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3D-PTV on large particles in the free-surface vortex

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Summary

Wastewater pumping stations can experience problems due the presence of floating particles of solidified fat and grease. To transport this debris, the ability of free-surface vortices as transport mechanism is investigated. An experimental set-up is developed where the behaviour of large particles (0.02 - 0.04 m) in the vortex flow are analysed. An 3D-particle tracking method based of 6 iPhone® cameras was used to record the position of the particles in the vortex. Based on the measured particle acceleration, the hydrodynamic forces on the particle are derived. This novel 3D-PTV method was found to generate consistent information on the movement of the particles in the vortex flow field.

Keywords

Floating debris, pump sump, vortex, 3D-PTV

Introduction

Wastewater pumping stations (WWPS) can experience problems due to the presence of floating debris in the pump sump. This floating debris mainly consists of solidified fat, grease and oil (hereafter called FOG)) and the individual particles can accumulate to a closed floating layer. The presence of FOG can result in pump failures, which may result in a 16% increase of yearly volume of Combined Sewer Overflows (CSO) as shown by Korving (2006) for a specific case study. Moreover, the removal of the FOG is an expensive, very unhygienic and labour intensive work and should be minimized. To solve the FOG problems, a research project is started on mechanisms preventing the formation of FOG layers in pump sumps. The use of a free-surface vortex as transport mechanism of individual FOG particles is defined as a solution to prevent the accumulation of these layers (Duinmeijer & Clemens 2016). To investigate this transport mechanism, an experimental-setup is developed to investigate the transport ability of the vortex. A state-of-the-art method (3D-PTV) is used to record the motion of artificial FOG particles in the vortex. Based on the measured particle acceleration, the hydrodynamic forces acting on the particle can be derived which is used to validate a theoretical model predicting the behaviour of particles in the free-surface vortex. This paper addresses the first results of this novel 3D-PTV method.

Material and methods

General experimental set-up

The experimental set-up consists of a transparent tank of 0.60 m diameter and 1.0 m high, see Fig. 1. The tank is placed in a 0.7 x 0.7 m transparent container to compensate light refraction when recording images. The set-up is a closed system with a pump discharging water in the tank that flows through an outlet in the bottom back to the pump. A separation tank of 0.3 x 0.3 x 0.4 m is placed between the tank outlet and the pump suction side for separating experimental particles from the closed system. The flow rate is measured with a Kobold type DMH Magnetic-Inductive Flowmeter. The flow enters the tank through two horizontal Ø25.9 x 1.9 mm inlet pipes located adjacent to the tank wall and 0.5 m above the tank bottom. The flow circulation *Γ*, which is a governing parameter in strong vortex formation, is varied by vary the distribution of the total flowrate over both pipes by adjusting the flowrate of one pipe with a control valve. The undisturbed water depth in the tank is 0.9 m.

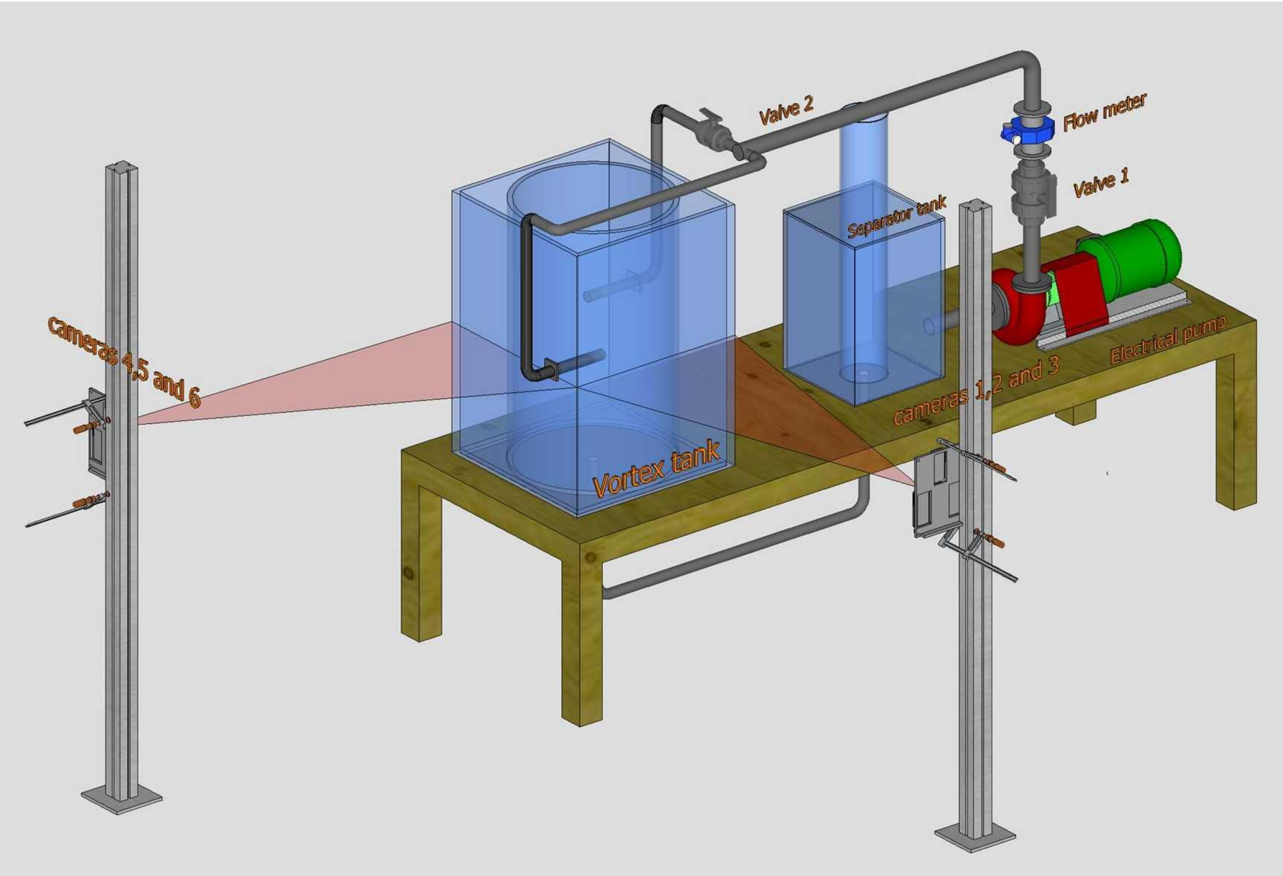

***Fig 1**. Experimental set-up to investigate the free-surface vortex transport ability of large floating particles.*

3D-PTV set-up

The 3D-PTV is established by placing camera stations on two perpendicular sides of the tank, see Fig. 1. Each station holds three iPhones® in a triangular layout. The iPhones® cameras were selected because of their high video footage at a frame rate of 120 and 240 fps. The experimental particles were coated with a UV-fluorescent paint and the experiments were recorded under UV-light provided by LED strips located at the top, bottom and corners of the tank, see also the left picture of Fig. 2. This method enables the six cameras only to track the particles eliminating other objects that could introduce errors in the particle tracking software. The synchronization of the six cameras was done by setting a LED light that emits a pulsed light signal, this allows to identify the timestamp for the recorded frames by each camera, this also allowed for a continuous synchronisation between cameras in the post processing of the results. Each individual camera was calibrated using the method proposed and described by Heikkila & Silvén (1997) to correct for lens distortions. The 3D-PTV coordinate system has its z-axis with its origin at the tank bottom and a maximum of z = 0.9 m at the undisturbed water level.

3D-PTV processing

After recording the particle track, the video of each camera is breakdown in individual frames. Each frame is corrected for lens distortions. The next step is determining the particle positions in the *x-z* plane (3 camera's) and *y-z* plane (3 cameras) using a custom made Matlab® code. Next, the positions of all cameras are synchronized. The next step is to determine the 3D line on which the particle is observed for each camera by using another Matlab® code. Subsequently, an estimate of the uncertainty of the particle position is determined. More detailed information on this novel 3D-PTV processing will be published later on.

3D-PTV Results and discussion

Particle position in the free-surface vortex

Fig 2. shows a preliminary result of the presented 3D-PTV method. The left picture shows snapshots of the recorded track of a 38 mm sphere at typical free-surface vortex characteristics (flow circulation, flow rate and outlet diameter). The picture shows the track of the particle starting at the outer field just below the water surface. The particle travels with a helical movement towards the vortex air core and travels then along the vortex air core in downward direction. The right picture shows the calculated positions of the sphere in the *x-y-z* plane as function of time giving a good agreement with the experimental observed particle positions.

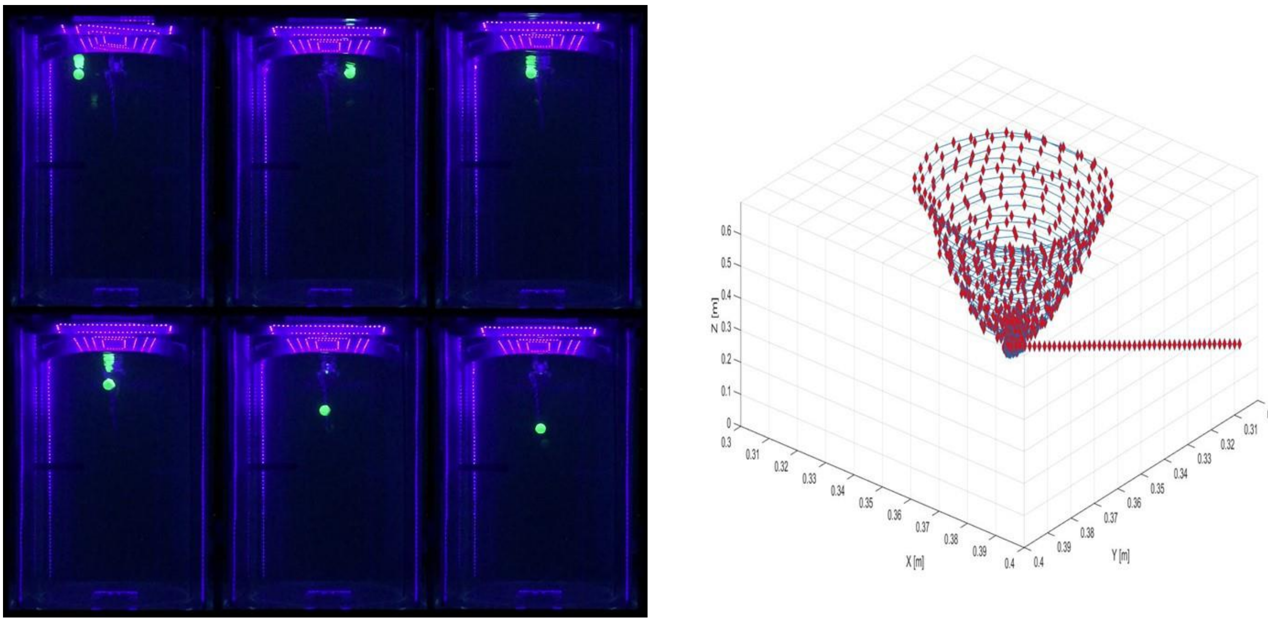

Fig 2. *Left: Recorded particle track of a 38 mm sphere in a free-surface vortex. The particle starts in the outer field of the vortex and travels then along the vortex air core in downward direction. Right: calculated particle positions in the x-y-z plane using the 3D PTV method.*

Hydrodynamic forces acting on the particle

Given the position difference vector $\vec{p}$ of the particle at two moments in time, the velocity vector $\vec{v}$ (ms^{-1}) is estimated as follows:

$$\vec{v}(t + 0.5\Delta t) \approx \frac{\vec{p}(t + \Delta t) - \vec{p}(t)}{\Delta t}$$

The acceleration vector $\vec{a}$ (ms^{-2}) follows from:

$$\vec{a}(t + \Delta t) \approx \frac{\vec{v}(t + 1.5\Delta t) - \vec{v}(t + 0.5\Delta t)}{\Delta t}$$

Finally, the resulting force vector $\vec{F}$ (N) acting on the particle is:

$$\vec{F}(t + \Delta t) \approx V(\rho_p + C_a \rho_f)\vec{a}(t + \Delta t)$$

with V (m^3) the particle volume, ρ_p and ρ_f (kgm^{-3}) the particle and fluid density respectively and C_a an added mass coefficient to take into account the mass of the displaced fluid.

As example, fig. 3 shows the calculated velocities of a large spherical particle in the 3D-vortex flow. The graph evidently shows that the circumferential particle velocities, ${V_\theta}^2 = {V_x}^2 + {V_y}^2$, are more than an order of magnitude higher than the particle velocities in z-direction. As also clearly observed in the experiments, the particle initially has a positive downward velocity (z-velocity) along the air core of the vortex. After a few seconds, the particle settles in the centre of the vortex inner core field (the solid body rotation part) and comes to a virtual stand-still (apart from some minor oscillations in x and y direction) because of a balance between the axial drag force acting on the particle and the particle buoyancy force.

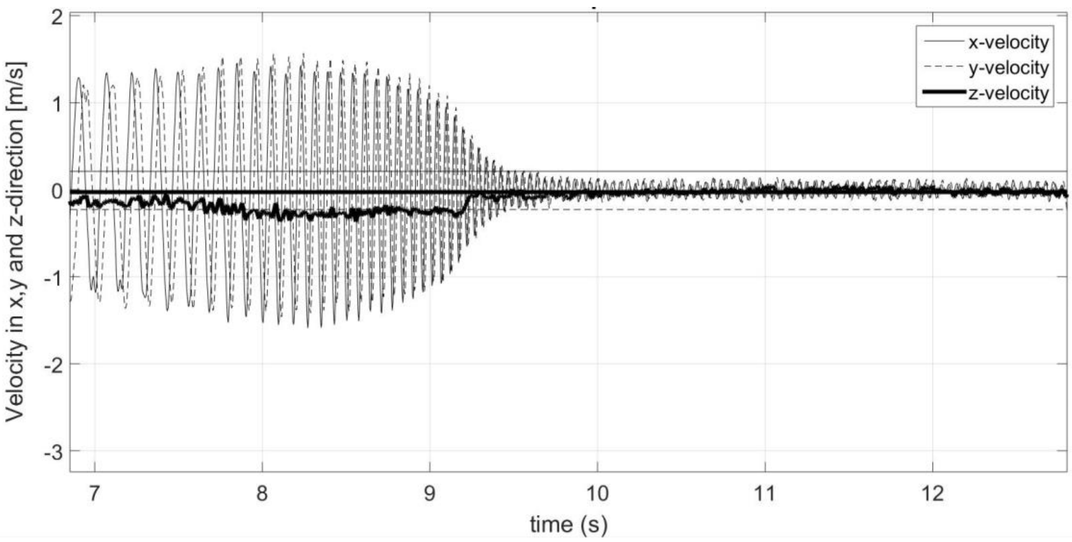

***Fig. 3**. Particle velocities in x,y,z-direction. As can be seen the particle initially has a positive downward velocity (z-velocity). After a few seconds, the particle settles in the centre of the vortex and comes to a virtual stand-still (apart from some minor oscillations in x and y direction).*

Fig. 4 shows the calculated accelarations in x,y,z-direction of a sphererical particle in the free-surface vortex. It is noted that accelerations in the x-y plane in the order of magnitude of 100 ms^{-2} (10 g) are recorded.

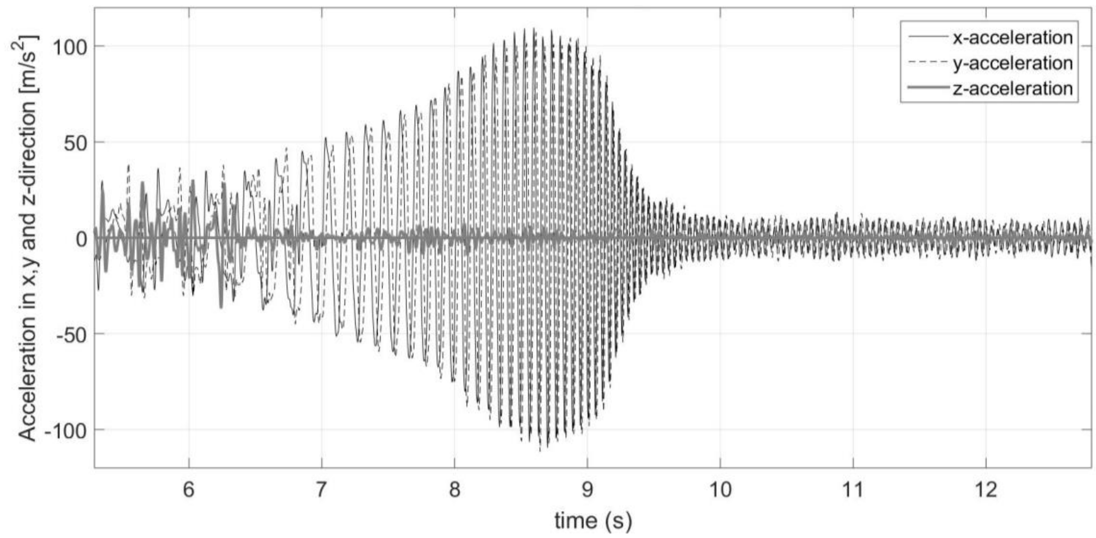

***Fig. 4**. Particle accelarations in x,y,z-direction. It is noted that particle accelarations in the order of magnitude of 100 ms-2 are recorded.*

Error distribution of the presented 3D-PTV method

The *x,y,z*-position of the particles is determined by multiple triangulations (9-15 depending on the visibility per time-step for each camera). A first estimate for the uncertainty is obtained from a singular value decomposition of the estimates obtained. So far the uncertainties (σ) in *x* and *y* position obtained are in the order of magnitude of 10^{-4} m, the uncertainty in the *z*-direction is in the order of magnitude of 10^{-3} m. Further calibration and minor adjustments in the setup are to be made in order to obtain a higher accuracy in the *z*-position. An important issue is the disrupting effect of reflection of the particles image in the water-air interface, especially when the particle is close to the water surface at the top of the tank ($z \approx 0.9$ m) unreliable results are obtained, see Fig. 5. When the particle is submerged at a depth of > one particle diameter, this problem vanishes.

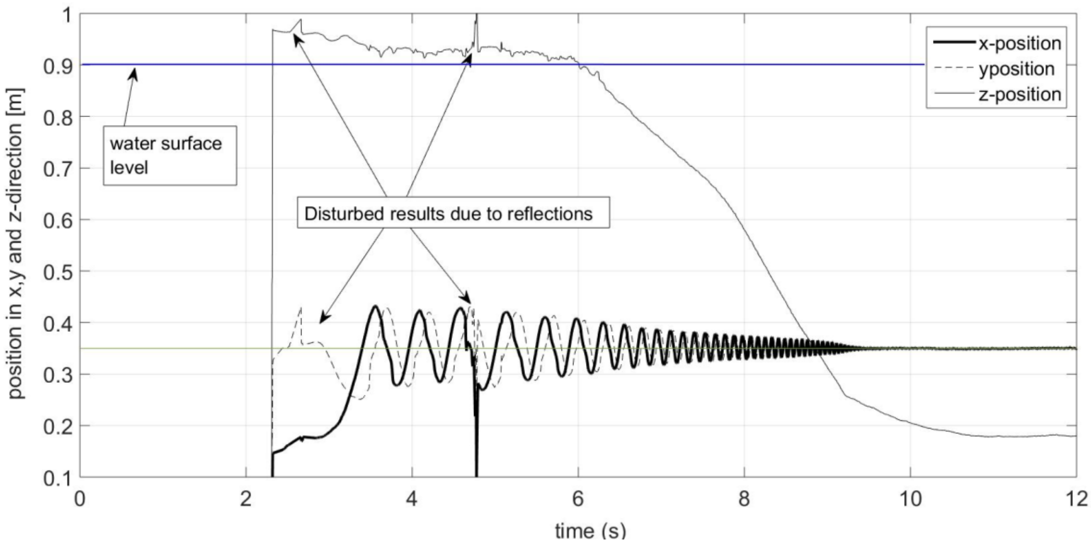

***Fig. 5.** x,y,z-positions as obtained from the PTV method. As can be seen erroneous resuts are obtained when the particle is close to the water surface (z = 0.9 m), the measured z-coordinate displays values > 0.9 m. This error vanishes at z-coordinates of about one particle diameter d below the water surface (z < 0.9 - d).*

Conclusions

The presented novel 3D-PTV method to determine the position, accelerations and forces acting on large particles of different shapes in the free-surface vortex works successfully. Future work will concentrate firstly on enhancing the accuracy in z-position and the further analysis of the results of > 800 experiments in which hydraulic free-surface vortex conditions and particles characteristics like size, shape, mass and density are varied.

Acknowledgements

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