95% of the turbulence intensity is resolved.

6.3. Pros and cons of the near-bed turbulence PIV measurements

PIV-data are capable to be used for spatio-spectral analysis of the turbulence of rough bed flows. Exemplarily, we examined two PIV recordings achieved in the near-bed region of an open channel flow over porous rough bed with covering a broad diversity of fluvial Reynolds-numbers. Typically 95–98% of the expected turbulence intensities in streamwise and in vertical direction were able to be resolved. However, the present experimental set-up could not be used for PIV measurements within the interstices of the grains, mainly due to the lack of optical access and misleading laser reflections of the grains surfaces.

7. Conclusions and recommendations

The present paper summarizes the most important results, obtained with Particle-Image-Velocimetry (PIV) measurements in environmental flows that have been performed at the Institute for Hydromechanics, Karlsruhe Institute of Technology (KIT), under the guidance of Gerhard H. Jirka.

The different PIV applications presented in this paper show that this technique is on one hand a powerful tool to visualize flow properties within the water column (Sections 4–6) or at the water surface (Sections 2 and 3). Velocity distribution, recirculating flow areas, and typical eddy sizes can be observed immediately. On the other hand it has been shown, how PIV can be used to quantify turbulent flow properties and turbulent flow structures. RMS-velocities, vorticity, and swirling strength are standard parameters to be determined from PIV vector maps.

The accuracy of PIV results is strongly related to the appropriate choice of every single element of the measurement system, how they fit together and how they fit to the expected flow parameters (dynamic range, turbulence intensity, minimal and maximal eddy size). The analysis in Section 6 estimates that more than 95% of the variance of the velocity signal is captured using appropriate spatial and temporal resolution. To reach such results, the choice of camera speed, camera resolution, size of the field of view, illumination system, and all the aspects of seeding needs to be carefully prepared. Compared to point measurement systems like Laser-Doppler-Velocimetry or Acoustic-Doppler-Velocimetry, the possible number of errors that can be done during the preparation of an experiment is much higher. Another aspect compared to point

measurements is the large amount of data generated with PIV that need to be stored, evaluated, and archived.

Regarding the possibilities of PIV in environmental flows under laboratory conditions, it can be stated that the range of future applications and research projects is huge. Especially, the fact that the main part of a PIV-system can be used for very different applications regarding the size of the FOV or typical flow velocities makes PIV so attractive. The same camera with different lenses was used to analyze the flow within groin fields with flow structures of approximately 1 m (Section 3) and at the air/water interface where the resolved eddies were of the order of 1 mm.

PIV is not only restricted to the analysis of fluid motion. It can be applied to every kind of motion that is related to certain changes in intensity pattern of a digital image. For the localization of shear layers in granular material (Nübel and Weitbrecht, 2002), a commercial PIV-system was tested positive. Promising results could also be achieved by the determination of the dune speed in rivers through the water surface without interrupting the experiment.

References

- Adrian, R.J., Christensen, K.T., Liu, Z.C., 2000. Analysis and interpretation of instantaneous turbulent velocity fields. *Exp. Fluids* 29, 275–290.
- Altai, W., Chu, V.H., 1997. Retention Time in Recirculating Flow, in '27th IAHR Congress'. IAHR, Delft, Holland.
- Arita, M., Jirka, G.H., 1987. Two-Layer Model of the Saline Wedge. Part 1: entrainment and interfacial Friction. *J. Hydr. Engrg* vol. 113 (10), 1229–1248.
- Brevis, W., Weitbrecht V., Niño Y., Jirka, G.H., 2007. An integrated cross-correlation/relaxation method algorithm for Particle Tracking Velocimetry measurements in turbulent flows, *Proc. of HMEM 2007*, Lake Placid.
- Brunk, B., Weber-Shirk, M., Jensen, A., Jirka, G.H., Lion, L.W., 1996. Modeling natural hydrodynamic systems with a differential-turbulence column. *J. Hydr. Engrg* 7 (122), 373–380.
- Cowen, E.A., Monismith, S.G., 1997. A hybrid digital particle tracking velocimetry technique. *Exp. Fluids* vol. 22, 199–211.
- Detert, M., 2008. Hydrodynamic processes at the water-sediment interface of streambeds, doctoral thesis, Karlsruhe Institute of Technology, <http://digbib.ubka.uni-karlsruhe.de/volltexte/1000008267>.
- Detert, M., Nikora, V.I., Jirka, G.H., 2010a. Synoptic velocity and pressure fields at the water-sediment interface of streambeds. *J. Fluid Mech.* vol. 660, 55–86.
- Detert, M., Weitbrecht, V., Jirka, G.H., 2010b. Laboratory measurements on turbulent pressure fluctuations in and above gravel beds. *J. Hydr. Engrg.* vol. 136 (10), 779–789.
- Farmer, D.M., Armi, L., 1988. The flow of Atlantic water through the Strait of Gibraltar—the flow of Mediterranean water through the Strait of Gibraltar. *Proc. Oceanogr.* vol. 21 (1), 1–21.
- Foucaut, J.M., Carlier, J., Stanislas, M., 2004. PIV optimization for the study of turbulent flow using spectral analysis. *Meas. Sci. Techn.* vol. 15, 1046–1058.
- Fujita, I., Muste, M., Kruger, A., 1998. Large-scale particle image velocimetry for flow analysis in hydraulic engineering applications. *J. Hydraul. Res.* vol. 36 (3), 397.
- Giordano, R., Astarita, T., Carluomagno, G.M., 2008. Modulation transfer function of stereo particle image velocimetry technique. *Aeronaut. Sci. 26th Int. Congr.*
- Herlina, Jirka, G.H., 2008. Experiments on gas transfer at the air-water interface induced by oscillating grid turbulence. *J. Fluid Mech.* vol. 594, 183–208.
- Hinterberger, C., Frohlich, J., Rodi, W., 2007. Three-dimensional and depth-averaged large-eddy simulations of some shallow water flows. *J. Hydr. Engrg* vol. 133 (8), 857–872.
- Jirka, G.H., 2001. Large scale flow structures and mixing processes in shallow flows. *J. Hydr. Res.* vol. 39 (6), 567–573.
- Kühn, G., 2008. Untersuchungen zur Feinsedimentdynamik unter Turbulenzeinfluss, doctoral thesis [in German], Karlsruhe Institute of Technology, <http://digbib.ubka.uni-karlsruhe.de/volltexte/1000007360>.
- Kloosterziel, R., Carnevale, G., 1999. On the evolution and saturation of instabilities of two-dimensional isolated circular vortices. *J. Fluid Mech.* vol. 388, 217–257.
- Kloosterziel, R.C., van Heijst, G.J.F., 1992. The evolution of stable barotropic vortices in a rotating free-surface fluid. *J. Fluid Mech.* 239, 607–629.
- Lawrence, G.A., 1993. The hydraulics of steady two-layer flow over a fixed obstacle. *J. Fluid Mech.* vol. 254, 605–633.
- McWilliams, J.C., 1984. The emergence of isolated coherent vortices in turbulent flow. *J. Fluid Mech.* 146, 21–43.
- Meselhe, E.A., Peeva, T., Muste, M., 2004. Large scale particle image velocimetry for low velocity and shallow water flows. *J. Hydr. Engrg* vol. 130 (9), 937–940.
- Morin, V.M., Zhu, D.Z., Loewen, M.R., 2004. Supercritical exchange flow down a sill. *J. Hydr. Engrg.* vol. 130 (6), 521.
- Nübel, K., Weitbrecht, V., 2002. Visualization of localization in grain skeletons with particle image velocimetry, *ASTM. J. Test. Eval.* vol. 30 (4), 322–328.
- Negretti, E.M., (2007), Hydrodynamic instabilities and entrainment in two-layer stratified flows down a slope, doctoral thesis, Karlsruhe Institute of Technology, <http://digbib.ubka.uni-karlsruhe.de/volltexte/1000006963>.
- Negretti, E.M., Socolofsky, S.A., Rummel, A.C., Jirka, G.H., 2005. Stabilization of cylinder wakes in shallow water flows by means of roughness elements: an experimental study. *Exp. Fluids* vol. 38 (4), 403–414.
- Negretti, M.E., Zhu, D., Jirka, G.H., 2007. Barotropically induced interfacial waves in two-layer exchange flows over a sill. *J. Fluid Mech.* vol. 592, 135–154.
- Negretti, M.E., Zhu, D.Z., Jirka, G.H., 2008. The effect of bottom roughness in two-layer flows down a slope. *Dyn. Atm. Oceans* vol. 45 (1–2), 46–68.
- Nezu, I., Nakagawa, H., 1993. Turbulence in Open-channel Flows. Monograph Series, A.A. Balkema, Rotterdam.
- Nikora, V.I., 1999. Origin of the -1 spectral law in wall-bounded turbulence. *Phys. Rev. Lett.* vol. 83 (4), 734–736.
- Pope, S.B., 2000. *Turbulent Flows*. Cambridge University Press.
- Raffel, M., Willert, C., Kompenhans, J., 1998. *Particle Image Velocimetry*. Springer Verlag, Berlin.
- Rummel, A.C., Socolofsky, S.A., Von Carmer, C.F., Jirka, G.H., 2005. Enhanced diffusion from a continuous point source in shallow free-surface flow with grid turbulence. *Phys. Fluids* vol. 17 (7).
- Seol, D., Jirka, G.H., 2010. Quasi-two dimensional properties of single shallow water vortex with high initial Reynolds numbers. *J. Fluid Mech.* vol. 665, 274–299.
- Uijttewaalt, W.S.J., Jirka, G.H., 2003. Grid turbulence in shallow flows. *J. Fluid Mech.* vol. 489, 325–344.
- van Heijst, G.J.F., Kloosterziel, R.C., 1989. Tripolar vortices in a rotating fluid. *Nature* 338, 569–571.
- von Carmer, C.F., 2005. Shallow turbulent wake flows: momentum and mass transfer due to large-scale coherent vortical structures, doctoral thesis, Karlsruhe Institute of Technology, <http://digbib.ubka.uni-karlsruhe.de/volltexte/1000003453>.
- von Carmer, C.F., Rummel, A.C., Jirka, G.H., 2009. Mass transport in shallow turbulent wake flow by planar concentration analysis technique. *J. Hydr. Engrg* vol. 135 (4), 257–270.
- Weitbrecht V. 2004. Influence of dead-water zones on the dispersive mass transport in rivers, doctoral thesis, Karlsruhe Institute of Technology, <http://digbib.ubka.uni-karlsruhe.de/volltexte/1242004>.
- Weitbrecht, V., Kuhn, G., Jirka, G.H., 2002. Large scale PIV-measurements at the surface of shallow water flows. *Flow Meas. Instrumentation* vol. 13 (5–6), 237–245.
- Weitbrecht, V., Socolofsky, S.A., Jirka, G.H., 2008. Experiments on Mass exchange between Groin fields and the main stream in rivers. *J. Hydr. Engrg.* vol. 134 (2), 173–183.
- Zhu, D.Z., Fouli, H., Okyere, Y.A., 2002. Exchange flow through an opening. *J. Hydr. Res.* vol. 40 (3), 341–350.