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The Interaction Between Inflow and Recirculating Flow in Mixing Tanks

Interaktion zwischen Zulauf und Rezirkulationsströmung in Mischbehältern

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Abstract

Jet inflow into a large tank can induce a slow recirculation flow which interacts with the inflow jet. The present work studies both the static and the dynamic dependencies of this interaction. Laboratory experiments have been performed in a model water tank with turbulent inflow jet of varying jet Reynolds numbers. Planar particle image velocimetry was used to obtain horizontal two-component velocity fields of the resulting flow. Through mean field analysis and comparison to the self-similar behavior of a free jet, the static aspects of the inflow and recirculation interaction are investigated. The recirculating back flow generated by the inflow jet influences the otherwise self-similar behavior of the jet. Regarding the dynamic aspect of the interaction, proper orthogonal decomposition (POD) has been carried out on the flow fields in order to study the modal behavior of the flow. The inflow jet is found to oscillate both horizontally and vertically. Higher harmonic oscillations have also been observed.

Introduction

Storage Tanks are a vital component of drinking water supply networks. They act as storage tanks or buffer pressure fluctuations in the system. Turbulent inflow jets can provide efficient mixing in tanks as first investigated by Fossett and Prosser 1949. The complex flow structure developing in storage tanks, especially in the case of tanks fed by turbulent inflow jets, can lead to vast differences in residence times for different regions of the tank (see for example Tian and Roberts 2008). Sedimentation behavior of suspended particulate matter is also directly affected by the flow structure inside the tank. A single-port turbulent jet inflow into a partly filled rectangular tank will induce a recirculating flow inside the tank in case of a fill cycle as well as for the flow-through operation (filling and drawing of the tank occurring simultaneously). The focus of this work is to investigate the interaction between the inflow jet and the recirculating flow induced by it in order to eventually enable assessment and improvement of mixing performance and residence times in the different regions of a mixing tank.

Experimental Procedure

The experiments were performed in a hexahedral laboratory glass tank with a footprint of $L \times W =$ 81 cm × 62 cm. The water enters the tank through a double-bent pipe with a jet nozzle ending 15 cm from the near wall through which the pipe enters and the jet pointed horizontally and

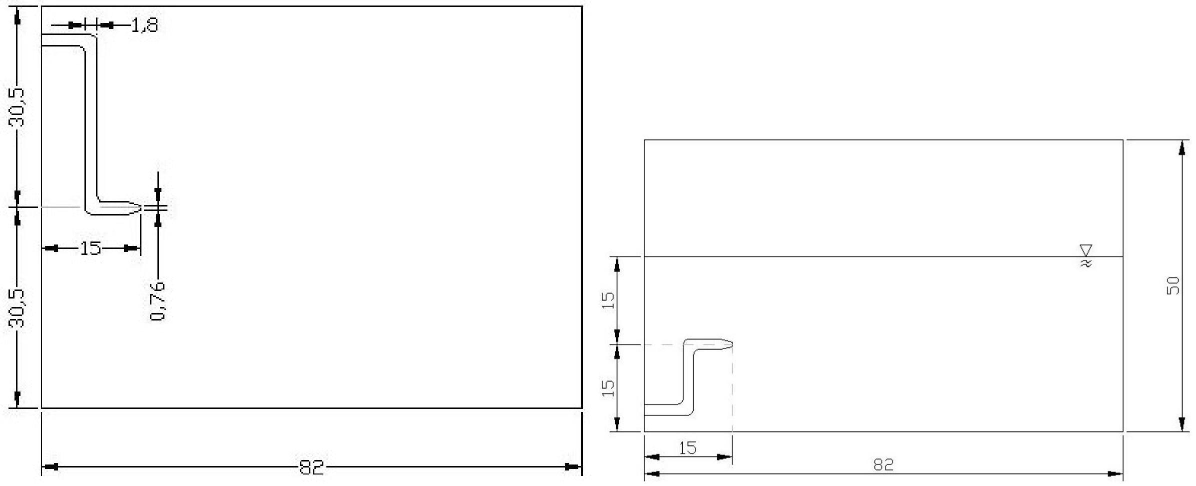

Figure 1: top view (left) and side view (right) of the hexahedral laboratory tank with inflow jet nozzle, measurements in [cm]

parallel to the side walls at mid-depth as depicted in figure 1. The water exits the tank through a hole in the near wall near the bottom of the tank next to the entry pipe hole (upper left corner of the top view in figure 1). The tank was operated as a flow-through tank with constant water level $H = 30\,\text{cm}$. Measurements were done for jet Reynolds numbers of 5000, 7500, and 10 000. A horizontal laser sheet was projected into the tank using a Spectra-Physics 4 W Ar-Ion continuous-wave laser as a light source. Three planes at different depths were measured consecutively for each experiment ($h = 1/3H$, $h = 2/3H$, and in the jet axis level $h = .5H$). Images were recorded using a ccd camera (Allied Vision Prosilica GE1650) mounted above the tank looking down and recording at 32 Hz acquisition frequency. Recording time was 20 minutes per experiment, resulting in approximately 38 000 consecutive frames used for both the mean field analysis as well as the modal analysis. In-house code was used for image acquisition, pre- and post-processing, and for the Proper Orthogonal Decomposition while the open source code Prana PIV was used for PIV cross correlation.

Results and Discussion

The flow inside the mixing tank exhibits a characteristic pattern as depicted in figure 2. The blocked out part in the lower left corner of the figure is the area where the jet nozzle of the inlet pipe blocked of the laser sheet in the mid-depth plane. The jet issues from the end of the inflow nozzle (at approximately $x = 0.2L$ with x as the jet axial direction). For a short distance, the axial velocity is too high for the tracer particles to be captured by the present PIV system. Reliable axial velocity fields in the jet core are produced starting at $x \approx 0.4L$ for the intermediate Reynolds number case (Re$=$ 7500). Once the jet hits the far wall of the tank, the flow is deflected both vertically and horizontally. The horizontal measurement plane in figure 2 shows the horizontal components of this deflection as two counter-rotating vortical structures in the two far corners of the tank (right-hand wall in figure 2). A back flow occurs with fluid flowing back towards the entry side of the tank and the recirculating fluid is partly entrained back into the jet. In the near half of the tank (left half of figure 2) it can be observed that the flow direction of the recirculating flow seems to cross the inflow jet without fluid being entrained into it. This is due to the recirculating fluid flowing above and below the inflow jet axis towards the tank outflow opening at the bottom

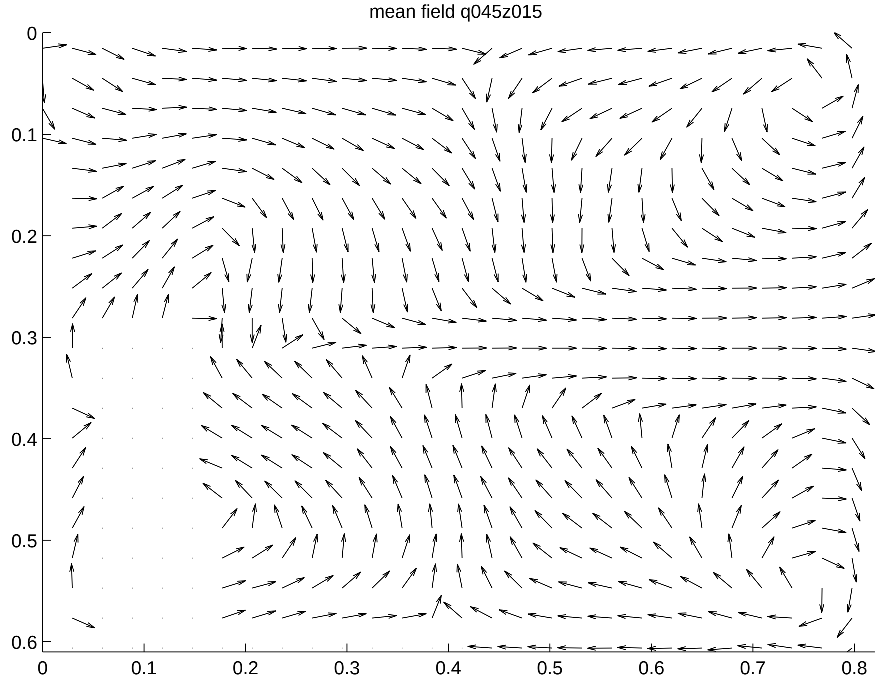

Figure 2: top view of mean flow directions in the mid-depth plane for Reynolds number 7500, dimensions in [m]

of the near end corner (top left in figure 2), but this motion cannot be directly observed in the PIV results due to the horizontal orientation of the measurement plane.

Major characteristics of jets are self-similarity and spreading rate S (see for example Rajaratnam 1976). Once fully developed, the free jet is self-similar so that the axial velocity profile plots of any axial location along the jet should collapse into one curve when non-dimensionalized with the centerline velocity and the jet's half-width (the radial location where $u = .5u_{center}$). The non-dimensional axial jet profiles are depicted in figure 3 and it can be seen that the jet exhibits self-similar behavior in its core up to about one half-width from the centerline. Further outwards, the axial velocities deviate from self-similarity depending on the axial position of the jet as the recirculating flow in the tank influences and deforms the jet. Thus, the region of self-similarity inside the jet can be seen as the zone where the jet flow dominates whereas the tank recirculation dominates the flow in the rest of the tank. The spreading rates of the jet are depicted in figure 4 for different axial locations in the far half of the tank. Hussein et. al. 1994 have done extensive measurements for the free jet where a constant spreading rate is expected and two typical empirical values, $S = 0.096$ and $S = 1.02$ have been plotted into figure 4 for reference. As can be seen, the jet in the present case shows a relatively wide range of S for a given axial location depending on Reynolds number. Also, the calculated spreading rates for the left and right side of the measured jet plane differ as the recirculating flow is not symmetric to the jet axis. Yet, the mean spreading rate (solid line) is close to the free jet spreading rates up to about $x = .7L$. From there on, spreading rates increase vastly as the influence of the main recirculating vortical structures increases. This corresponds to the behavior of the profiles in figure 3, where it can be seen that up to $x = .73L$ the profiles show self-similarity within 2 half-widths of the centerline and even beyond, whereas from $x = .77L$ on the profiles start deviating from self-similarity already outwards of one half-width.

The divergence fields of the mean flow are depicted in figure 5 for the case of Re $= 7500$ in two measured planes, the mid-depth jet axis plane ($h = .5H$) and the plane 5 cm below

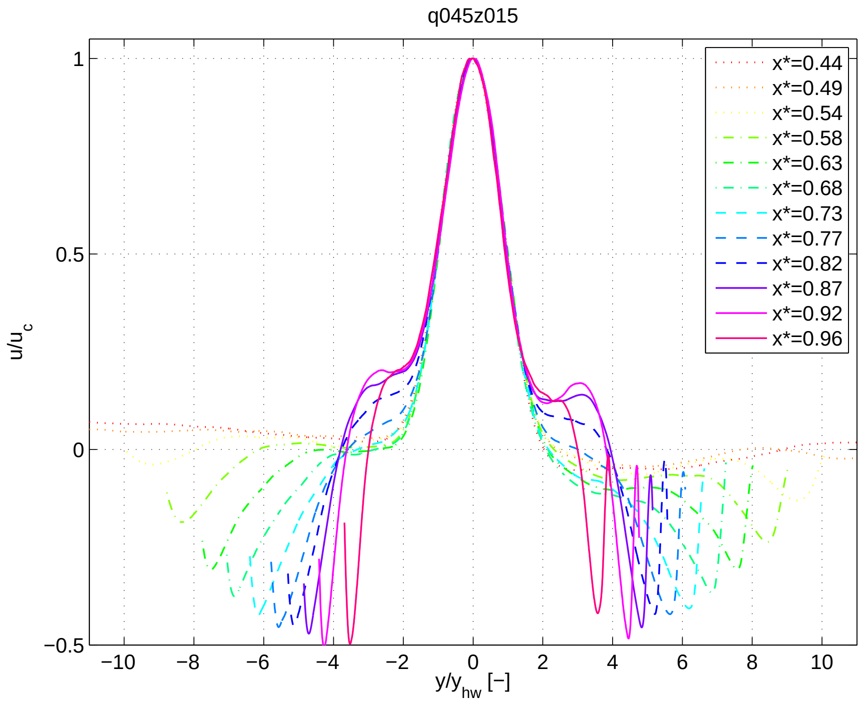

Figure 3: non-dimensional axial velocity profiles of the jet at Reynolds number 7500

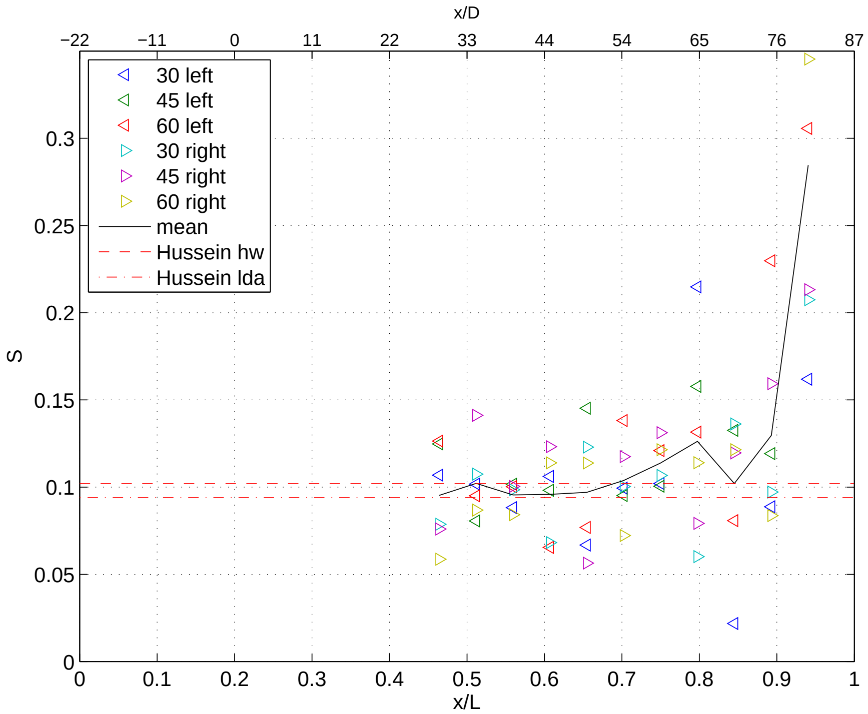

Figure 4: left and right side spreading rate of the jet for different reynolds numbers compared to empirical spreading rates of free jets; case numbers 30, 45, and 60 correspond to the three Re numbers 5000, 7500, and 10 000

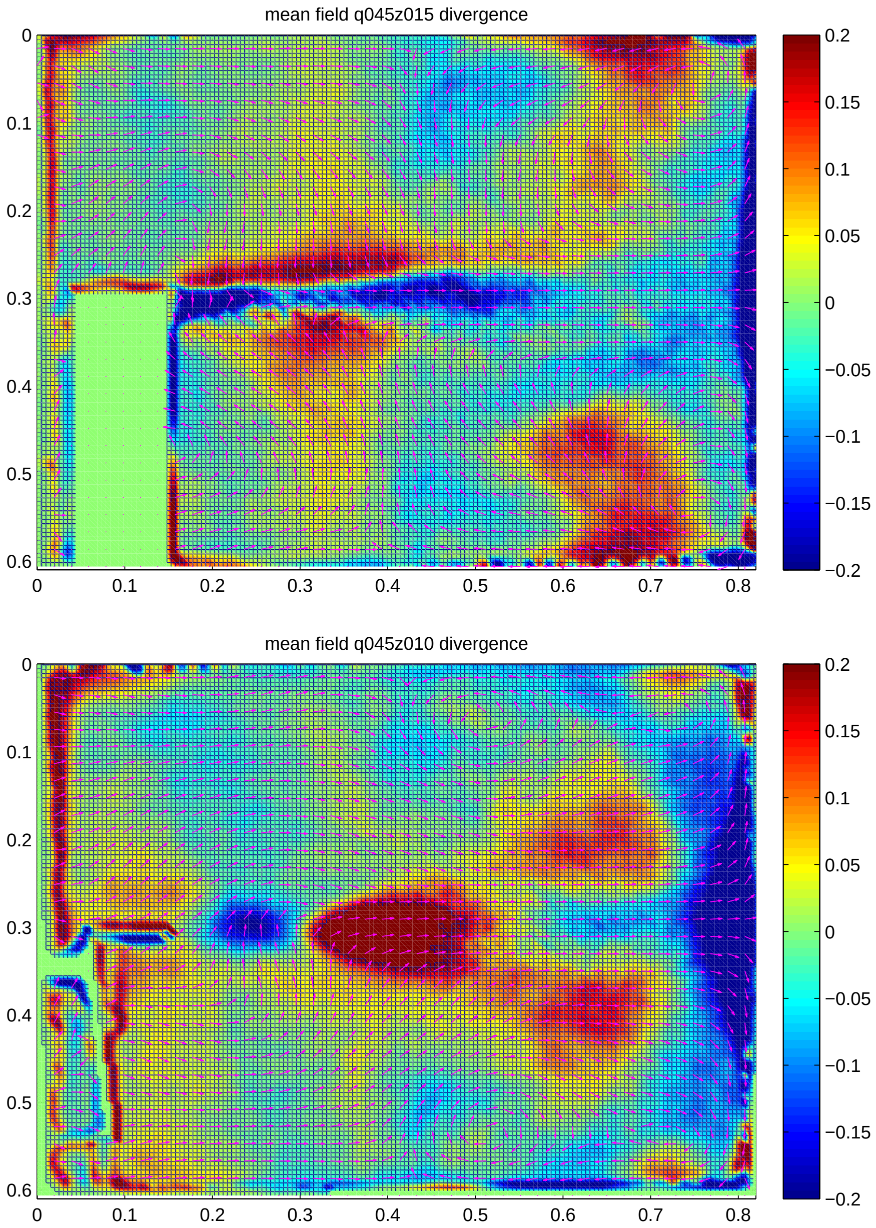

Figure 5: Divergence fields of the mid-depth (top) and lower plane (bottom) at Reynolds number 7500

($h = 1/3H$). Care must be taken when interpreting the divergence field within the jet itself in the near half of the tank as the velocity measurements did not capture the full velocity scale as mentioned above. When looking at the far end of the tank (right-hand side of figure 5) the negative divergence near the impinging wall shows the deflection of fluid out of the measured plane. The main recirculating vortical structures formed by the in-plane deflection of the jet do exhibit a strong vertical component as shown by the larger divergence in these structures. This means that these vortical structures are not simply horizontal recirculating vortices but in fact are part of 3D vortical structures, formed by both, the horizontal as well as the vertical deflection of the jet at the impinging wall.

In addition to the mean flow analysis, a preliminary modal analysis of the jet inflow has been conducted. The jet was found to oscillate in the tank. This principal behavior is known for jets in confined spaces and has been summarized by, among others, Rockwell and Naudascher 1978. Proper Orthogonal Decomposition was employed to analyze the fully developed part of the inflow jet. Figure 6 shows the three highest-energy modes. Mode 1 exhibits opposing axial velocities on either half of the jet along its main axis, meaning different axial velocities to the left and right of the centerline. Superimposing this mode as an oscillatory motion over the mean flow reveals it to be horizontal flapping of the jet from left to right akin to the behavior of a comparable plane jet flowing into a cavity. The jet velocity vectors of mode 2 are uniformly oriented in the main jet axis. An oscillation of this mode therefore implies a pulsing motion of the jet's axial velocity. The jet inflow, however, is steady-state and closer analysis revealed this mode to be the vertical flapping motion of the jet. Recorded in-plane axial velocities are highest, whenever the jet is vertically aligned with the measurement plane, and decrease when the jet dips up or down out of the measurement plane. The jet thus exhibits an oscillatory flapping motion with two degrees of freedom. Higher harmonic oscillations have also been observed in the jet and mode 3 serves as an example of this. The axial velocity differences between the left and right half of the jet along its main axis are comparable to mode 1, but now there is a singular point at $x \approx 0.7L$ with the jet oscillating between the outlet nozzle and said point and oscillating with a flapping motion between the point and the free end at the impinging wall. Note that this singular point again coincides with the x-location from which on the deviation of the mean jet from free-jet behavior rapidly increases.

Summary and Outlook

The confinement changes the geometry and behavior of the inflow jet compared to a free jet. The three-dimensional geometry of the tank induces a vertical component upon impingement of the jet and the flow pattern thus differs from the more common reference case of a plane jet in a cavity. The vertical component in the two main recirculation structures show that these are in fact not plane vortices but part of an obliquely oriented three-dimensional vortical structure. Accordingly, the recirculating flow and likely the entrainment back into the inflow jet is not directly comparable to the plane case as part of the recirculating flow dives underneath and over the inflow jet towards the tank exit.

In the present three-dimensional case, vertical as well as horizontal oscillations of the jet were found in the modal analysis. In both dimensions, the jet exhibited not only simple flapping with the jet nozzle as the sole singular point but also higher harmonic oscillations. These oscillations may influence the recirculating flow further and thus might be one possible aspect that explains the deviation of the recirculating flow patterns from the plane jet case.

In order to systematically quantify the influence of both, the characteristic, 3D mean flow pattern observed as well as the three-dimensional oscillations, further measurements are proposed. The measurement system is to be enhanced by adding a second camera in order to enable in-plane stereo PIV measurements that will yield 2D3C velocity fields that include the vertical flow component in order to verify the shape and orientation of the macroscopic recirculation structures observed here. In addition, three-component velocity fields will enable direct analysis of the coupling of vertical and horizontal oscillations in order to identify the actual three-dimensional motion of the oscillation.

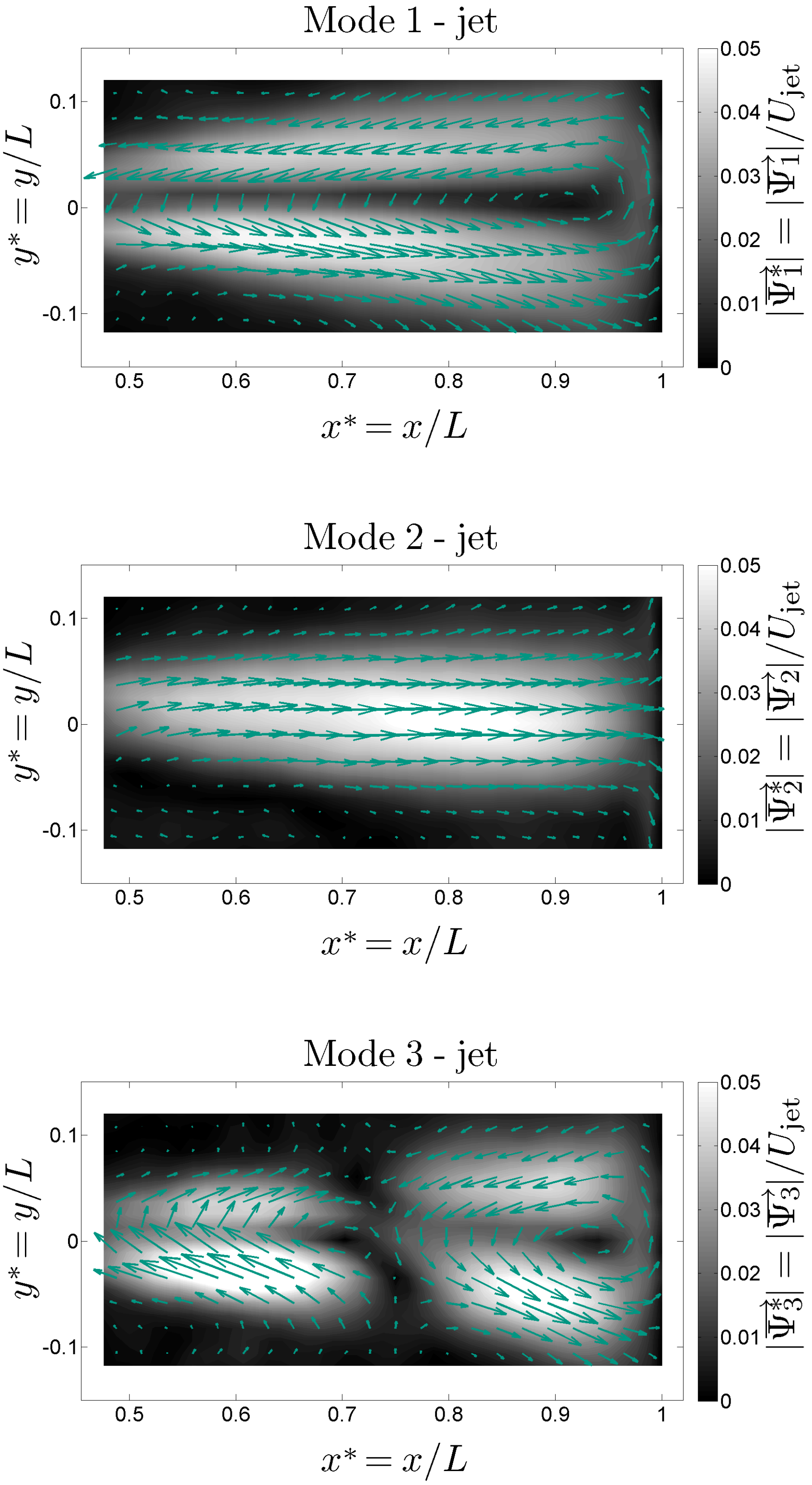

Figure 6: Modes 1 to 3 of the POD of the mid-depth plane, view of the area surrounding the jet

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