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Flow Mapping of a Jet in Crossflow with Stereoscopic PIV

Meyer, K. E.*1, Özcan, O.*2 and Westergaard, C. H.*3

*1 Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Lyngby, Denmark.
*2 Department of Aeronautics and Astronautics, Technical University of Istanbul, 80626 Istanbul, Turkey.
*3 Dantec Dynamics A/S, Tonsbakken 16-18, DK-2740 Skovlunde, Denmark.

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***Abstract*:** Stereoscopic Particle Image Velocimetry (PIV) has been used to make a three-dimensional flow mapping of a jet in crossflow. The Reynolds number based on the free stream velocity and the jet diameter was nominally 2400. A jet-to-crossflow velocity ratio of 3.3 was used. Details of the formation of the counter rotating vortex pair found behind the jet are shown. The vortex pair results in two regions with strong reversed velocities behind the jet trajectory. Regions of high turbulent kinetic energy are identified. The signature of the unsteady shear layer vortices is found in the mean vorticity field.

***Keywords*:** jet in crossflow, stereoscopic PIV, flow mapping.

1. Introduction

Jets in a crossflow are of great practical relevance in a variety of engineering applications such as chemical unit operations, gas turbines and waste disposal into water bodies or the atmosphere. The characteristics of a jet in crossflow are primarily dependent on the ratio of the jet to crossflow momentum R or the velocity in case of unheated and incompressible flows. As reported by Andreopoulos and Rodi (1984), at high velocity ratios R the near field of jets in a crossflow is controlled largely by complex inviscid dynamics and the flow further downstream is influenced by turbulence. Experiments by Fric and Roshko (1994) and Kelso et al. (1996) show that there exists a complex vortical flow structure in the near field of the jet. In addition to the horseshoe vortex, ring-like vortices (jet shear-layer vortices) and counter rotating bound vortex pair, Fric and Roshko (1994) observed up-right wake vortices which extend vertically from the wall to the jet.

The majority of existing experimental data were obtained with hot-wire anemometry which is insensitive to flow direction and can give large errors in regions of high turbulent kinetic energy which may be larger than the mean kinetic energy of the crossflow. Measurements with Laser Doppler Anemometry (LDA) do not have these limitations. An example is the detailed LDA measurements by Özcan and Larsen (2001) performed in the same flow facility as used in the present study. Point-measuring techniques like LDA are very time consuming. In contrast, Particle Image Velocimetry (PIV) offers in the order of 1000 independent velocities in a single measurement. If the integral time scale of the flow is comparable to the sampling frequency of the PIV system, this means that PIV can perform measurements in planar grids several orders of magnitudes faster than LDA. Measurements in a jet in crossflow with PIV have been performed recently by Kim et al. (2000), Kim and Park (2000), Özcan et al. (2001) and Meyer et al. (2001).

The present work uses a fast technique for measuring all velocity components in a three-dimensional grid. The system consists of a stereoscopic PIV camera configuration mounted on a traversing mechanism together with light sheet optics. With this system, it is possible to measure velocities in a detailed three-dimensional grid with more than 10000 grid points with 200 samples in each point; all within one hour. The result forms the basis of a topological investigation of a complex three-dimensional flow.

2. Experimental Method

Experiments were conducted in a wind tunnel with test section width equal to 300 mm and height equal to 600 mm. The Reynolds number based on the free stream velocity (U_∞ = 1.5 m/s) and the jet diameter (D = 24 mm) was nominally 2400. The jet is issued normal to a flat plate raised from the sidewall of the tunnel. The length of the pipe employed to produce the jet flow was sufficiently large so that fully developed pipe flow approached the jet exit. The mean velocity of the pipe flow was nominally 5 m/s and the jet to crossflow velocity ratio was therefore R = 3.3. This velocity ratio was chosen to supplement existing numerical and experimental studies, notably those of Yuan and Street (1998), Yuan et al. (1999), Özcan and Larsen (2001), Meyer et al. (2001) and Kim and Park (2000). The boundary layer on the flat plate approaching the jet was also turbulent with a boundary layer thickness of $d_{99\%} \approx 70$ mm. More details of the experimental flow facility are described in Özcan and Larsen (2001) which reports LDA measurements in the incoming pipe flow and flat plate boundary layer. These measurements show that characteristics of turbulence in incoming flows agree well with experimental and computational data available in the literature. It was important to establish and document well-defined incoming conditions of this flow because computational studies have been known to be fairly sensitive to the state of turbulence in incomings flows (see Yuan et al., 1999).

Components of mean velocity and Reynolds stress were measured using a digital stereoscopic PIV system as illustrated in Fig. 1. The system consisted of two Kodak Megaplus ES 1.0 cameras with 60 mm Nikon lenses mounted in Scheimpflug condition. The angle between the cameras was approximately 80° and the recordings used an F-number of 2.8. The light sheet was created with a double cavity Nd-YAG laser delivering 100 mJ light pulses. A light guiding arm was used to connect the laser with the light sheet forming optics. Both the light sheet forming optics and the cameras were mounted on the same traversing unit. The light sheet thickness was 1.5 mm. The light sheet was perpendicular to the wall and parallel with the free stream as illustrated in Fig. 1. This gave data in y-constant planes. The area covered by both cameras was 108 × 86 mm. Image maps were recorded with an acquisition rate of 0.5 Hz. 200 instantaneous vector maps were used to calculate the processed data in each plane. A total of nine planes were taken. All data were thus taken in 60 minutes. The uncertainty of mean velocity is estimated to be below 10% of U_∞. This is adequate for a study of flow structures. A quantitative study of turbulence (or second moments) would require a higher number of instantaneously vector maps.

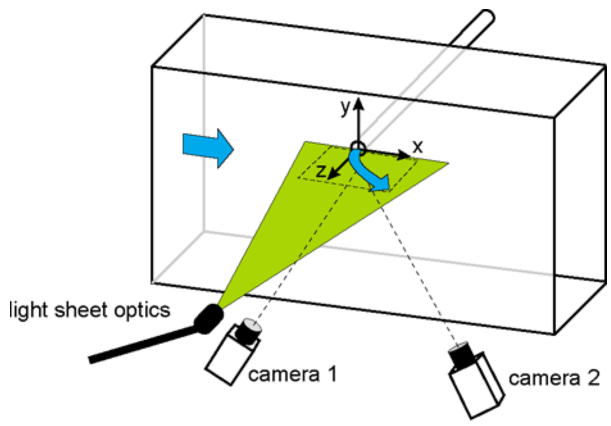

Fig. 1. Experimental set-up. Cameras and light sheet optics are mounted on the same traversing unit.

Seeding consisting of 2-3 μm droplets of glycerine was added to both the main flow and the jet. The seeding concentration in main flow and jet was adjusted to be equal based on visual evaluation of the PIV images. The measuring system was controlled by a Dantec PIV2100 processor and the data was processed in 32 × 32 pixel interrogation areas with Dantec Flowmanager version 3.4 using adaptive velocity correlation. A 25% overlap was used between interrogation areas. The geometrical information needed for the reconstruction of the three components of velocity was based on images of a calibration target. Images of the target (aligned with the light sheet) were taken with both cameras in five different planes in the out-of-plane direction. The reconstruction was performed by a linear transformation using the calibration. The final vectors maps contained 33 × 37 three-component velocity vectors.

3. Results and Discussion

Data taken in the same flow facility at z-constant planes (Meyer et al., 2001) have demonstrated that the flow is symmetric in the $y = 0$ center plane. The acquired data therefore assume this symmetry and only cover positive values of y. A total of nine y-constant planes starting at the center plane $y = 0$ and ending at the plane $y = 2D$ were taken. The measurement domain is defined by: $-1 < x/D < 3.5$, $0 < y/D < 2$, $0 < z/D < 3.5$. The grid resolution is $0.25D$ in the y-direction, $0.14D$ in the x-direction and $0.10D$ in the z-direction. The data are presented in terms of the three-dimensional mean velocity field and the turbulent kinetic energy. The qualitative flow structures found in the present study are in good agreement with the LDA data taken in the same flow facility by Özcan and Larsen (2001).

Figure 2 shows stream traces released in a rectangular grid in the plane $z/D = 0.3$. Figure 2 also shows colormaps of the velocity component U in the x-direction at the center plane ($y = 0$) and at $x = 3.5D$. The planes with colormaps also show sectional streamlines. The plot shows how the stream traces upstream of the jet pass around the jet due to inviscid effects - almost as if the jet was a solid cylinder. In the wake of the jet, the stream traces reveal a complex vortical structure. Differences between the wakes of a jet and a solid cylinder are discussed in Fric and Roshko (1994). The streamlines shown in the center plane ($y = 0$) tend to converge in the jet.

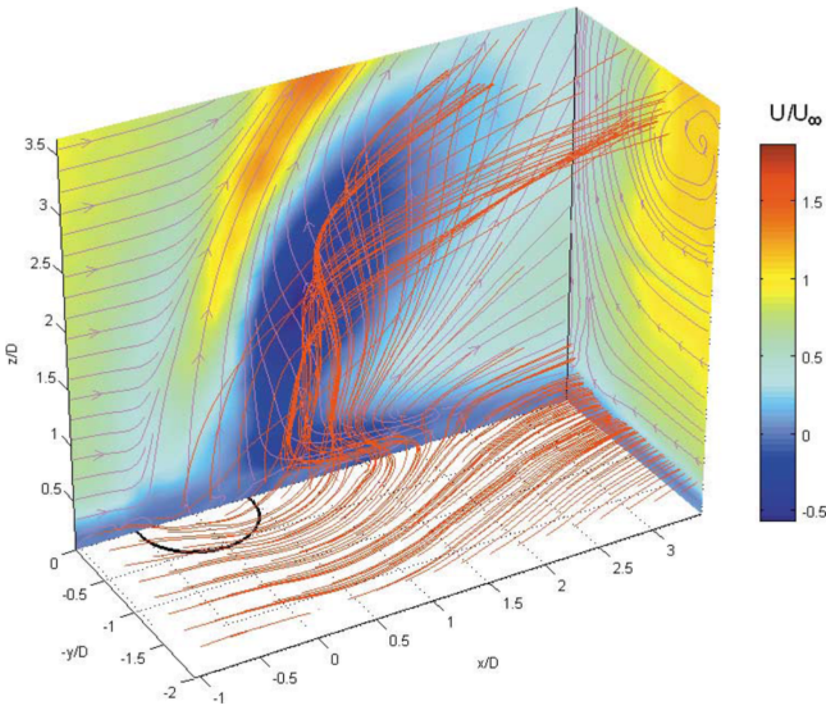

Fig. 2. Mean velocity field. Colormaps show velocity component in x-direction, U/U_∞. Red lines are stream traces started from a rectangular grid at $z/D = 0.3$. Magenta lines on colormaps are sectional streamlines.

Following Yuan and Street (1998), we will use the streamline started at the coordinate systems origin as an indicator of the jet trajectory. Stream traces released less than one jet diameter from the jet axis go into a strong vertical vortex situated one jet diameter downstream of the jet core. This vortex is a result of the counter rotating bound vortex pairs found behind the jet trajectory. The counter rotating vortex pairs have instantaneous features (see Kim and Park, 2000) that are not revealed in the presented plots. A projection of the same vortex is seen in the sectional streamlines shown on the $x/D = 3.5$ plane. The colormap at the center plane reveals two regions of reversed flow (negative U) downstream of jet. The first region is close to the wall and extends downstream to $x/D = 2$. The stream traces entering this region makes a sharp turn and then have the main velocity component in the upstream direction. The second region is found near $x/D = 1$ and $z/D = 1.5$. Here, the largest negative values of U ($U/U_\infty < 0.5$) are found, but the streamlines in the center plane reveal that the velocity component W in the z-direction is even larger.

The velocity vectors in the vicinity of the wall are somewhat contaminated with noise due to light reflections from the wall. This shows up as wiggles in the streamlines in the center plane close to the wall.

Figure 3 shows colormaps of the velocity component *W* in the *z*-direction at the center plane ($y = 0$) and at $z = 1.3D$ plane where sectional streamlines are also shown. The high velocity core of the jet is clearly seen before it bends downstream for $z/D > 2$. At $z/D = 1.3$, the jet core is elongated in the *y*-direction. Behind the jet core, a vortex, that is a result of the counter rotating bound vortex, pair is clearly seen. This is responsible for the negative *U* velocity component found here. Just at the jet exit, very low levels of the *W* velocity component are erroneously seen. Here, the highest velocities are expected. Some particles made visible by the second laser pulse are inside the pipe during the first laser pulse and they do therefore not contribute to the velocity estimate. This causes a strong velocity bias towards zero.

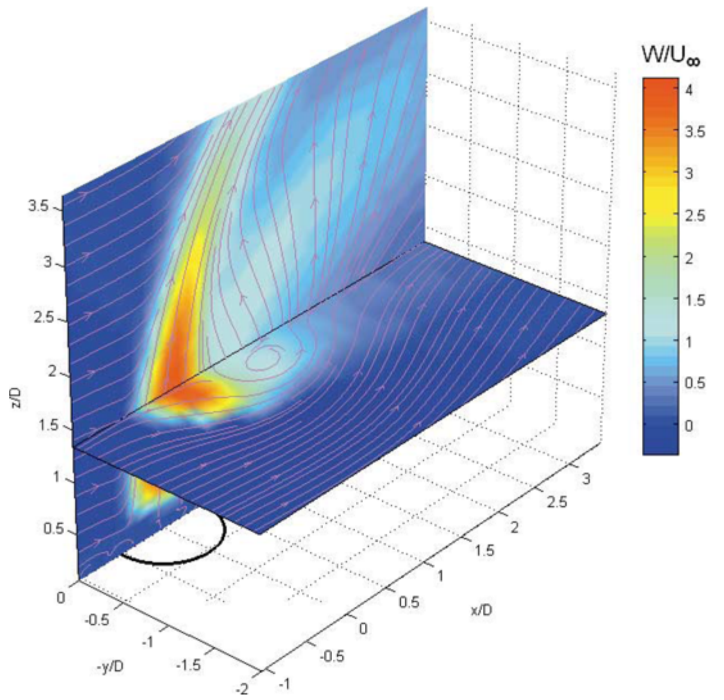

Fig. 3. Mean velocity field. Colormaps show velocity component in *z*-direction, W/U_∞. Magenta lines on the colormaps are sectional streamlines.

Figures 4 and 5 show colormaps of *U* and turbulent kinetic energy *k*, respectively. The turbulent kinetic energy has been calculated using all relevant Reynolds stresses. The colormaps are shown at the center plane ($y = 0$), and at the planes $z/D = 1.0$, $x/D = 0.9$ and $x/D = 3.5$. At the center plane, sectional streamlines are shown as magenta lines. At the other planes, three-dimensional velocity vectors are indicated with red arrows. Figure 4 supplements Fig. 2. The highest level of *U* is found about one diameter from the center plane in a region next to and just downstream of the jet core. This is caused by the inviscid passage of the crossflow around the jet. Figure 4 also illustrates that the region of reversed flow behind the jet is quite thin in the *y*-direction. The velocity vectors also show that the flow has its main direction in downstream directions except for the region in and just downstream of the jet.

In Fig. 5, it is seen that the jet core contains low turbulence levels. Please note that an erroneously high level of turbulence is found just at the jet exit. As explained above, a strong velocity bias causes errors in the velocity estimates at this position. Increased level of turbulence is seen in the shear layer formed between the jet and the crossflow. Here, the highest levels are found to be $k/U_\infty^2 \approx 0.7$ in a region just upstream of the jet trajectory at a distance of 2-3*D* from the wall. A high velocity gradient between main flow and reversed flow behind the jet is also seen in Fig. 4 in the $x/D = 0.9$ plane. As expected, high levels of *k* are also seen in this region. The highest levels of turbulence are found in a small region located at $(x/D, y/D, z/D) = (1.0, 0.5, 1.0)$. This region is slightly downstream of the point with highest *U* velocity component seen in Fig. 4. The very high levels of *k* found in this region are probably also caused by unsteady flow structures related to the creation of the counter rotating bound vortex pairs.

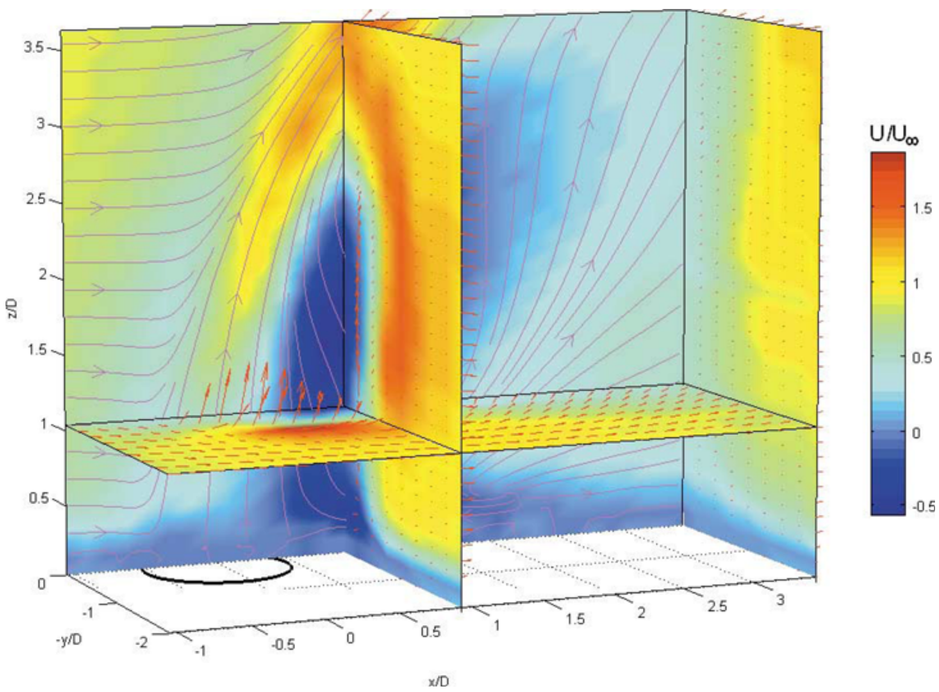

Fig. 4. Mean velocity field. Colormap shows U/U_∞. Red arrows are velocity vectors. Sectional streamlines are shown on the y = 0 plane.

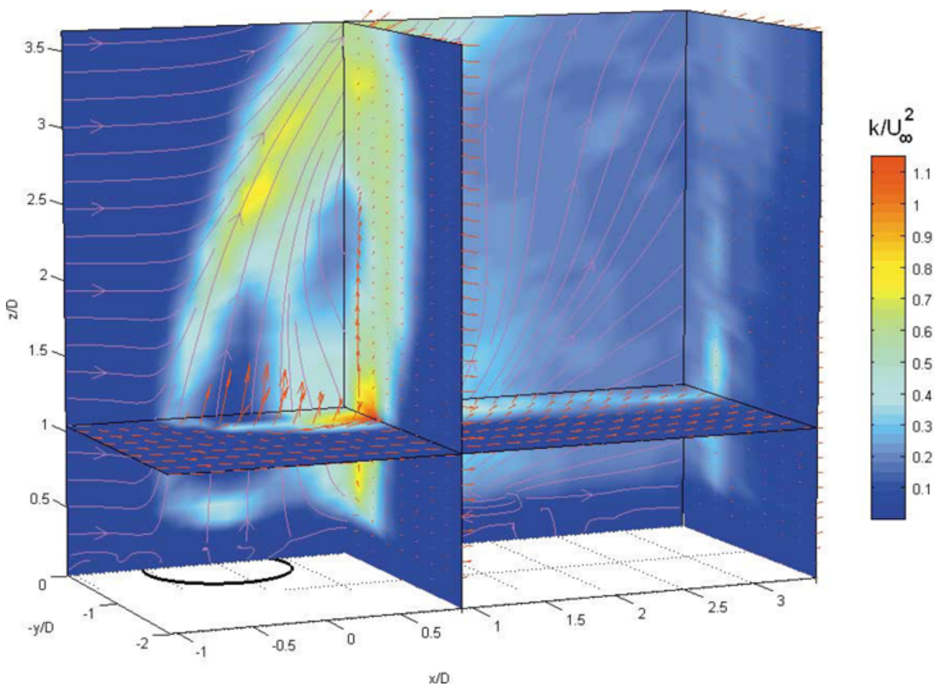

Fig. 5. Turbulent kinetic energy k/U_∞^2 shown on colormaps. Red arrows are velocity vectors. Sectional streamlines are shown on the y = 0 plane.

Figure 6 presents a colormap of the normalized y vorticity component. On the plane of symmetry, the y component is the only nonzero component of the vorticity vector. Isosurfaces of y vorticity component corresponding to −9.4 and 6.6, which are respectively denoted by blue and red colors, are shown in Fig. 6. The isosurfaces resemble three fingers, which stick out from the plane of symmetry. LDA data presented by Özcan and Larsen (2001) show similar peaks in the y vorticity and suggests that there may be additional peaks for $z/D > 2$.

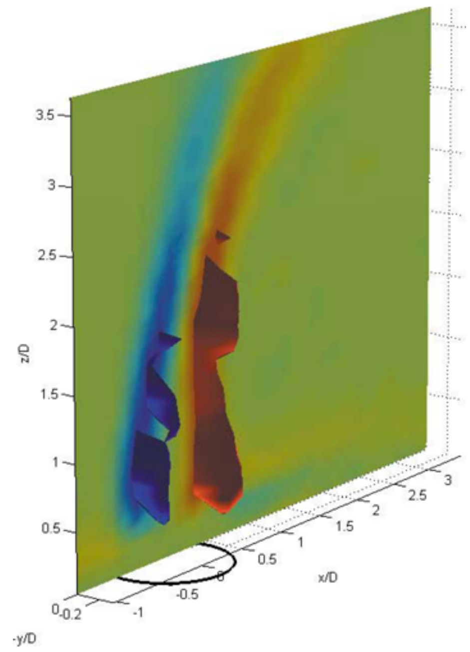

Fig. 6. The *y*-component of the normalized vorticity vector shown as a colormap with red and blue colors indicating positive and negative vorticity, respectively. Red and blue isosurfaces show constant levels at 6.6 and –9.4, respectively.

The peaks in *y* vorticity probably originate from the upstream and lee-side vortex loops (shear layer vortices) in the vortex skeleton model proposed by Lim et al. (2001). The shear layer vortices are moving in the jet directions. A trace of these vortices in the mean vorticity field suggests that the creation of the vortices to some extent is fixed in space. However, this should be investigated in a data set with higher statistical accuracy than the present. The upstream and lee-side vortex loops merge into the counter rotating vortex pair through side arms in the model of Lim et al. (2001).

4. Conclusion

Complex three-dimensional flows like the investigated jet in crossflow are difficult to understand without full three-dimensional data available. In the present study, stereoscopic PIV measurements performed in a one hour period provided a reasonably accurate three-dimensional data set suitable for flow visualization. Interpretation of the data requires three-dimensional plots similar to the ones presented in the paper. However, full justice to the plots is only obtained when they are rotated "online" to get a better sense of the three-dimensionality.

The data presented give a good insight in the formation of the counter rotating bound vortex pair. The data also show two regions of reversed flow behind the jet. However, the horseshoe vortex expected in front of the jet is probably situated too close to the wall to be captured with the used camera set-up. High levels of turbulence in terms of the turbulent kinetic energy *k* are observed in regions with interaction between jet and free stream and at the boundary of the largest region with reversed flow behind the jet. Very high levels of *k* are found in a small region one diameter downstream of the jet axis and half a diameter from the center plane. A closer study of unsteady flow structures would probably give a better understanding of this region. The upstream and lee-side vortex loops (shear layer vortices) are intrinsically unsteady and therefore are not observable in the time-averaged streamline patterns. Despite this, the vortex loops leave their signature on the mean vorticity field as shown in the present study, which support the vortex skeleton model proposed by Lim et al. (2001).

The combination of laser light intensity, particle size and camera does not give optimal conditions for accurate recording of particle positions. The calculated particle image size is somewhat smaller than one camera pixel. This results in some uncertainty in the estimated particle displacements. The uncertainty of mean velocities is estimated to be below 10% of the free stream velocity. This uncertainty can be reduced significantly by improved optical conditions (e.g. a more sensitive camera) and by a higher number of samples. However, the accuracy is sufficient for a study of general flow structures. Also, the results are in qualitative agreement with LDA measurements performed in the same flow facility. For a detailed study of flow and Reynolds stresses, a sampling size larger than 200 vector fields per plane is required.

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Author Profile

Knud Erik Meyer: He received his Ph.D. degree from Technical University of Denmark in 1994 on a study of heat transfer in tube bundles involving both experiments and CFD calculations. He is now an associate professor in experimental fluid mechanics. Present research interests are optical flow measurements (LDA, PIV, LIF) and a number of industrial flow applications.

Oktay Özcan: He received his Ph.D. degree in Mechanical Engineering in 1982 from the University of California at Berkeley. He worked at the NASA-Ames Research Center as a postdoctoral research associate in 1982-1983 and also in 1988-1990. He was a visiting professor in the Departments of Energy and Mechanical Engineering at Technical University of Denmark between 1999 and 2001.

Carsten H. Westergaard: He received his M.Sc. degree in Mechanical Engineering in 1991 from the Technical University of Denmark and his Ph.D. in 1994 within optical measurements of turbulent structures, specifically particle image velocimetry. The work included high-resolution measurements in turbulent pipeflows at the lab. of Prof. Adrian at University of Illinois and development of optical correlation techniques based on photorefractive crystal with Prof. Buchhave at the Physics Dept., DTU. Later, he worked in Danish wind turbine industry performing calculations and measurements within the fields of aerodynamics, aeroacoustics, aeroelasticity and structural dynamics for wind turbine blades. Through a number of EC projects, CFD applied to wind turbines was studied. Today he is product manager for PIV and related products at Dantec Dynamics.