Time-resolved stereoscopic PIV experiments for validating transient CFD simulations

Markus Honkanen[1], Johanna Heikkinen[2], Pentti Saarenrinne[1], Jarmo Korpijärvi[2]

Abstract This paper presents Time-Resolved Stereoscopic Particle Image Velocimetry (TRSPIV) experiment to resolve transient flow structures in a lab-scale mixing tank. The pathlines of individual trailing vortices are tracked in the TRSPIV data obtained in the turbine discharge zone. In addition, a Lagrangian Particle Tracking algorithm is utilized to track particle pathlines in the flow field. The experimental data is utilized in the validation of transient Computational Fluid Dynamics (CFD) simulations. An extensive set of CFD simulations has been performed on the tank using two turbulence models – Transient RANS model (SST-k-ω) and Scale Adaptive Simulation (SAS). Model validation against the experimental data showed that the SAS model was able to capture the main characteristics of the trailing vortices, while the vortex trajectories terminated too early in the SST predictions. The further validation of SAS model is obtained by comparing the statistics of simulated fluid particle trajectories and measured tracer particle trajectories.

Experiments

TRSPIV experiments have been carried out with a commercial LaVision PIV system that consists of two high-speed, digital, double-frame CMOS cameras (PCO) that obtain 630 Hz frame rate with a resolution of 1280x1024 pixels and a high-speed Nd-YLF laser (New Wave, Pegasus) with a 10 mJ pulse energy at kHz pulse rate. The lab-scale mixing tank and the measurement setup are shown in Figure 1a. The cameras are arranged in an angular displacement system that is geometrically calibrated to view a 49x36x1 mm^3 measurement volume in the cross section of the mixing tank. The area of interest is located in the turbine discharge zone and it is perpendicular to the plane of two carrier bars. All three components of fluid velocity are acquired in the measurement plane from image sequences of illuminated tracer particle images. Figure 1b shows an instantaneous 2d-3c fluid velocity field in a turbine discharge zone.

a) b)

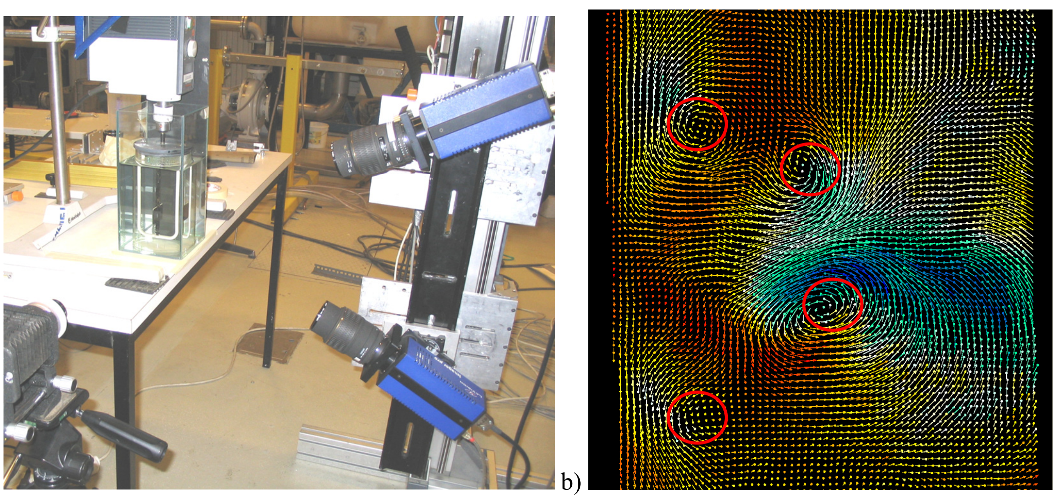

Figure 1. a) Experimental setup and b) an instantaneous 2d-3c velocity field in a turbine discharge zone. Vector colour shows the tangential velocity (red = 0 m/s, blue = 0.4 m/s). Vortices are shown with red circles.

[1]Tampere University of Technology, Energy and Process Engineering P.O.Box 589, FIN-33101 Tampere, Finland
Correspondence to: Markus.Honkanen@tut.fi

[2]Numerola Ltd. P.O.Box 126, Väinonkatu 7C, FIN-40101 Jyväskylä, Finland

1300 velocity fields are measured at 192 Hz sample rate, which corresponds to the total of 18 rotation cycles at 160 rpm turbine speed. The turbine blade moves exactly 5 degrees between each resolved velocity field. The time delay between the frames of each double-frame image is 0.6 ms, which ensures that the measured velocity fields are truly instantaneous. The minimum Kolmogorov time scale is about 1.25 ms, minimum velocity scale is 0.03 m/s and the minimum length scale is about 40 μm. The spatial resolution of measurements is 7 times the Kolmogorov length scale and the time resolution of measurements is 4 times the Kolmogorov time scale. Therefore, the turbulent kinetic energy can be resolved almost totally, but only about half of the turbulent kinetic energy dissipation rate is measured. The large-scale flow structures and their instabilities are measured with high accuracy.

CFD model validation with experimental data

Instead of turbulence quantities, the large-scale flow structures are characterized and the experimental results are utilized in the model validation. The periodic and aperiodic (turbulent) motion of trailing vortices is resolved both in experiments and in simulations. Figure 2 shows the 3D trajectories of trailing vortices at 160 rpm turbine speed detected in the experimental data and in the simulated data calculated by SAS and SST turbulence models. It can be seen that the SAS turbulence model provides results that are similar to the experimental data. Some discrepancies can be noted with small blade angles (0-10º), where the experimental data shows more scatter. On the other hand, the measurement locations close to the blade are more prone to errors than angles further away from the blade. When turbulence is described by the SST model, vortices are not detected at blade angles > 120º but they vanish on the vessel wall boundary layer. This implies that the dissipation of the turbulent structures is overestimated. SAS also slightly over-estimates dissipation compared to experiments.

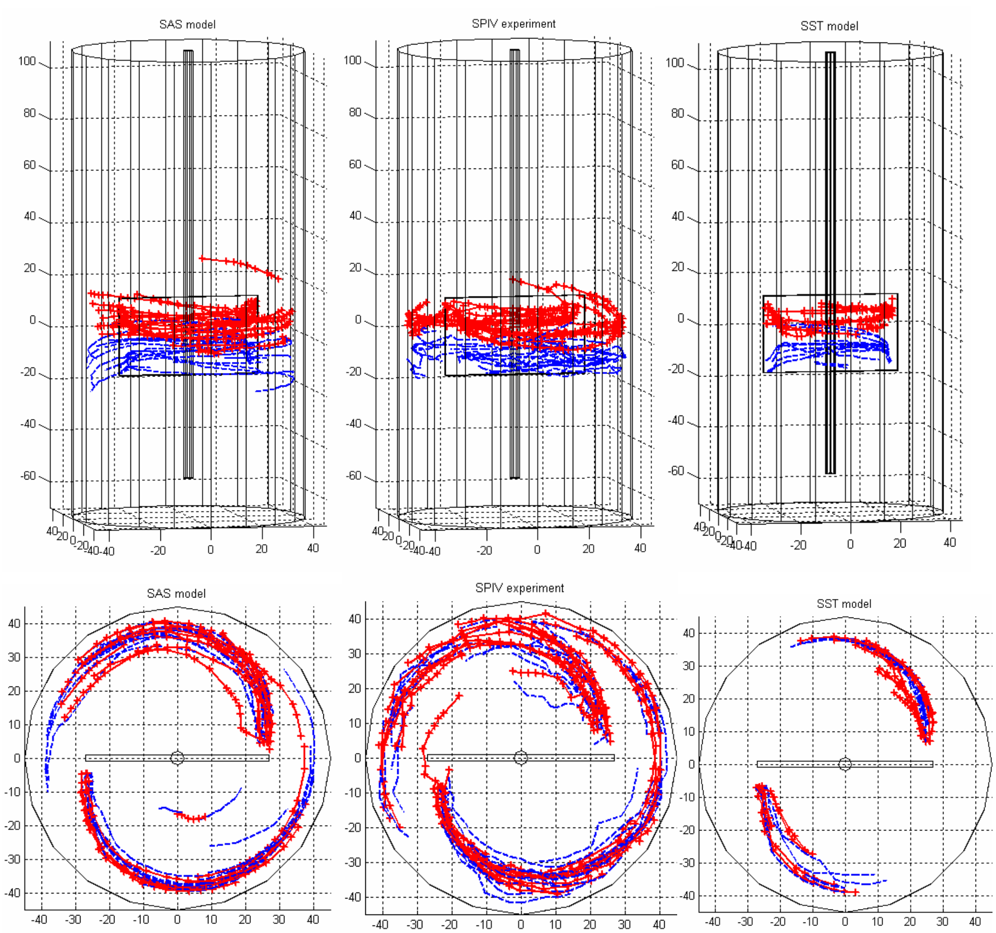

Figure 2. The three-dimensional trajectories of trailing vortices. Left SAS model, middle experimental, right SST model. The upper images show the side view, lower the top view.