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Experimental investigation of shallow mixing layers at a river confluence using 3D-PTV

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Abstract

The present study investigates a simplified laboratory model of a river confluence (shallow mixing layer) using 3D-PTV to improve the understanding of the 3-D interaction between the large-scale turbulent motions (Kelvin-Helmholtz instability) and small-scale turbulent motions (Tollmien-Schlichting instability). A shallow recirculating glass flume (sides and bed) with dimensions of 9 m x 1.5 m x 0.25 m is used to study the flow dynamics under one hydraulic turbulent condition, i.e. a water depth of 6.5 cm and a bed slope of zero. 3D-PTV measurements are made from the end of the splitter to approximately 15 depths in the downstream direction. The data from the velocity measurements is post-processed and analyzed to obtain the velocity flow field and contours of time-averaged velocities, the growth of the mixing layer width, the Reynolds stress behavior in the horizontal plane, time autocorrelations of spanwise velocity fluctuations, energy spectra of spanwise velocity fluctuations, the velocity profile of the mixing layer with downstream distance, and vorticities in the mixing layer.

1. Introduction

A shallow mixing layer is a flow, found in nature, with streamwise and spanwise dimensions that exceed the vertical dimension (Jirka and Uijttewaal 2004). Due to the shallowness, the flow i) is vertically confined resulting in quasi 2-D flow features (large-scale turbulent motions) growing in the horizontal plane and ii) is subject to sufficient influence of bottom friction to stabilize the large-scale turbulent motions and the streamwise velocities, and also causes 3-D small-scale turbulent motions (Chu and Babarutsi 1988, Uijttewaal and Booij 1999, Uijttewaal and Booij 2000, Booij and Tukker 2001, Uijttewaal 2009). The mixing mechanism in shallow mixing layers has been described as depending, to differing degrees, on the large scale quasi 2-D horizontal turbulent motions and the 3-D turbulence from the bottom friction (Babarutsi and Chu 1998, Booij and Tukker 2001, van Prooijen and Uijttewaal 2002). Their relative effect on the coherent structures affecting mixing remains unclear. For example, small-scale three-dimensional turbulence is claimed to be important by some (Booij and Tukker 2001), and negligible by others (van Prooijen and Uijttewaal 2002).

Shallow mixing layers are important in hydraulic, environmental, and geophysical situations, as they play a key role in the lateral and longitudinal transport of mass (contaminants and sediments) and momentum as well as for their property of mixing these quantities. Their understanding is vital in the prediction of shallow flows, sediment transport and erosion, and pollutant transport.

2. Experimental study

2.1 Experimental setup

A brand new recirculating glass flume (sides and bed) with dimensions of 9 m x 1.5 m x 0.25 m with two reservoirs (inlet and outlet) is used in this study. An in-line mounted centrifugal pump ($8x8x9^{1/2}$) fed from the outlet reservoir supplies the inlet reservoir via two diffusers. To create two parallel streams of different velocity, the inlet reservoir is separated into two by a blunt-ended splitter plate of 3 mm thickness, located at the midplane of the inlet tank. The total length of the splitter plate is 3.65 m, with an effective length of 1.75 m (effective as water travels this distance in a horizontal plane). The flow rate is controlled just upstream of the diffusers with butterfly valves. To distribute the flow uniformly over the whole width of the reservoir and to decelerate it, the diffusers inside the inlet reservoir are T shaped with circular holes uniformly located over the bottom half of their circumference. A uniform flow into the flume is enabled using a transition curve to connect the channel to the inlet reservoir.

The flowrate is measured at each supply pipe entering the inlet reservoir with a flow meter (SITRANS F M MAG 5100 W). A depth gauge measures the water level during experiments at the end of the splitter plate. To guarantee a suitable water quality, two filters working in series are installed in the supply line. First a sand filter (Jacuzzi Laser 192) is put in place, to remove suspended particles and hence reduce turbidity, followed by a water softener (Pentair model 268/764), to reduce the hardness of the water, i.e. carbonates. Homogeneous thermal conditions for the tests are established by filling the tank with water, controlled by a thermal valve, at the ambient room temperature.

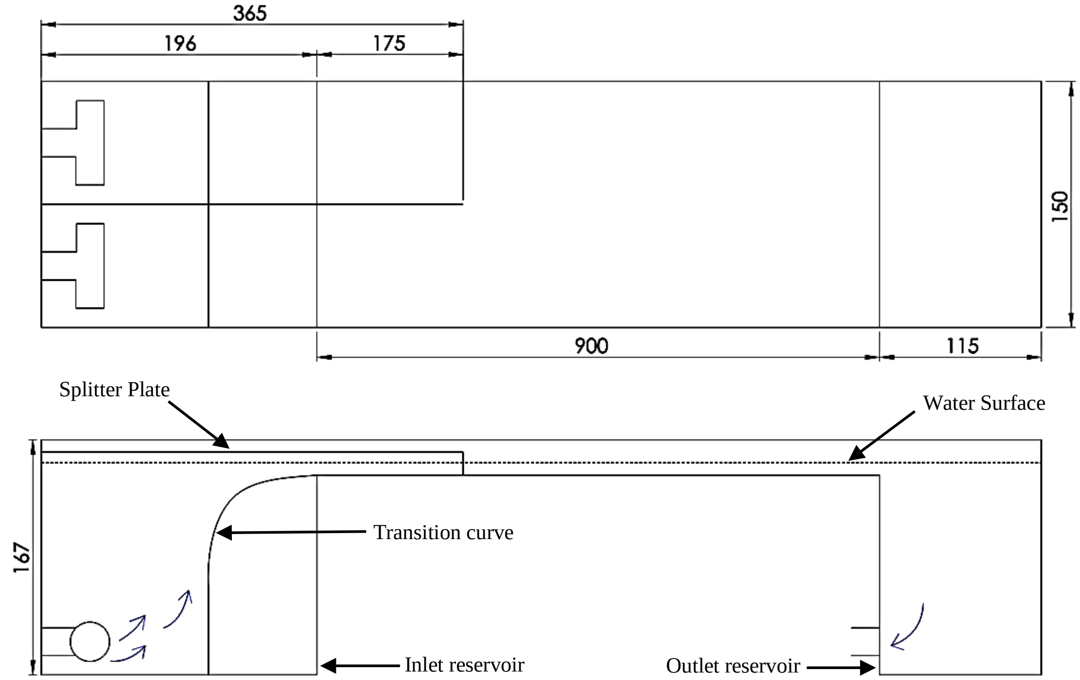

Figure 1: Recirculating flume – top view and side view. Dimensions are given in cm. Arrows denote the direction of the flow

2.2. Hydraulic conditions

Shallow flows are typically present when the width of the flow is ten to a hundred times larger than the depth (Chu, Liu et al. 2004, Uijttewaal 2014), or when the vertical length scales are much smaller that the horizontal scales (typical aspect ratio 5% or less) (Talstra, Uijttewaal et al. 2006). Experiments are run under one water depth condition, 6.5 cm, guaranteeing a width-to-depth ration of 23. With this water depth, a turbulent flow regime and subcritical flow are guaranteed, important hydraulic conditions to respect as in natural rivers the flow is always fully turbulent (Re > 2,000), with small Fr (except for mountain rivers) of the order of < 0.1. Previous studies have emphasized the importance of keeping the Fr below 0.5 to ensure the flow is not affected by surface disturbances (Uijttewaal and Booij 2000, van Prooijen and Uijttewaal 2002). The bed slope of the channel is set to zero as very small slopes are characteristic of low-land rivers.

2.3 3D-PTV

To study the flow dynamics, a nonintrusive velocimetry technique allowing the determination of velocities and trajectories in a three-dimensional observation volume is used, i.e. 3D-PTV. Measurements are made from the end of the splitter to a distance of approximately 15 depths in the downstream direction using three high-resolution (2016x2016 pixels) CCD cameras (pco.dimax CMOS high-speed) with images recorded from below the glass flume bed to capture the flow domain. Information on the flow field is extracted from the image sequences using an open source software, OpenPTV (Consortium 2014). The flow is seeded with neutrally buoyant particles, illuminated with halogen lamps and 3D-PTV calibration is accomplished by means of a solid calibration object (30 cm x 30 cm x 7 cm).

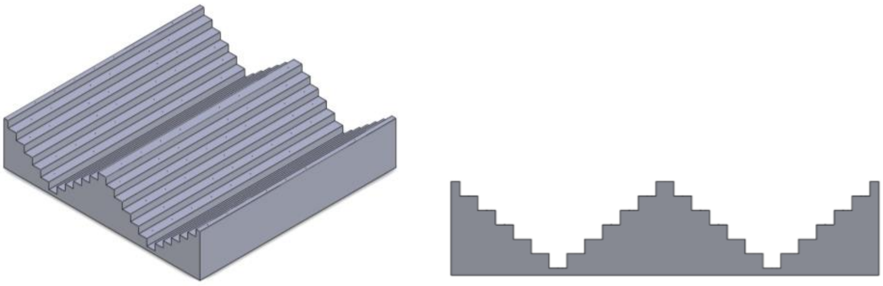

Figure 2: Calibration object

2.4 Expected results

From the raw data output obtained by applying 3D-PTV, a post-processing process will be made to acquire and analyze the velocity flow field and contours of time-averaged velocities, the growth of the mixing layer width, the Reynolds stress behavior in the horizontal plane, time autocorrelations of spanwise velocity fluctuations, energy spectra of spanwise velocity fluctuations, the velocity profile of the mixing layer with downstream distance, and vorticities in the mixing layer. To obtain the 3D velocity and vorticity fields, the polynomial fit by Luthi et al. is employed (Luthi, Tsinober et al. 2005).

3. Conclusions

The brand new flume is almost ready to be used, which means that electronics have been tested, hydraulic conditions as well as water quality verified, and 3D-PTV setting and testing is nearing completion. The images below reflect the current stage of the project. Experimental results are not yet available, however, experimentation will begin in the coming days.

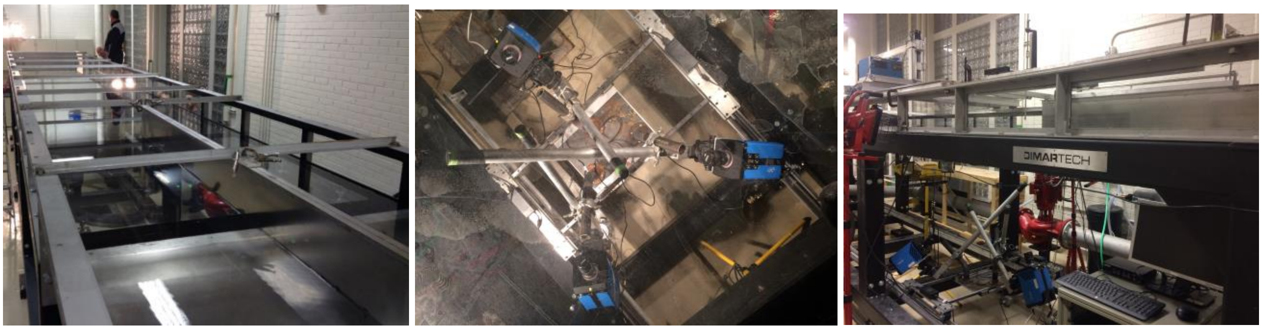

Figure 3: Recirculation flume overview and setup

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