Fachtagung “Experimentelle Strömungsmechanik”
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Bestimmung des Einflusses von tangentialem Impuls auf die Bildung von luftziehenden Hohlwirbeln in Pumpenzuläufen mittels Particle Image Velocimetry

Determination of the Influence of Tangential Momentum on Air-Core Vortex Formation at Pump Intakes by Means of Particle Image Velocimetry

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PIV; experimentell, luftziehende Hohlwirbel, tangentialer Impuls, Pilotanlage
PIV; experimental; air-core vortex; tangential momentum; pilot plant

Abstract

Air entrainment into centrifugal pumps poses a great risk for the safe operation of cooling circuits, since it leads to the reduction of cooling capability or even the break-down of the cooling circuit. In the case of emergency or after-cooling systems in nuclear power plants as well as cooling systems for exothermic reactions this can cause great harm to the plant as well as the environment. The cause of air entrainment is the formation of air core vortices in the pump intake regions of cooling circuits. On the surfaces of water bodies, a rotating air-core vortex occurs when water is pumped out with a high volume flow while a circulation is present in the water body. The size of the air core vortex is depending on various parameters, most notably the volumetric outflow, the submergence of the outlet, the outlet diameter and the induced tangential momentum. Further parameters which are important, especially in small-scale systems, are the viscosity of the water and the surface tension between the water and the surrounding air.
The prediction of vortex formation in pump intakes is challenging due to the huge variety of intake geometries and sizes as well as inflow conditions. A detailed analysis conducted by the American National Standard Institute (ANSI) for a broad range of existing intake geometries lead to the development of a correlation to estimate the critical condition for air entrainment based on the pump intake diameter and the Froude number (Hydraulic Institute, 2012). Although the correlation is very useful due to its simplicity and geometry independence, it fails to correctly predict the critical conditions when disturbances cause a stronger tangential momentum in the intake region.
Experiments are carried out to determine the influence of tangential momentum and volumetric outflow on the size and shape of the air core in both a laboratory and a pilot plant scale. The setups, while differing in size, are geometrical similar and consist of closed loop systems with cylindrical vessels (D_{LAB} = 0.29 m, D_{PILOT} = 4.0 m) in which the vortices are created and investigated. Different tangential momenta have been induced by changing the vertical angle of the inflow. The flow regimes and the horizontal velocity fields in the vortex core region at different heights are investigated by using Particle Image Velocimetry (PIV) and dye experiments. The PIV measurements in the laboratory scale are conducted by mounting the camera in a fixed angle below the transparent vessel thus enabling the recording of the vortex core. In the pilot plant an optical access point and a precision optics mirror are necessary to enable the recording of the vortex core region due to the large size of the vessel. After a thoroughly data-processing the obtained results were compared with literature values both from numerical simulations and experimental investigations as well as theoretical models.

The experiments show that the inflow angle β and thus the induced tangential momentum, has a great influence on the air-core development. Especially in the case of small scale systems, like the investigated laboratory plant, is the air-core length highly depending on the induced momentum. Neither the Burgers-Rott model, nor the correlation of the American National Standard Institute are able to correctly predict the occurring air-core length or the critical submergence

Theoretical background

The fluid dynamics behind air core vortices and their formation have been a topic of research for a long time, starting with the first models by Rankine in 1858 (Rankine, W. J. M., 1858). Roughly a century later Burgers and Rott developed a theoretical single-phase model, based on the Navier-Stokes equation. With this model the velocities inside a free surface vortex can be calculated for a symmetrical and time independent system. While the axial and radial velocities are only correctly predicted within the vortex core region the equation for the azimuthal velocity

$$u_\theta = \frac{\Gamma}{2\pi r} \cdot \left[1 - exp\left(-\frac{ar^2}{2\nu}\right)\right] \tag{1}$$

with the circulation

$$\Gamma = \oint_C u dc \tag{2}$$

and the axial acceleration inside the vortex core

$$a = \frac{2\nu}{r_m^2} \tag{3}$$

is also applicable outside the vortex core region (Burgers J., 1948, Rott N., 1958). The circulation and the axial acceleration can further be used to calculate the length

$$L = \lim_{r\to\infty} h(r) - h(0) \approx \frac{a \cdot ln(2)}{\nu \cdot g}\left(\frac{\Gamma}{4\pi}\right)^2 \tag{4}$$

and shape of a theoretically occurring air-core vortex (Ito et al., 2010). Recent studies, which use the model of Burgers-Rott or variations of it, include the work of Cristofano et al., 2016 and Li et al., 2008, while other groups focus on the model introduced by Rankine (Sun & Liu, 2016). Another approach is the use of empirical correlations, based on conducted experiments and simulations. A widely used correlation is the correlation of the American National Standard institute (ANSI)

$$\left(\frac{h}{d}\right)_{crit} = 1 + 2.3 \cdot Fr, \tag{5}$$

which was validated for a broad range of inlet structures and different sizes and shapes. Here the critical submergence h, where an air core vortex would reach into the pump inlet, is only depending on the outlet diameter d and the Froude number

$$Fr = \frac{u}{\sqrt{g \cdot d}}, \tag{6}$$

with u being the inlet velocity and g the gravitational constant. The ANSI correlation is a simple yet rough tool to determine critical operation conditions and is limited to flows with a “moderate circulation” (Hydraulic Institute, 2012).

Experimental Setup & Results

The experiments are conducted in two different scaled setups, a 10 l laboratory plant and a 50 m³ pilot plant. The two setups are almost identical in setup, consisting of closed loop pump circuits with cylindrical shaped vessels, where the vortex formation is observed (see Figure 1). The geometrical scaling factor, regarding the pump outlet diameter and the submergence depth as critical length scales, is 13.3.

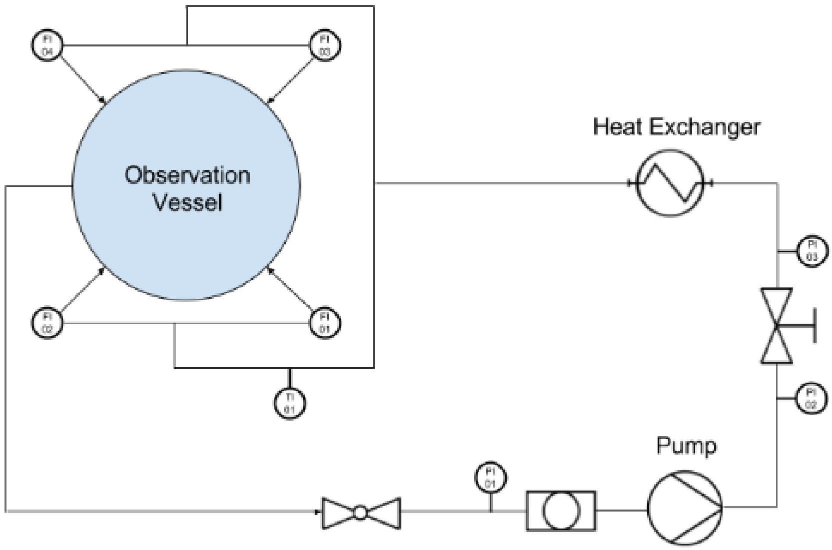

Figure 1: P&ID flowsheet for the Pilot Plant setup.

<u>1. Laboratory Scale</u>

To enable an optical access, the vessel side and bottom are made from acrylic glass with a diameter of D_{LAB} = 0.29 m. The circular pump outlet (d_{LAB} = 15 mm) is located in the center of the bottom. From the outlet the flow is led through a 90° elbow bend and enters the circular pump (HTM 10) in horizontal direction. The flow is pumped through a heat exchanger and a flow meter before it is diverted equally in four separate flows and led back into the observation vessel. The four separate inflows into the observation vessel are arranged in a circular array on the horizontal plane, to generate symmetrical flow conditions in the vessel (see Figure 2). For the defined generation of tangential momentum, inflow pipes with varying vertical angles (β = 15°, 30° and 45°) are used are used (see Figure 3). The submergence depth is kept stable for all conducted experiments at h_{LAB} = 0.11 m.

Table 1: Parameter Field for the investigation of induced momentum, T = 20 °C, p = 1 atm.

Investigated Parameter	Laboratory Plant	Pilot Plant
Inflow Angle β/°	15, 30, 45	15, 45
Froude number Fr/-	0.5, 0.7, 1.0, 1.4, 2.3, 2.8	0.5, 0.7, 1.0, 1.4
Submergence depth h/m	0.11	1.46
Vessel diameter D/m	0.29	4.0
Pump inlet diameter d/m	0.015	0.2

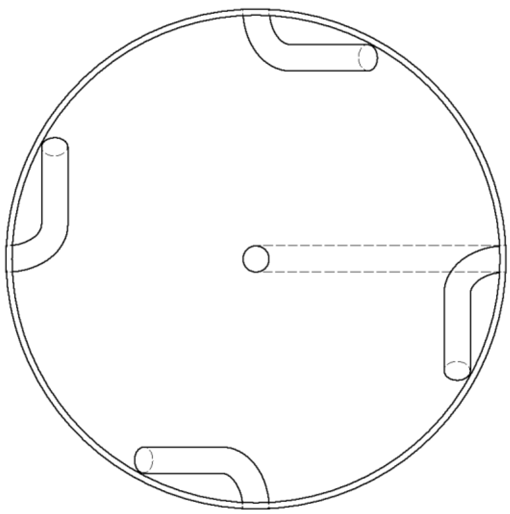

Figure 2: Top view sketch of the observation vessel, showing the circular array of the inflow pipes.

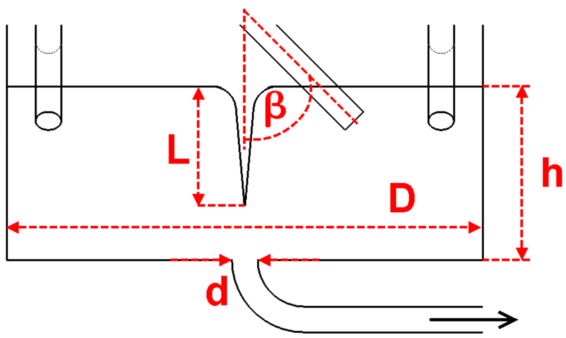

Figure 3: Side view sketch of the observation vessel, visualizing the inflow angle β.

In a first setup the appearing air core lengths are recorded for all four different vertical inflow angles and varying Froude numbers (see Table 1), using a Nikon D7100 camera with an AF-S DX NIKKOR 18–55 mm lens. After a stable vortex is created 100 pictures are taken with a time step of Δt = 1 s in between. Each measurement is conducted a second time on another day to exclude external influences from the results. The recorded pictures are then processed using a Matlab-Script written at the institute. The resulting air-core length are then nondimensionalized with

$$L^* = L \cdot h^{-1}, \tag{7}$$

where L is the measured air core length in m. The dimensionless air core length for the varying inflow angles can be seen in Figure 5 plotted over the Froude number. Error bars indicate not measurement errors, but the observed minima and maxima in the air core length and thus the air core stability for each combination of inflow angle and Froude number. It can be seen that for a given Froude the air core length and stability number greatly depends on the inflow angle and therefor on the induced tangential momentum, with increasing inflow angle the vortex becomes stronger and more stable. This effect, which was already expected, can now be quantified. The moderate circulation, for which the ANSI correlation (see eq. 5) can be applied, equals an inflow angle of 15°.
Furthermore, dye experiments are performed, where drops of dye are injected into the invisible vortex core to visualize the flow conditions (see Figure 4).

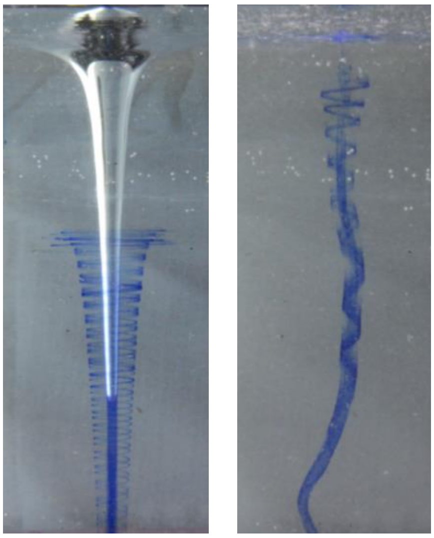

Figure 4: Dyed vortex cores for Fr = 1.0 and inflow angles of β = 45° (left) and β = 15° (right).

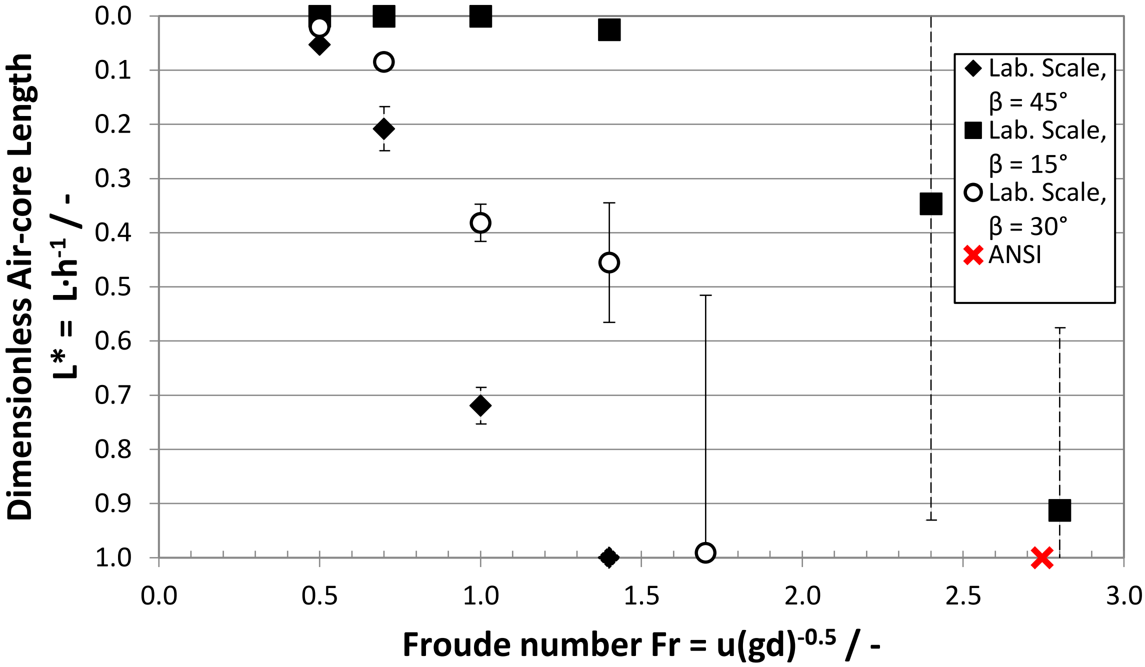

Figure 5: Results of the Air-core measurements in the laboratory plant for varying inflow angles and Froude numbers. Error bars indicate the fluctuations in the air core length. The cross indicates the critical Froude number according to the ANSI correlation.

In a second setup the horizontal velocity fields around the vortex are measured using Particle Image Velocimetry. As a light source a double pulse laser (Dantec, Nd:YAG, λ = 532 nm) is used to create a 1 mm thick horizontal light sheet. For recording a PCO1600 CCD-camera with a Zeiss Makro Planar 2/50 ZF.2 lens is placed under the vessel. The camera is placed under the bottom of the vessel in an angle between 37° and 58.5°, depending on the measurement level, to enable the recording of the vortex core region, without the outlet pipe blocking the view. As tracer particles acrylic glass encapsulated Rhodamine B particles with a size distribution of d_p = 20 – 50 µm are used. The measurements are conducted in two different heights above the outlet (h_1 = 0.035 m and h_2 = 0.07 m) with a recording frequency of 10 Hz and a total amount of 500 double pictures per measurement. Investigated are the inflow angles of β = 15°, 30° and 45° for the Froude numbers of 0.5, 0.7, 1.0 and 1.4. Since the recordings are not orthogonal to the measuring plane a pre-processing is performed to dewarp the raw data, using the PIVmap3 tool of the PIVTEC GmbH. After dewarping the pictures are processed using the PIVView2C program (PIVTEC GmbH). The processing is performed, using a standard FFT (Fast-Fourier-Transformation) correlation and a three step grid-refinement (160x160 px², 128x128 px² & 96x96 px²) with an overlay of 66%. Peak detection is done with a Least Square Gauss fit (3x3 points) with an outlier detection by maximum displacement (20 px) and maximum displacement difference (5px). The calculated data is then further processed using a Matlab script to calculate the azimuthal and radial velocity as well as the vorticity and the circulation. Since the vortices move along the horizontal plane a moving grid is implemented which follow the vortex movement. The vortex movement decreases with increasing inflow angle β, since the stronger tangential momentum has a stabilizing effect on the vortex. Vector fields are visualized using Tecplot, for Fr = 1.0, h_1 = 0.035 m and the inflow angles of 15° and 45° are shown in Figure 6.

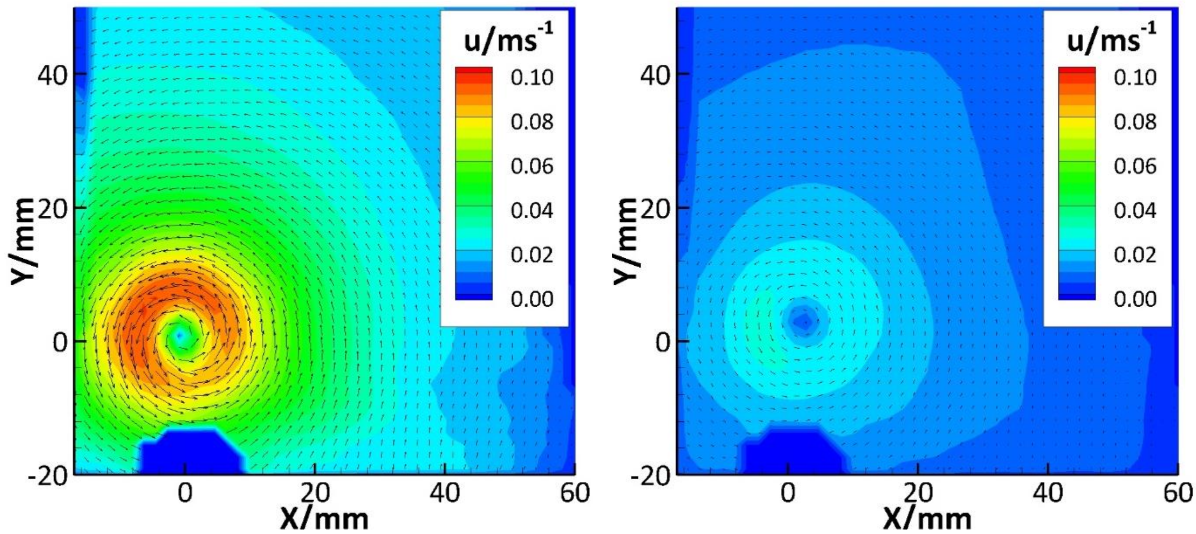

Figure 6: Horizontal velocity profiles for Fr = 0.7 and h_1 = 0.035 m, summarized over 20 double pictures each. For an inflow angle of β = 45° (left) and β = 15° (right).

2. Pilot Plant Scale

The observation vessel of the pilot plant (D_{PILOT} = 4.0 m) is welded from steel sheets, inside the vessel an intermediate bottom is constructed at a height of 1.2 m above the ground. A picture of the plant can be seen in Figure 7. The pump outlet is located in the center of the intermediate bottom and has a diameter of d_{PILOT} = 0.2 m. The submergence depth is kept constant at h_{PILOT} = 1.46 m above the pump outlet. Equal to the laboratory scale a 90° elbow bend is leading from the pump outlet to the circular pump (KSB, Mega CPK, Q_{max} = 1.100 $m^3 \cdot h^{-1}$). The inflow into the tank is according to the laboratory scale with four pipes in a circular array, creating a symmetrical inflow into the vessel in a defined angle. In this setup the flow is measured in each of the four inflow pipes separately. For the optical access inspection glasses in the side of the vessel and an endoscopic access point under the intermediate bottom are use. The measurements of the air-core length are performed similar to the laboratory experiments, but only for the inflow angles of β = 15° and 45°. The results are plotted in Figure 8. Unlike the results in the laboratory scale, no correlation between inflow angle and air-core length can be seen, but the smaller inflow angle of 15° also results in a higher instability and more fluctuation in the air-core length.

Figure 7: Picture of the pilot plant observation vessel inside the TUHH experimental hall.

Particle Image Velocimetry measurements have been conducted, using a High-Power LED as a light source and polyamide particles (Grilltex, d_p = 80 – 200 µm) as seeding particles. The high power LED is mounted in front of an inspection glass which is located 0.3 m above the intermediate bottom. The camera (PCO 1600, Zeiss Makro Planar 2/50 ZF.2 lens) is mounted inside the endoscopic access point on a horizontal slide. With the help of an optical mirror and a window inside the intermediate bottom, the vortex core region can be measured at a height of h_3 = 0.6 m above the pump outlet. The recordings are currently evaluated and will be given during the presentation.

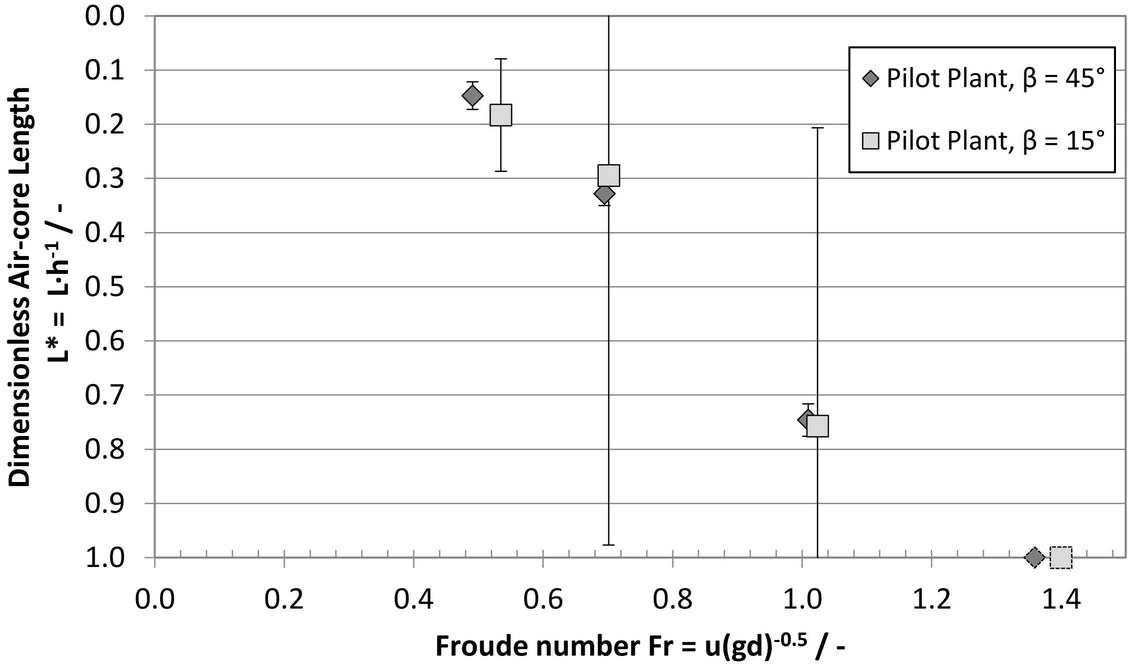

Figure 8: Results of the Air-core measurements in the pilot plant for varying inflow angles and Froude numbers. Error bars indicate the fluctuations in the air core length.

Discussion

From the horizontal velocity fields the azimuthal and the radial velocity over the radius can be obtained for each time-step. With eq. 2 the circulation can be calculated from the azimuthal velocities. With the downward acceleration gained from the vortex core radius (eq. 3), the Burgers-Rott model can be fitted to the results. In Figure 9 the azimuthal velocities and the Burgers-Rott fit are plotted over the radius for $\beta = 15°$ & $45°$ (Fr = 0.7 and $h_1 = 0.035$ m). While the azimuthal velocity profiles are in fairly good agreement, the theoretical air-core length calculated using equation 4 are way too low in case of the higher inflow angle (see Table 2).

Table 2: Air-core length for the laboratory scale, measured in the experiments and calculated with eq 4.

β	L_{exp}/mm	L_{theo}/mm
15°	0.0	0.1
45°	23	0.6

This difference in the air core length might be due to the fact that the Burgers-Rott model is a single-phase model, while in reality there is a surface boundary and the influence of the air-core formation on the vortex core. In the small scale of the laboratory plant surface tension has a huge influence on the formation of the air-core, but is not considered in the model. Further experiments as well as numerical simulations are currently carried out to investigate further into this matter.

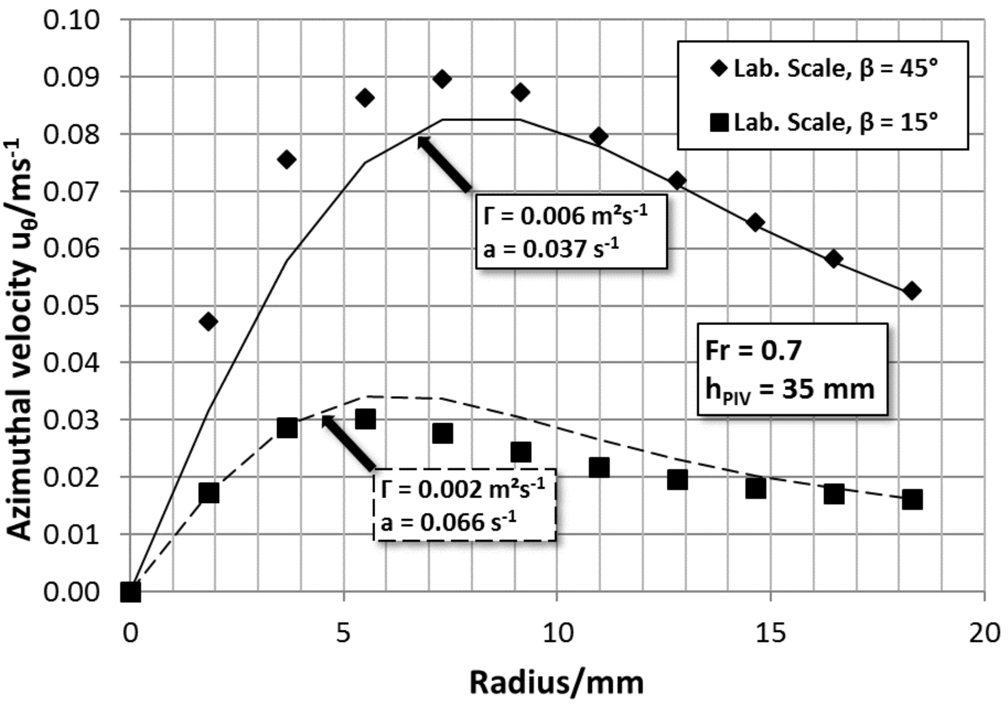

Figure 9: Azimuthal velocities for two inflow angles in the laboratory scale. The squares are measured azimuthal velocities, the lines are the azimuthal velocities calculated with the Burgers-Rott model (eq. 1).

Conclusions

The experiments show that the inflow angle β and thus the induced tangential momentum, has a great influence on the air-core development. Especially in the case of small scale systems, like the investigated laboratory plant, is the air-core length highly depending on the induced momentum. Neither the Burgers-Rott model, nor the correlation of the American National Standard Institute are able to correctly predict the occurring air-core length or the critical submergence. In both cases the air-core length are vastly under predicted. Therefor further experimental data is needed to improve the models and correlations to get more reliable results in the future.

Acknowledgements

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