# PROPELLER INFLOW CONDITIONS OF INLAND VESSELS IN DIFFERENT WATER DEPTHS

**Benjamin Friedhoff,** DST, Germany
**Katja Hoyer,** DST, Germany
**Sven List,** DST, Germany
**Matthias Tenzer,** DST, Germany

*Vessels in inland waterway transport sail in a wide range of waterway conditions and sometimes extremely shallow water. Propellers positioned in the viscous wake of the hull operate in an inhomogeneous inflow. Knowledge of the complex wake field is of utmost importance for a proper and efficient design of the propulsor system. Shallow water effects strongly alter this wake field. The flow passing between the waterway bottom and the hull is more and more blocked and the water needs to be drawn in from the sides. To provide propeller designers with generic information of these phenomena, four representative inland vessels with differing aft ships and an identical bow were designed and manufactured in model scale. All designs have the overall dimensions of GMS class and are propelled by ducted propellers mounted on conventional shafts. Two single-screw and two twin-screw arrangements were chosen. This family of vessels was compared using both RANSE CFD computations and extensive model tests in DST's large shallow water basin at different water depths. The test campaign includes propulsor open water tests, model resistance and model self-propulsion tests. Furthermore, stereo particle image velocimetry (3C-PIV) measurements were conducted for detailed flow data with cameras and laser mounted in the observation tunnel underneath the towing track. The results show significant differences in the power demand for the investigated aft bodies at different water depths. Further, wake fractions and flow fields are compared.*

## 1. Background

Nowadays approximately 19 000 vessels operate on the European network of inland waterways with its total length of about 40 000 kilometres. Each of these vessels relieves the road from 40 to 180 heavy goods vehicles (HGV). A large pushed convoy with six lighters and a total capacity of 12 000 tons corresponds to 650 HGVs or 400 waggons on the rail [4]. Even though the transport on inland waterways inherently has superior energy efficiency and, therefore, low fuel costs per tonkilometre there is a strong motivation to maximize the cost-effectiveness. Cargo holds should be as large as possible and often need to match the dimensions of a certain number of containers. The general dimensions of the vessels are usually limited by lock sizes or regulations on specific waterways. This results in long parallel midship sections and short fore- and aftbodies. Finally, downtime due to shallow water in weather scenarios with low discharge needs to be avoided. The vessels should be able to continue sailing economically and safe even with very small draught. Hekkenberg [1] gives a good overview of the most important factors determining the economic viability of inland navigation and inland vessels.

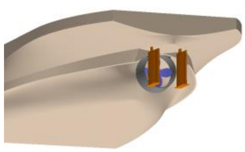
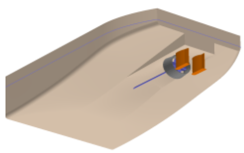
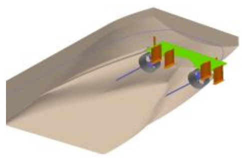
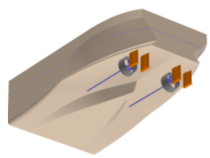
To meet these requirements various designs have been developed incorporating short aft hulls, highly loaded ducted propellers and devices like propeller tunnels and aprons to avoid ventilation at small draughts. Modern inland vessels can operate at draughts going below the propeller diameter [5]. Nevertheless, the hydrodynamics of these full hullforms with large block coefficients are challenging and strongly influenced by the underkeel clearance. The resulting power demand limits the energy efficiency and may significantly affect the economic efficiency with increasing fuel costs. Due the permanently changing sailing conditions, optimization based on operational experience with existing vessels is very limited in inland navigation. Some vessels are studied using CFD computations and model tests, which allows improving major unfavourable ship lines before the vessels are built at full scale. However, these investigations are limited to individual new-built ships and very few sailing conditions. Additionally, no data is available for older vessels which shall be equipped with updated propulsion systems. Extensive tests like PIV measurements are out of scope for most new-built projects.

To provide ship designers and propeller manufactures with generic information of these phenomena, four representative inland vessels were designed and manufactured in model scale. All designs have the overall dimensions of GMS class and are propelled by ducted propellers mounted on conventional shafts. This family of vessels was compared extensively using computational and experimental fluid dynamics (CFD and EFD) at three different water depths.

## 2. Hull geometries

To cover the wide variety of hull geometries in the existing fleet four cargo vessels with principal dimensions of L x B x $T_{max}$ = 110 m x 11.44 m x 3.2 m and differing aft ships were designed. All of them share the same bow shape and use ducted propellers in conventional shaft arrangement. Two designs are single screw vessels while the other two have propellers and ducts on port and starboard side. The latter is beneficial at low draught or very shallow water and fulfils redundancy requirements for some waterways. These four designs were built and equipped in scale 1 by 16 for model tests. The rudders where omitted for CFD and EFD. All investigations were performed at a draught of 2.8 m. The differing characteristics and shapes are listed in Table 1 below.

*Table 1 Characteristics of the four designs*

| | M2051 | M2052 | M2053 | M2054 |
|---|---|---|---|---|
| $n_{Propeller}$ | 1 | 1 | 2 | 2 |
| $D_{Prop}$ [m] | 1.75 | 1.75 | 1.60 | 1.60 |
| $V_{T=2.80\,m}$ [m³] | 3088 | 3150 | 3162 | 3129 |
| |  |  |  |  |

## 3. Model tests

Extensive model tests were done in DST's large shallow water basin. This testing facility is 200 m long, 10 m wide, has an even concrete bottom and can be operated at any water depth up to 1.20 m. A unique feature of this basin is the observation tunnel with 60 mm thick acrylic windows underneath the towing track. This optical access was used for particle image velocimetry (PIV) measurements described below. To evaluate the hull-propulsor interactions, not only self-propulsion tests but also bare hull resistance and propulsor open water tests were performed. The British method was applied with three propeller rates for each model speed. Three different water depths of 7.5 m, 5.0 m and 3.5 m at full scale were compared.

## 4. Numerical investigations

To evaluate the hydrodynamic performance and flow details, the four designs were compared using RANSE computations with the commercial software package ANSYS Fluent. This software is based on the finite volume method and solves the integral equations for the conservation of mass, momentum and energy. In this technique, the volume of interest is divided into a huge number of small elements, called control volumes. In order to model the turbulence behaviour of the fluid the SST-Model from Menter [5] was used within this project. In addition to the calculation of pressure and velocity fields, the wave elevation was calculated using the volume of fluid method. The dynamic floating position, i. e. trim and sinkage due to forward speed, was also considered.

In order to gather all gradients of the fluid and to resolve the free surface elevation a large number of elements was necessary. The numbers of nodes for the computational domain varied between 4 and 6 million. To reduce the number of cells, hybrid grids were used for the calculation. The far field was discretised with a structured grid consisting of hexahedrons and the domain near the ship hull was discretised using tetrahedrons in combination with prism layers at the wall.

## 5. Detailed flow measurements

Particle image velocimetry is a powerful, non-invasive, laser-based method to study fluid motions like the flow conditions around ship models. Small particles in the water serve as tracer particles, which are illuminated by a pulsed laser. The laser beam is spread into a light sheet of finite thickness, to give a defined sample volume. In 3C-PIV applications the reflections of the particles are captured by two cameras in a stereo set-up. There are always two pictures taken with a precisely defined separation in time by each camera. Thus, the movement of the particles within both pictures can be analysed and a flow velocity can be determined. Using the stereo effect and the parallax allows determining not only the velocities in plane, but also the third velocity component perpendicular to the light sheet plane. Raffel et al. provide further details on the fundamentals of PIV techniques [3].

Complex flow phenomena and the limited access to the propulsor location make detailed flow measurements e. g. for the validation of CFD computations a challenging task in shallow water conditions. A PIV set-up towed parallel to the model in a watertight housing cannot be used as it is often done in tests of models with sufficient underkeel clearance. Design details like propeller tunnels or aprons reducing the risk of ventilation also block the optical access for PIV measurements in the propulsor region. Additionally, the interference of the housing and the flow around the model is more pronounced in shallow water.

Therefore, the PIV equipment was installed at a fixed location in the observation tunnel under the towing track. An InnoLas SpitLight PIV DPSS frequency-doubled Nd:YAG-Laser with two diode-pumped cavities was used. Due to the diode pumping, the beam quality is almost independent of orientation and motions. With a double pulse frequency of 100 Hz the pulse energy is about 60 mJ. Two Phantom v9.1 high speed CMOS cameras with 2 MP resolution and 6 GB internal memory each are used with 85 mm lenses mounted on Scheimpflug adapters. 14 bit colour depth allows sufficiently high contrast, even in most challenging applications. Polyamide particles with a diameter of 100 µm were used as tracer. Acquisition and post-processing were done with different subversions of the software package DaVis 8 by LaVision.

All models and appendages where coated with fluorescent paint. Band-pass filters at the camera lenses were used to block the light emitted from the fluorescent surfaces in the light sheet and to reduce the influence of background light. This significantly reduces the reflections on the model surface and allows the detection of particles closer to the hull.

The light sheet was aligned with the y-z plane perpendicular to the forward motion of the model. Stereovision requires two different oblique viewing angles of the two cameras to the same field of view in the light sheet. In this application both cameras were mounted on the same side of the light sheet to achieve the best optical access. Initial tests showed that the different refractive indices of air, acrylic glass and water give too heavy distortion when the optical path is inclined to capture the field of view with the cameras directly. Therefore, the cameras were mounted vertically under the window and first surface mirrors were installed above the observation window in the towing tank with sufficient space in between for the passing models. Figure 1 shows the schematic setup for the PIV measurements. However, even with the chosen approach with mirrors in the basin optical masking of parts of the propeller plane cannot be fully avoided.

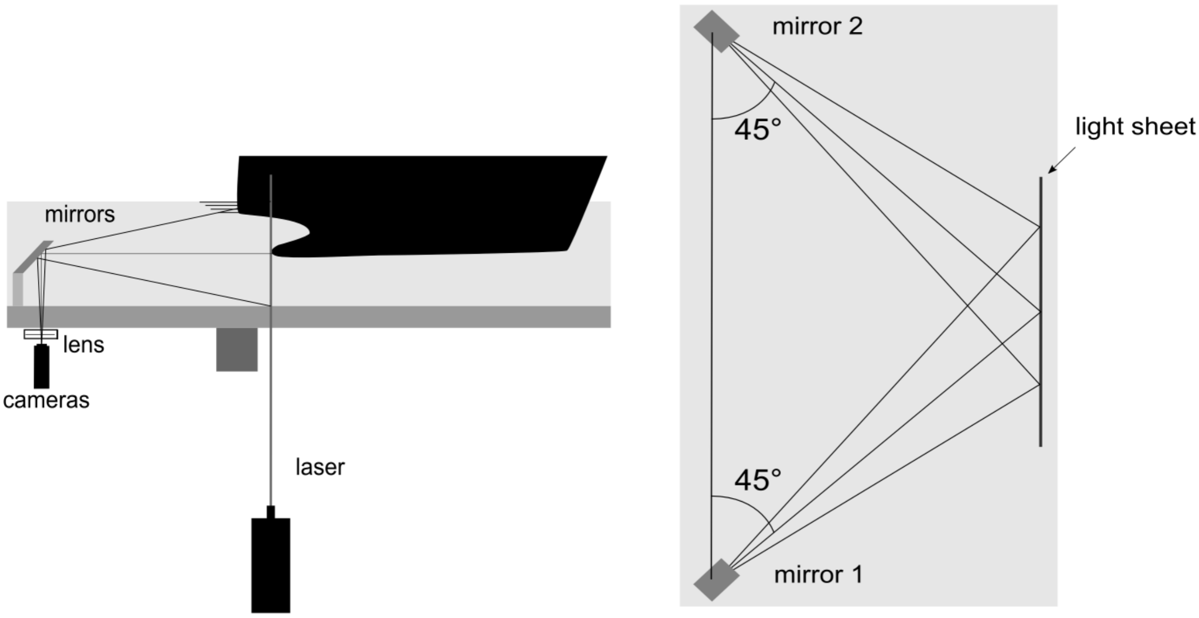



*Figure 1 - PIV Setup. (left) side view. (right) top view*

The conditions in the wake of ship hulls with flow separation are highly unsteady. Vortices of different length scales detach from the ship's surface and travel downstream. Thus, instantaneous vector fields from PIV are not representative and do not suffice for the validation of CFD computations. To reduce the uncertainty of PIV data and to derive adequate results for further analysis as many vector fields as possible need to be compared, filtered and averaged. This is a challenging task for applications where the stationary equipment is passed by the model. Here at least ten test runs were performed for each condition (different model and/or water depth). Figure 2 illustrates this approach. Each pair of raw images was processed independently. Afterwards, three consecutive vector fields for each run were averaged. With the sampling rate of 100 Hz this equals two periods of 0.01 s plus the interframe interval in time and a spatial averaging over e. g. ~20 mm at a towing speed corresponding to 14 km/h at full scale. The averaged data is then once more averaged over all performed test runs for the same conditions.

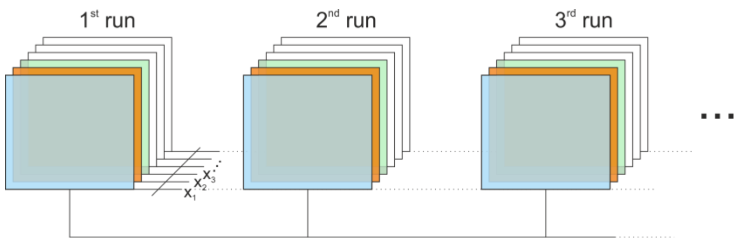



*Figure 2 - Averaging scheme for the PIV vector maps from different runs and x-positions.*

## 6. Results

Propellers positioned in the viscous wake operate in a complex and inhomogeneous inflow. Shallow water effects strongly alter this wake field. With reducing underkeel clearance the flow passing between the waterway bottom and the hull is more and more blocked and the water needs to be drawn in from the sides. These effects can be observed in different results. The most relevant characteristic number is the power demand for a given speed. Figure 3 shows the plots of delivered power against ship speed for four models and the three tested water depths. The well-known disproportionate increase of power demand with speed becomes more pronounced while the attainable ship speed is more and more reduced with decreasing water depth. While the single-screw design M2051 performs best in all test-conditions, the results for the other three designs are not straightforward. They swap order with changing water depth. The twin-screw design M2053 is very close to the reference M2051 at high water depth, but performs worst with small underkeel clearance. The other twin-screw design M2054 is worst with sufficient water between hull and waterway bottom but doing well in shallow water conditions. Looking at the magnitude of differences between the designs clearly demonstrates the need for proper hydrodynamic investigations for vessels operating in confined water. At 3.5 m water depth almost a factor of 2 can be found in the power demand between the best and the worst design.

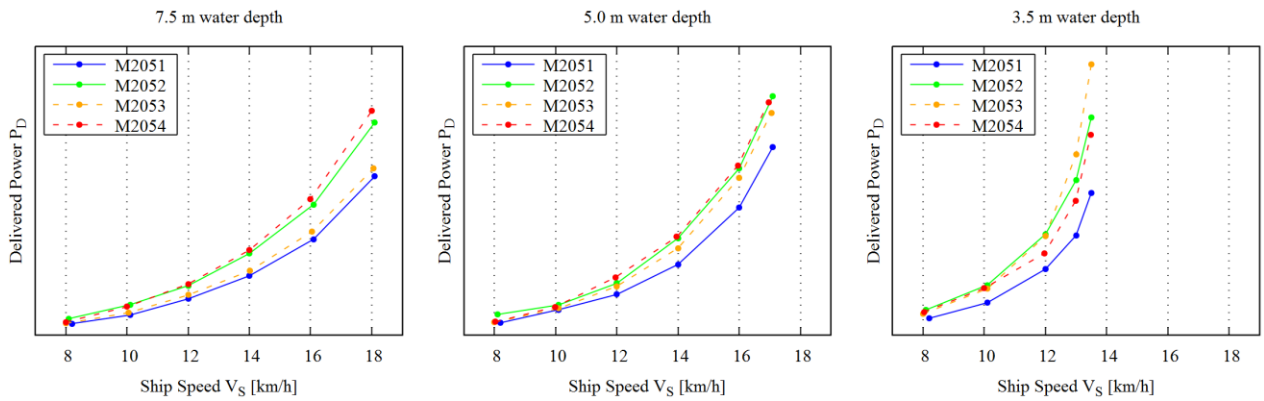



*Figure 3 - Delivered power vs. velocity. Comparison of all vessels at 7.5 m (left), 5.0 m (middle) and 3.5 m (right) water depth*

The thrust identity approach was used for all self-propulsion tests to compare the operating conditions with the open water tests. With the non-dimensional thrust coefficient $K_T = T/\rho n^2 D^4$ the corresponding advance coefficient $J = V_A/nD$ can be read from the propulsor open water characteristics. Using the known propeller rate $n$ the corresponding axial inflow velocity $V_A$ is derived and the wake fraction $w = 1 - V_A/V_\infty$ calculated. The results are plotted in Figure 4 for the full scale ship speeds 12 km/h at 3.50 m depth, 14 km/h at 5.00 m and 16 km/h at a water depth of

7.50 m. There is a clear tendency towards increasing wake fractions in low water depths. However, this effect is much more pronounced for the single screw vessels and especially for M2052. As this approach does not take into account the inhomogeneous distribution in the wake field and the in plane velocity components *v* and *w* induced by the hull's wake, more detailed analysis is required based on detailed flow measurements and/or CFD computations.

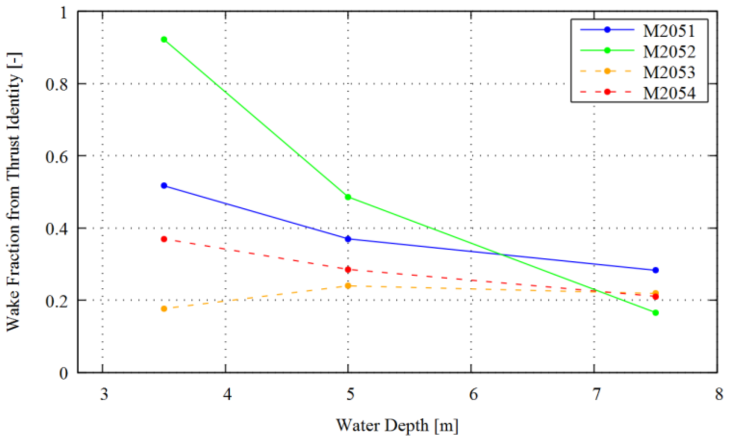



*Figure 4 – Wake fractions based on thrust identity for all four models and three water depths.*

CFD simulations based on the Reynolds averaged Navier-Stokes equations do not resolve the complex transient flows in the detached flow behind a ship's hull. Instead, the turbulence effects are modelled as steady state flow using different approaches. The quality of the results is highly dependent on the right choice of (local) grid resolution and calculation parameters. PIV is a valuable tool to validate the results with detailed measurements. Figure 5 shows a comparison of the CFD results (left) with PIV measurements (right) for M2052 at 7.50 m (top) and 3.50 m water depth (below). The non-dimensional wake fraction is illustrated with colour contours while the in-plane components *u* and *v* are presented as vectors. Acceptable agreement can be seen for both cases. The overall level of wake fractions matches well. The turbulent flow in the experiment smears out the wake shadow of the stern tube, clearly visible in the CFD results at the larger water depth. The masking of the upper edge of the propeller tunnel can be recognized in the vector fields form PIV measurements.

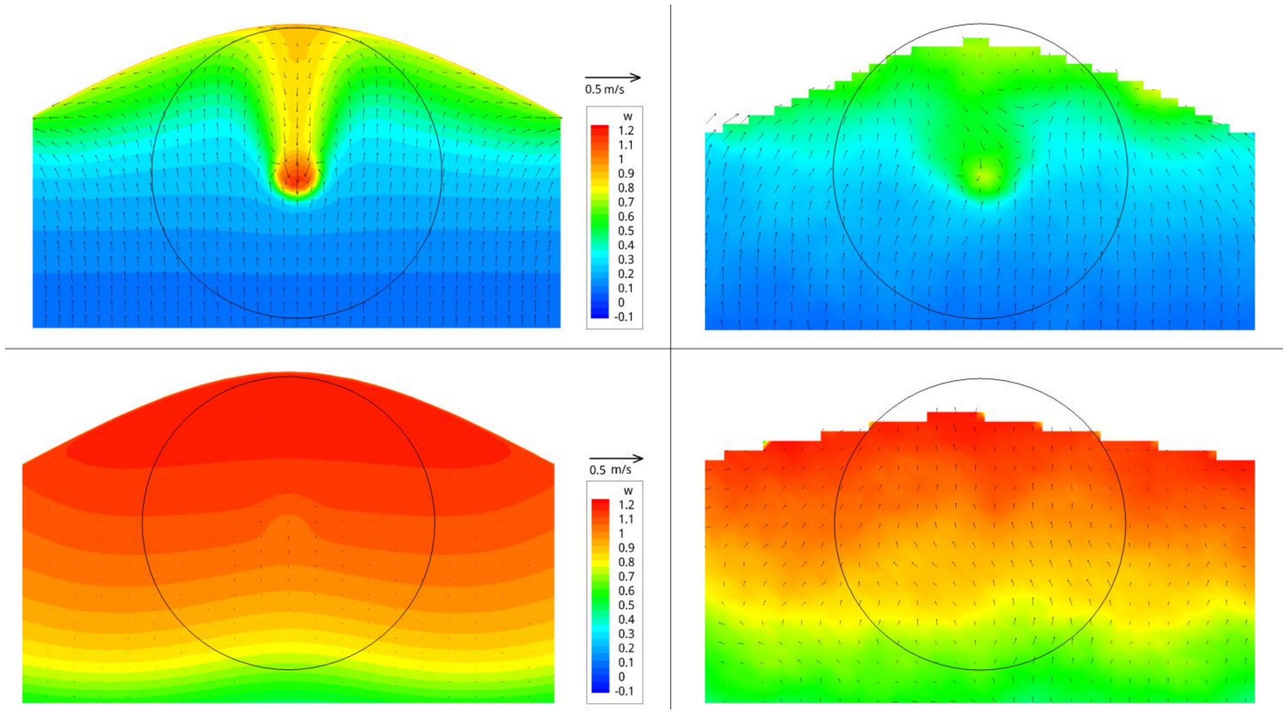



*Figure 5 – Comparison of computed (left) and measured (right) wake fields for M2052. Top row at h=7.50 m and bottom for h=3.50 m water depth.*

Due to the masking in some PIV measurements, especially for the twin-screw vessels, the CFD results are used for further analysis. Figure 6 shows the wake fields for all models and the highest and lowest considered water depth. Even at sufficient water depth the full hull-forms and the shapes preventing propeller ventilation at low draughts generate high wake fractions compared to propeller inflows at slender hulls. Differences between the hulls are larger than expected from the values shown in Figure 4 derived from thrust identity. Especially hull shape M2051 shows a wake fraction of approximately $w=0.5$ in the propeller plane compared to $w=0.3$ derived indirectly from the model tests. Possibly, this difference can be explained by the propeller induced velocities in the effective wake field. In some cases flow separation occurring at the bare hull is withdrawn by the suction of the propeller. The results derived from the identity approach above suggest, that this effect works well for M2051 and the two twin-screw vessels but not in the same way for M2052.

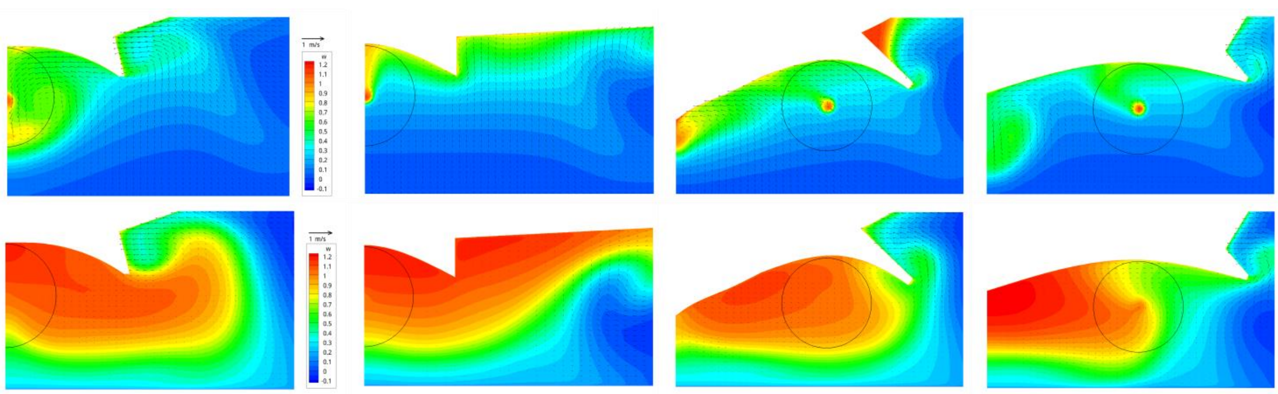


*Figure 6 – Computed wake fields of the four models M2051 to M2054 (left to right). Top row for water depth h=7.50 m and bottom row for h=3.50 m.*

The vectors with the $u$ and $v$-velocities demonstrate the advantage of advanced computations or measurements compared to conventional wake measurements with Pitot tubes. Especially for the twin screw vessels the information of the axial velocities is not sufficient. M2053 shows a strong rotation of the nominal wake in the propeller plane for the higher water depth. This can be used by choosing the right rotational direction of the propellers.

## 7. Summary

Day to day testing experience shows that for many inland ships in shallow water sometimes no advance coefficient can be identified by classic thrust or torque identity comparing with the open water characteristics. Behind the vessel sailing at a reasonable speed the propeller inflow is even worse than at zero speed in the open water test. Little to no systematic data on the influence of ship design and water depth is available today. The project reported herein was initiated two years ago to fill this gap. It is funded by the German Federal Ministry of Transport and Digital Infrastructure (Project-No.: 97.357/2015) and will help to improve energy efficiency of inland waterway transport for new-built and retrofit vessels. Equipment providers and ship designers can use the results to optimize ship lines and propulsor configurations.

Further investigation will focus on the differences between effective and nominal wake fields. PIV measurements will be performed in front of the operating propeller and compared to CFD computations with a body force model for the propeller and in some cases also with the rotating propeller geometry. A smaller model with scale 1 by 32 was already prepared to get more insight into the scale effects on wake fields. With the validated CFD methods the propeller inflow conditions at full scale will be computed and analysed.

## 8. References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