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Transparent water tunnel for educational purpose of fundamental flow phenomena and Laser-optical measurement techniques

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Abstract

A closed-loop water tunnel for educational purposes was planned and constructed at Brandenburg University of Technology Cottbus-Senftenberg (BTU CS). The water tunnel provides insight into the flow characteristics when an object is submerged in fluid flow. Special attention is given to the fully transparent measurement sections to enable Flow visualisation and Laser-optical measurements inside the water tunnel.
The water tunnel with total length of 4.8m consists of a settling chamber and contraction followed by first test section, a second contraction and second test section, followed by the water storage container, pump and recirculation pipes. Acrylic glass is used for the contractions and both test sections and enables optical access from all four sides. The first test section has a cross section of 10cm x 30cm and length of 100cm. Both nozzles are designed two-dimensional by a 1:3 contraction ratio, giving the second test section dimensions of 10cm x 10cm and length of 100cm. The recirculating water can be operated at different flow speeds, allowing free stream velocities in first test section of 14mm/s up to 27mm/s.
Various lab-experiments are situated inside this water tunnel to train students fundamental fluid mechanics and flow measurement techniques. Different models can be mounted by magnetic hold: circular cylinders of different diameters, NACA 0024 aerofoil, NACA 4412 aerofoil, a rectangular block and many more. The flow measurement techniques that are taught using the water tunnel are Flow visualisation, Particle Image Velocimetry (PIV), stereo PIV, Particle Tracking Velocimetry (PTV). Shake the box PTV and Laser-Doppler Velocimetry (LDV).

Introduction

Understanding fluid dynamics is important in many domains such as aerospace, mechanical, automotive engineering. Flow visualization has been a useful method for understanding the fluid flow over and around bodies. In principle, water tunnel and wind tunnel are working in the same way, except for their medium of flow. The growth of vortices can be seen clearly in water tunnel whereas in the wind tunnel the vortices are not visible clearly to the naked eye. The water tunnel can also be utilized for instructive reasons such as fluid dynamics course exercises to provide quick access to visualization medium for a way better understanding of different Flow behaviours, turbulence as well as measurement techniques learnt in the theoretical courses. For the laboratory experiments, a new water tunnel is built and described in this paper. The designed water tunnel has several components, where special attention is given to transparency of the system to allow different views and methods inside the system. Various models such as aerofoil and bluff bodies are placed inside the water tunnel, and the behaviour of flow over the models is analysed and studied. The water is seeded either using flow visualisation particles to observe vertical flow structures or by hollow glass spheres allowing Laser-optical measurement techniques such as Particle Image Velocimetry and Particle Tracking.

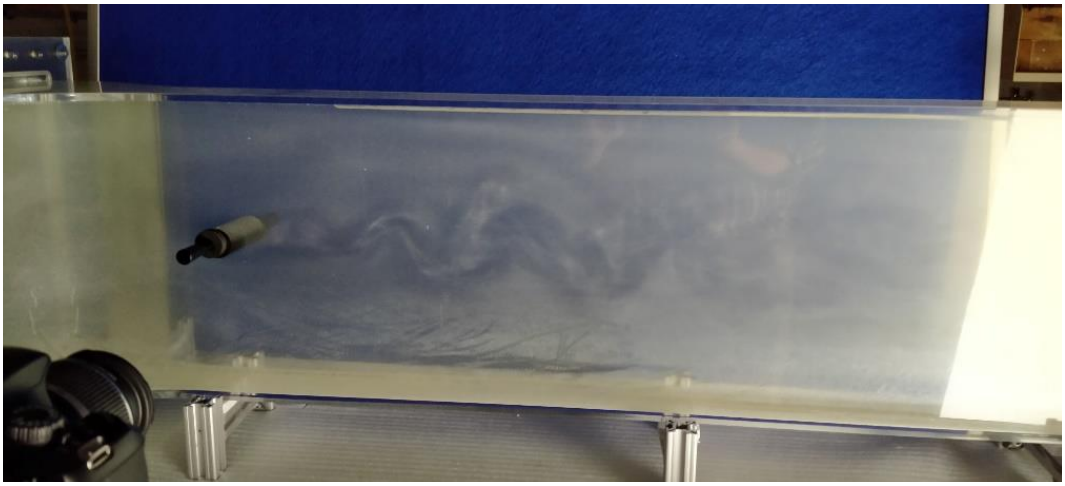

Figure 1: Image of the first test section of the water tunnel with flow visualization particles and a van-Karman street behind a cylinder at flow speed of 15mm/s.

Experimental setup

The design of the water tunnel starts from the aimed test section and flow velocities. The block diagram of the whole system is given in Fig. 2. To receive a suitable resolution for measurement techniques the main test section should be as large as possible, while the accessible size for the total experiment has an upper bound. This led us to the decision to use a cross sectional size of 30cm x 10cm with a length of 100cm. Additionally a second test section is followed with square cross section of 10cm x 10cm with also a length of 100cm, while a two-dimensional nozzle is used in between, also included for the lab experiments. The first contraction nozzle before test section 1 is also build two-dimensional to reduce the complexity for manufacturing. The nozzles are designed using two consecutive circle segments with radius of 17cm and angle of 45°, see Fig. 2 right. Nozzle and following test sections are manufactured in one piece to avoid disturbances in the water flow. These four segments are made of acrylic glass to give full optical access and built in two pieces by Heinz Fritz GmbH. Inside the test section it is planned to install different models to study the behaviour of the flow. To place these models we use magnets connected to the models and outside, holding the models though the acrylic glass. The experiment is designed to allow flow velocities of up to 33.3mm/s, corresponding to a flow rate of 6 l/min.

To ensure a smooth laminar flow inside the test section a settling chamber is placed in front of the first nozzle. The dimensions of settling chamber are 30cm x 30cm and 100cm length, it is made from 1cm thick PVC plates, mounted using M6 screws and sealed by flat rubber seal. Two frames are attached at both ends of the settling chamber using a special glue Loctite ESP110. Where one frame is attached to the baffle plate and the other frame is attached to the nozzle 1, four metal shafts are used between the baffle plate and nozzle 1 assembly to fix the settling chamber and ensure the sealing due to O-rings. The settling chamber has a top opening near nozzle 1. The main purpose of having this is to place the models inside the test section since there is no opening the test section 1. The dimensions of the top opening are 20cm x 20cm, to allow access by a person into the system. Four walls to prevent the overflow of water surround the top opening. The top opening has a lid made up of acrylic material and is fastened using M6 screws (figure 3.7). The top plate of the settling chamber has two air pressure valves. The air pressure valve at the inlet of the settling chamber is a glass valve allowing an inspection of the filling height, and another air pressure valve is on the lid, releasing the air while filling the water tunnel. The running fluid comes from a single recirculating pipe and is split into 16 water lines connected to a baffle plate at the inlet of the settling chamber. Some space is given inside the settling chamber to let the 16 inlets gently mix. Honeycomb grid is used to reduce the turbulent, vertical motion of the water. It damps transverse velocity components and directs the flow in the direction wanted. The honeycomb structure is an array of pipes with 6mm inner diameter and a length of 75mm. The local Reynolds numbers for these pipes is maximum 185.7 (assuming full usage of the running pump flow rate), ensuring a laminar flow at the end of the honeycomb structure. It is placed 32.5cm downstream the baffle plate and 60cm away from nozzle 1 to provide space for turbulence to decay.

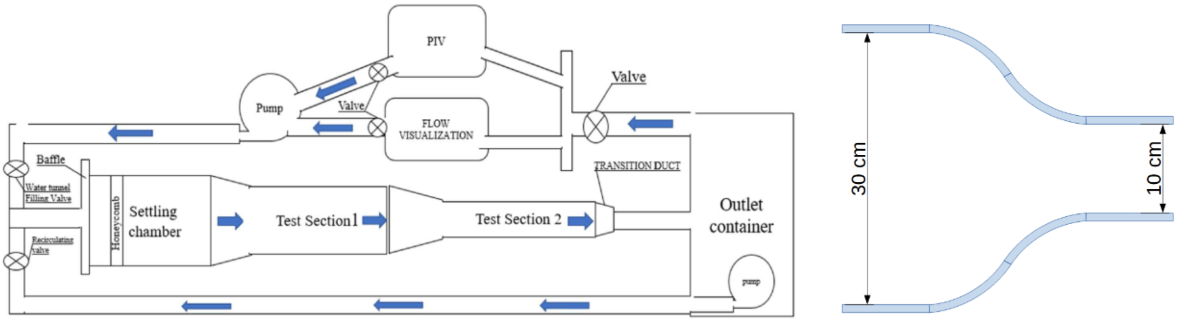

Figure 2: Right: Principle diagram of the entire system of the water tunnel with sections: Settling chamber / Inlet plenum, Nozzle 1, test section 1(30cm x 10cm), Nozzle 2, test section 2 (10cm x 10cm), Transition duct, Outlet Chamber with circulation pump and pipe as well as the filling and release path line including flow visualization and the PIV water reservoirs and the water tunnel filling pump. Left: Sketch of the design of the two-dimensional nozzles.

Using a Transition duct and flexible pipe after the test section 2, the flow goes into an outlet container (Volume of 300l), which also works as reservoir for the working fluid. The filling hight of the water is taken slightly above the settling chamber, at the settling chamber an air release pipe is used additionally. Thus, no hydrostatic pressure is given in the experiment. Inside the water reservoir the circulation pump (Aqua Forte DM-Varrio 10000m, Flow rate up to 9m^3/h) is placed, which recirculates the water in a pipe below the water tunnel to a baffle plate distributing the water into the settling chamber. Beside the recirculating line the water reservoir also allows unfilling the system into two different water containers. These can yield different working fluids, on our case we use either water with flow visualization particles (mica powder) or using water spherical particles suited for Particle Image Velocimetry (Potters Hollow Glass spheres P110).

The two storages are connected to the water tunnel filling pump (DAB Jet 300M), allowing a quick process to fill the water tunnel with the corresponding working fluid. The inlet of the water tunnel is operated by two valves, the water tunnel filling valve and the recirculating valve which are mounted to the platform. With the help of a brass hose connector, the pipes are attached to the baffle for the prevention of leakage, these pipes are interconnected using Y connecter and bought to a single inlet. The baffle plate is mounted to the settling chamber followed by nozzle 1 and nozzle 2 with the help of M6 screws. The transition duct is attached at end of the test section 2 with the help of silicone gel. This sealant is transparent and has better waterresistant properties. A water stop is applied at required areas to forbid any possible leakages. The outlet of the recirculating pump placed passes through the outlet container and is clamped to the recirculating valve. The flow is carried out from the outlet container to the water reservoir with the influence of gravitational force and is supervised by the valves. A drain valve is located underneath the settling chamber.

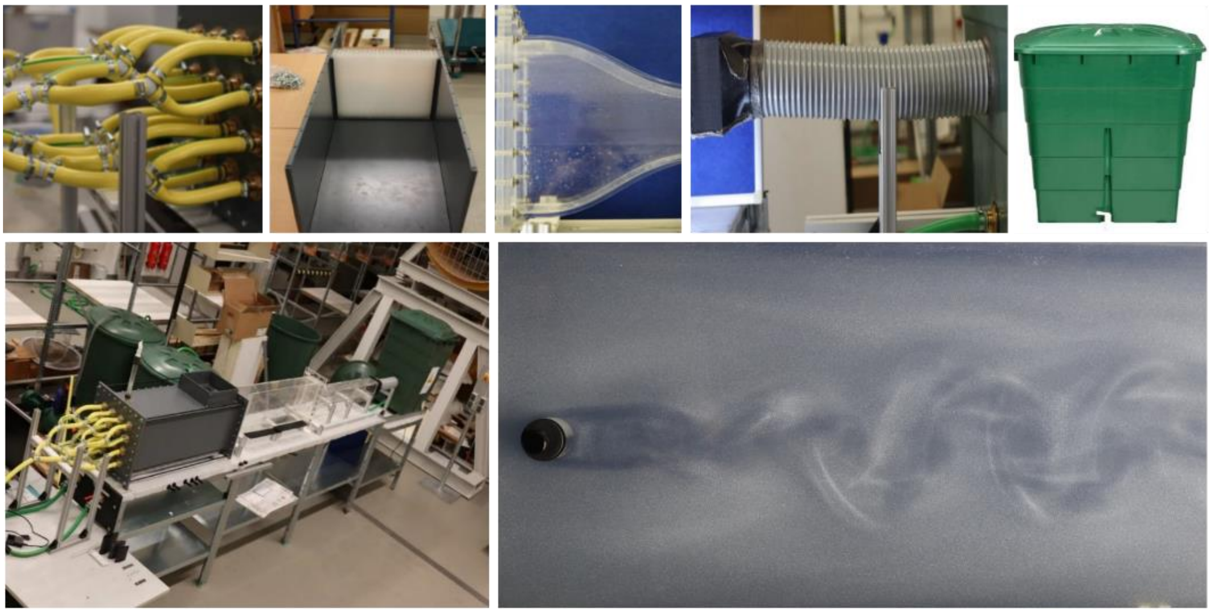

Figure 3: Images of the water tunnel setup: Top row from left to right: Baffle plate with inlet piping, look into settling chamber with honeycombs, nozzle 2, Transition duct and flexible pipe, outlet container; Bottom row left: Total setup, right: Flow visualization image of the van Karman street behind a cylinder.

Experimental procedure and models

The models for experiments are placed inside the water tunnel from the top opening of the settling chamber which is closed and sealed for running the experiments. The air pressure valve on this lid is kept open to release remaining air from the system while filling with water. While filling the recirculation path is closed and the circulation pump is off. The two water reservoirs containing PIV particles and flow visualization particles that are connected to the water tunnel filling pump are used to fill the water tunnel based on the experiment performed. Afterwards, the recirculating path can be opened and the recirculating pump is used to perform the experiments at various flow speeds. One outlet valve at the outlet container and one at the bottom of the settling chamber are used to empty the water tunnel after respective experiments, while the recirculation pump can be used to keep a flow inside the acrylic test sections and nozzles to prevent particles from settling down. Using the top lid of the settling chamber also the system can be cleaned by use of magnetic cleaning tool.

Flow visualization experiments are performed using Tracer particles. The dye injection method is not suitable for the closed-loop water tunnel, since the water is recirculating it contaminates the water and also disturbs the flow pattern. The dye also dissipates after a certain period. The tracer particles are distributed throughout the water tunnel and help to visualize the behavior of flow in the second nozzle and test section two (See Fig. 1). The tracer particles used for this experiment are Mica powder, which are small platelet particles with diameter of 5µm. The mica platelets reflects the light, additionally due to its unique shape, it aligns with the local shear. Thus, it aligns with vortices in the flow and allows the inspection, by the different light reflection behavior. The concentration of particles required to blend in water is 0.1g/liter. A LED light panel of 60cm x 120cm illuminates the particles with white light, reducing reflective spots at the glass walls and allows adjusting the intensity of light. Beside the visual inspection by eye, the flow behavior is captured using a camera as depicted in Fig. 1. As the flow velocities are small, the capture rate of typical commercial camera or smartphone usage is enough.

The models are installed to the experiment by the top lid of the settling chamber. They are equipped with a rubber-capsulated magnet, mounting it inside the water tunnel by a magnet from outside through the acrylic plate. A set of different models is established for the lectures taken in the system. 1) A rectangular block from acrylic glass of 2cm x 1cm x 31.5cm in width, thickness, and length, which is mounted by two magnets, allowing horizontal, angled and vertical orientations (c.f. Fig 4 left). 2) Cylinder of 3.5cm diameter and length of 9.8cm, fitting into width of test section (c.f. Fig. 3 bottom right). 3) Symmetrical airfoil NACA 0024 which is made by 3d print with a thickness of 2.4cm and chord line length of 10cm (Fig. 4 right) and width of 9.8cm. 4) Asymmetrical airfoil NACA 4412 with thickness of 1.0cm, chord line length of 8.33cm and width of 7.5cm. 5) Building bricks plate allowing different objects. Due to the simplicity of the mounting of objects, any further model can be adopted into the water tunnel.

Figure 4: Images of flow visualization of rectangular block situated vertically (left) and Airfoil NACA0024 at 20° angle of attack (right).

The principles of PIV is widely known and described, in the water tunnel a specialized system is adopted. As the expected flow velocities are in the size of up to 3cm/s, the complexity of frame rate, timing and light intensity is strongly reduced. The laser sheet used for this PIV technique is driven by continuous wave LED pumped laser (532nm, 75mW) equipped with a Fresnel lens to form a light sheet with 120° opening angle. The laser sheet is mounted to a stand and placed on top of the water tunnel, directing the light sheet vertically into test section 2 at mid gap. According to laser safety, the Green laser is housed into black box, reducing its risk assessment to laser class 1 for the optical visible path. Thus, experiments with students can be performed without safety restrictions. The tracer particles used for the PIV are potters hollow glass sphere 110P8, made from borosilicate glass with density of 1.1g/cm3 and mean diameter of the 11µm.

The camera model used for capturing the images and videos of the experiment is Canon EOS M50 with a base resolution of 24.1 megapixel. The lens mounted to the camera was a Canon EF-M 32mm lens. The aperture was set at f/2.0, images exposure time to 1/200s sensitivity of sensor to ISO160, capturing videos at 25fp for optimal recording. The above-mentioned whole setup was set at approximately 40 cm away from test section 1. Reducing the filling height of the water tunnel slightly allows opening the top lid of settling chamber to install a calibration grid and calibrate the recording images.

Educational laboratory experiments

Using the water tunnel, various experiments for the fundamental understanding of fluid mechanics and measurement techniques are possible. The flow visualization is performed over the rectangular block to analyze the flow behavior. The experiment is performed by placing the rectangular block horizontally, vertically, and at different angles of attack. The outcome of this experiment is to understand and visualize the vertical vortex formed when the rectangular block is placed vertically (Fig. 4 left), and to an insight of streamline when the model is positioned parallel to the flow. Positioning the block at certain angle of attack a strong vortex can be formed in the wake, similar to a side vortex formed at a train with side wind load. A second part of the flow visualization is carried by placing the NACA 4412 airfoil vertically to the bottom of the test section using the open tip of the airfoil to develop the wingtip vortices at the end of the trailing edge of the airfoil.
Additionally the flow in the transparent nozzle can be observed studying the streamline behavior and continuity effect rising the flow speed. Now the system can be even emptied while the recirculating flow rate is kept constant, showing a decreasing level changing the contraction ratio of the system. Additionally in test section 2, an open surface flow such as in a funnel can be studied. Keeping the system partially filled, the top lid of test section can be opened and a baffle plate can be used to excite waves to travel longitudinal through the test section 1, nozzle and test section 2.

Understanding instabilities in fluid mechanics is a crucial point. As one popular example the van Karman street is studied by both methods: the flow visualization and the later in the PIV lab experiment. Using flow visualization, the students can observe the formation of the patterns in the wake of a bluff body. The vertical size and shredding frequency can be measured at different flow speeds and the relation of Strouhal with Reynolds number is an outcome of this experiment. Setting the pump to slowly drive up the system also the formation of the instabilities from the first symmetric vortices in the wake, to laminar vortex street, up to the turbulent van Karman vortex street shows there beauty of nature.
Basic Particle Image Velocimetry can be performed by students themselves using various models and flow speeds. For the lab experiment the laser sheet is fixed to the central plane of the water tunnel (laser security reasons), the camera field of view and settings should be practiced and the particle images can be recorded. The given camera Canon EOS M50 does have a rolling shutter, which runs along the exposure time. Also in typical PIV setups cameras with a short time between two exposures need to be used to be able to detect small displacements of the particles in time and be able to resolve the velocity fields. The flow velocities of the water tunnel are very small, allowing the usage of customary accessible cameras as mentioned above. The time of the rolling shutter is negligible in contrast to the particles speed and the frame rate of 25fps is small enough to resolve the displacement of particles. So students are not restricted to use the given camera, it is also possible to record the images using their private camera systems or even smartphones. For the post processing, the students are encouraged to use Matblab or Python based libraries such as OpenPIV, MatPIV or PIVlab [Thielicke and Sonntag 2021], or to use the Smartphone application developed at TU Ilmenau SmartPIV [Cierpka 2021].

Particle Images taken during the PIV lab experiment at the lecture “Experiments in Aerodynamics and Fluid Mechanics” during semester 21/22 of the van-Karman vortex street are depicted in Fig. 5 (top). As an example, the data here were analyzed by the use of PIVlab [Thielicke and Sonntag 2021] using Matlab 2021a. The students can directly learn the usage of the different settings for PIV correlation such as the size of Interrogation Area (IA), filtering, some basic post processing and so on. This qualifies the students for a basic usage of PIV and also gives them the opportunity to study the van Karman vortex street quantitatively. The momentum dip behind can be examined, which leads to an estimation of drag, the shredding frequency can be computed, leading to a measure of the Strouhal number. These aspects are all transmittable to other flow problems to be studied in further detail.

In parallel to the EAFM lecture students are also trained in Computational Fluid Dynamics, where the van Karman street is also an example. Now the two lectures can be directly combined and give a better insight into the usage of numerical and experimental approach to aerodynamics and fluid mechanics.

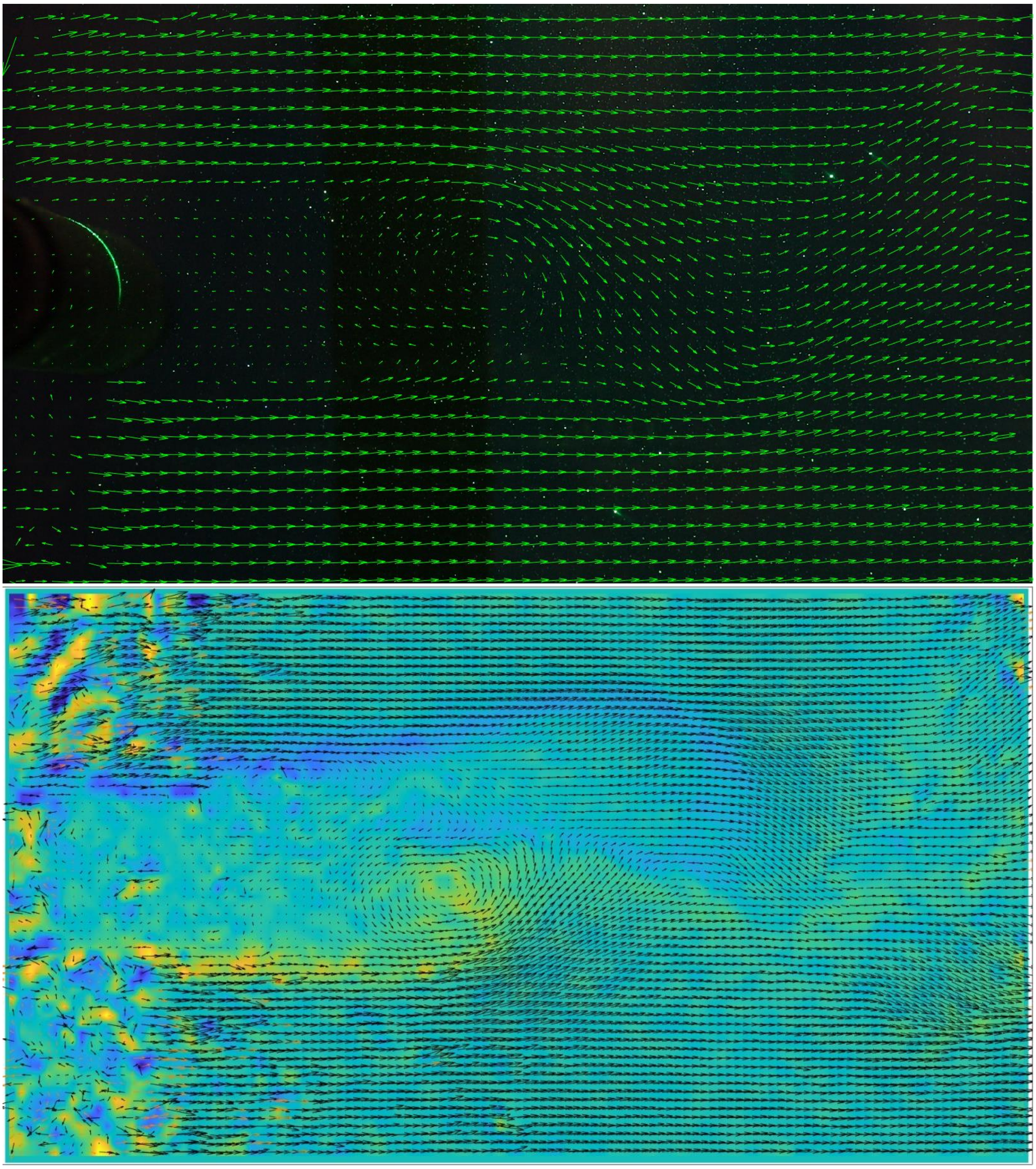

Figure 5: Results of the van Karman vortex street experiment inside the water tunnel using PIV. Top: Particle image and vector map with IA of 64px. Bottom: vector map and vorticity of IA calculation of 32px using PIVlab [Thielicke and Sonnntag 2021].

Further Experiments

The water tunnel is also suited for further optical flow measurement techniques and the study of different fluid flows around certain bodies. It is even possible to install a tripping device at the entrance of test section 1 leading to the opportunity to study a turbulent boundary layer. The laser Doppler velocimetry can be easily adopted to the water tunnel giving the opportunity to also teach this technique to students.
The water tunnel is also being used by Prof. Andreas Schröder for the lab experiments in their courses on image based measurement techniques. Here more techniques are taught such as Stereoscopic PIV, shake the box Particle Tracking, and temperature sensitive paint.

Although the water tunnel was designed for the purpose of educational usage for laboratory experiments, its flow characteristics are also suited for some research activities. Primarily it can be directly used to develop measurement techniques and serve as a fundamental reference experiment. Secondly bluff bodies of different geometries can be manufactured by 3D printing and installed into the water tunnel, giving a good understanding of the flow structures. The use of different surfaces and their influence onto the boundary layer in liquid flows are also suited to be studies as well as basic understanding of active flow control methods.

Summary

The newly designed and constructed closed-loop water tunnel for educational purposes provides insight to various the flow characteristics. To enable the access of flow visualisation and optical measurement techniques the test sections and nozzles of the system are transparent. The flow velocities are limited to maximal 27mm/s in test section 1, leading to very good opportunities recording the fluids motion by standard equipment. The flow quality is assured to be free of disturbances. The first test section has a cross section of 10cm x 30cm and length of 100cm. Both nozzles are designed two-dimensional by a 1:3 contraction ratio, giving the second test section dimensions of 10cm x 10cm and same length of 100cm. Various lab experiments are situated inside this water tunnel to train students fundamental fluid mechanics and flow measurement techniques. Different models are installed: circular, aerofoil NACA 0024, NACA 4412, rectangular block and others. Flow visualisation and Particle image velocimetry (PIV) are taught to students.

Acknowledgement

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Literatur

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