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On the challenges of precise velocity measurements in vertical convective wall jets

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Abstract

For the transition of our energy supply towards a higher share of renewables, thermal energy storage (TES) systems are, besides electric batteries and chemical energy storage systems, one promising solution to overcome the volatile nature of renewable energy sources. For the most efficient operation, the liquid storage material in the tank should be stratified by its temperature-dependent density. As a result, the cold fluid remains at the bottom, and the heated fluid rises to the top (Alva et al. (2018)). Typically steel tanks are used for TES, and thus, the wall material has a thermal diffusivity that is one to two orders of magnitude higher than that of the storage fluid. Consequently, the tank's sidewalls work as a thermal bridge between the stratified layers. In recent studies, the authors have shown that the resulting heat flux induces two counter-directed, convective wall jets near the sidewalls of the tank, which increase mixing of the stratification and thus lowers the exergy content and the storage efficiency (Otto et al. (2019, 2020)). Using a model experiment of a TES, the entire vertical extent of the detected wall jets is investigated. Hence, the typical flow structures of vertical, natural convection under the influence of non-zero temperature gradients in the ambient fluid can be analyzed, which can help to improve storage tanks in the future.

The velocity in the region of the wall jets is measured via 2d particle-image velocimetry (PIV) in a rectangular model experiment of 750 mm height on a base area of 375 mm × 375 mm made from polycarbonate. The jets evolve on the surface of an aluminum plate simulating the storage tank's sidewall. The measuring system consists of four cameras with a resolution of 2160 × 2560 pixels combined with objective lenses with 100 mm focal length capturing the raw images in a plane perpendicular to the aluminum wall. A Nd:YAG laser with a wavelength of 532 nm illuminates the measuring plane. Simultaneously using up to four cameras adjacent to each other and stitching their resulting vector fields, the vertical extent of the field of view increases from 38 mm up to 140 mm. Despite this, the field of view is still much smaller than the vertical extent of the model experiment, so that seven consecutive runs are performed to cover the entire height. Disturbing reflections of the laser light sheet on the aluminum wall are eliminated using optical filters for the cameras that are opaque for the green laser light in combination with fluorescently (Rhodamine B) dyed PMMA tracer particles with a diameter between 1–20 µm. The particles emit light at a wavelength of 610 nm (orange light) and can therefore be detected through the cameras' filters. During four separate measuring periods, where each lasts for two minutes, double frame images are captured with a time difference of 19.981 ms (maximum possible value) at a measuring frequency of 7 Hz. Figure 1 shows a schematic of the camera setup next to the model experiment and the measurement and evaluation procedure to finally receive one time-averaged velocity field per measuring period of the full height of the experiment.

The raw data evaluation process starts with calculating the vector fields of all cameras used at a certain measuring position and stitching them to one flow field of this position. Since the wall jets' horizontal extents are with 2–7 mm relatively small and they show high velocity gradients, the raw images are evaluated in both single-frame and double-frame mode. With a velocity threshold that corresponds to a pixel displacement of $\frac{1}{4}$ of the interrogation window size and the time difference of the single-frames, the resulting vector fields are masked and merged into one final vector field. This vector field consists of high velocities evaluated in double-frame mode and low velocities evaluated in single-frame mode (see Figure 2) thus minimizing the relative error. The algorithm used in this work is similar to the multi-frame PIV approach introduced by Hain and Kähler (2007). Figure 3 shows the time-averaged results of the first measuring period for each of the seven measuring positions in height.

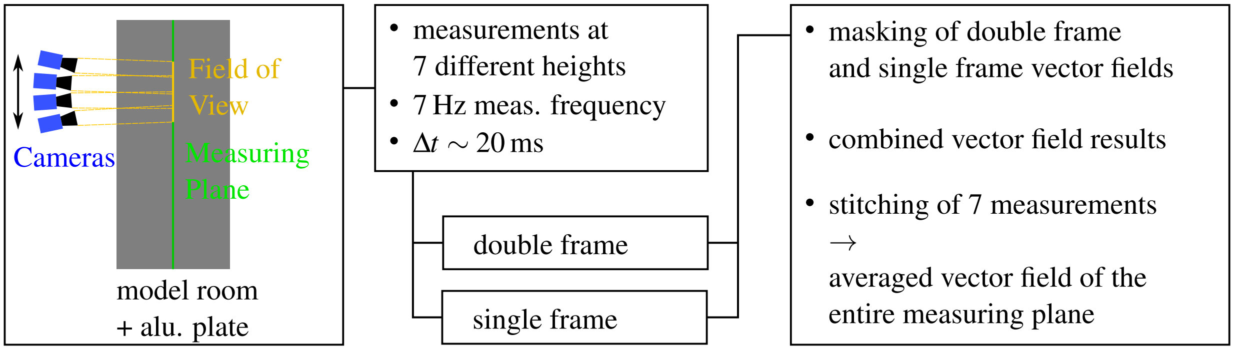

Figure 1: Schematic of the camera setup and the evaluation procedure.

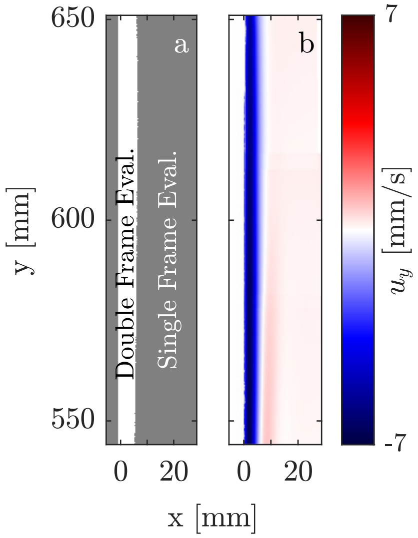

Figure 2: a) Masking areas of single and double frame evaluation. b) Resulting vertical velocity field after merging.

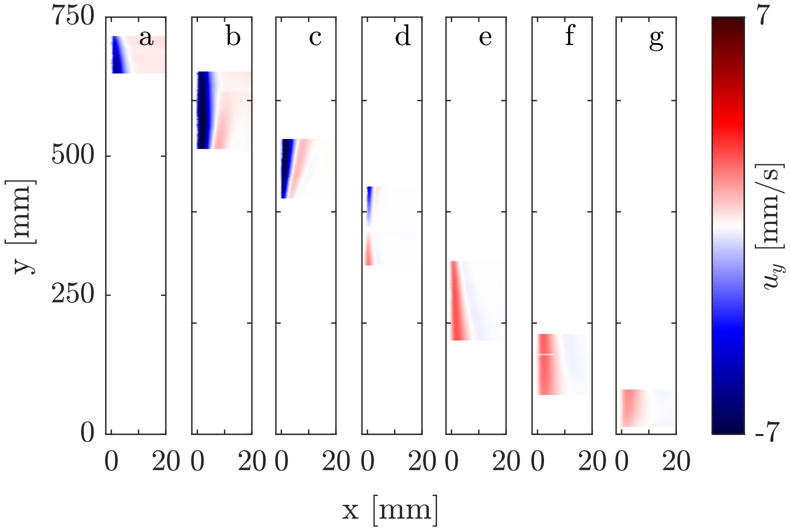

Figure 3: Resulting vertical velocity fields of the 7 measurements at different heights. Subfigure b) equals Figure 2b). Each subfigure shows the stitched velocity field of all cameras used during that measurement.

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