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OPTIMIZATION OF APPROACH FLOW CONDITIONS OF VERTICAL PUMPING SYSTEMS BY COMPUTATIONAL ANALYSIS AND PHYSICAL MODEL INVESTIGATION

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ABSTRACT

Approach flow conditions of intake structures should be in compliance with state of the art acceptance criteria for all operating conditions, to provide the required flow rates of cooling or circulating water properly. Specially for high specific speed vertical pumps the direct inflow should be vortex free, with low prerotation and symmetric velocity distribution.

Flow separation in front of open and covered intake structures can lead to free surface vortices. Depending on the strength, vortices can emerge a coherent air core, starting from the surface and entering the inlet nozzle directly. High mechanical load of the pump and decreasing hydraulic performance are an immediate consequence. Energy content, stability and position of a free surface vortex are determinated by intake system geometry and operating conditions.

By installing flow guiding devices, the generation of vortex formations can be prevented. Optimization steps should be accomplished with respect to installation costs and complexity on-site. Therefore the effectiveness of the improvements has to be verified.

Physical model investigations are common practice and state of the art to evaluate, to optimize and to document flow conditions inside intake structures. Nowadays, computational analysis is more and more adopted in this work field. A combination of both leads to well-defined and reproducible results within a wide application range. By this means prototype intake structures can be investigated and, if necessary, optimized for their best approach flow conditions.

In the report the optimization of insufficient approach flow by computational analysis and physical model tests is presented. Therefore various intake structures for cooling water systems - all having approach flow not in compliance with the acceptance criteria of common standards - were physically modeled and investigated. Simultaneously initial and optimized layouts were reviewed by numerical calculations of different kinds.

Calculated results are compared with model test and prototype data for different cases and operating points. Focusing on the occurrence of free surface vortices, methods of reproducing free surface vortices with numerical approaches will be presented and evaluated.

Keywords: free surface vortex, intake, model test, computational analysis, CFD

NOMENCLATURE

C	floor clearance [m]
c	flow velocity [m/s]
D	pump bell diameter [m]
Eu	Euler number
Fr	Froude number
f	frequency of separating flow [1/s]
L	characteristic length [m]
L_D	Length of approach flow channel [m]
l	characteristic length [m]
p	pressure [Pa]
Re	Reynolds number
Re_{crit}	critical Reynolds number
S	Shear stress tensor
S_D	submergence [m]
s	characteristic length [m]
U	characteristic velocity [m/s]
v_a	average velocity in the suction pipe [m/s]
v_b	tangetial velocity in the suction pipe [m/s]
W	bay width [m]
We	Weber number
X	back wall clearance [m]

Greek letters

ρ	density [kg/m³]
σ	surface tension [kg/s²]
ν	kinematic viscosity [m²/s]
Θ	swirl-angle [°]
Ω	rotation tensor

DESIGN CRITERIA FOR WATER INTAKE STRUCTURES

Approach flow conditions of vertical pumping systems are determinate by operating conditions and geometric parameters. The worldwide demand for smaller structures with increasing flow rates leads to conceptions of intake structures that outbid the recommendations of common standards. In some cases, limits specified in leading guidelines are exceeded, to reduce the volume of the intake to a minimum.

In all cases the capability of providing the required flow rates probably should be proved by physical model investigations. Nowadays, numerical analysis is more and more adopted in this process.

The basic design of an intake structure can be described by the following parameters:

- submergence (S_D)
- back wall (X) and floor clearance (C)
- bay width (W)
- length of approach flow channel (L_D)

Typically, these parameters are related to the pump bell diameter D.

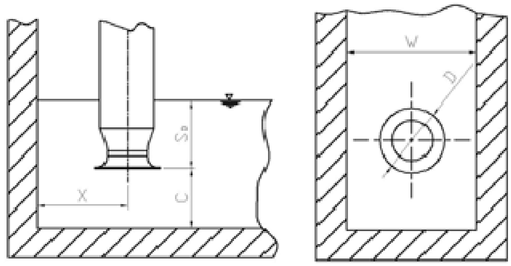


Figure 1: Characteristic dimensions of a pump sump

The Hydraulic Institute Standard HIS and the reports of the British Hydraulic Research Association BHRA (published by Prosser) and Padmanabhan are the most common standards concerning physical model investigations. All geometrical dimensions of pump sumps can be specified by dimensionless figures (C/D, X/D, W/D and S_D/D). /1/

PHYSICAL MODEL INVESTIGATION

With physical model investigations the approach flow conditions of intake structures are evaluated, optimized and documented. The evaluation considers three main criteria:

- vortex formation
- pre-rotation
- velocity distribution

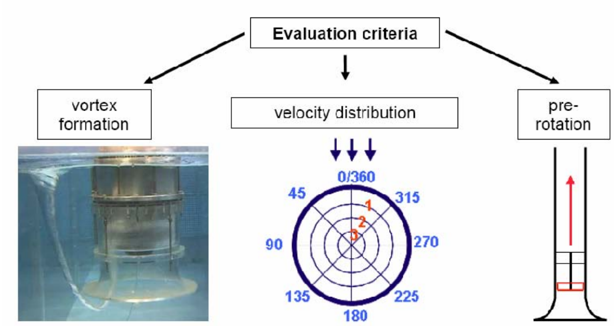


Figure 2: Characteristic evaluation criteria for physical model investigations

Optimization should always be done in respect to the feasibility and the costs on-site.

Documentation implies the recording of all significant flow patterns, such as vortex formations or separation flow, as well as the description and measurement data of all investigated operating points.

Geometrical and physical similarity are basic principles to allow a definite transfer of model test results to a prototype structure. By this means, preconditions have to be fulfilled to achieve similar flow conditions in the model and the prototype structure.

While geometric parameters are converted with the same scale factor, hydraulic parameters are quantified by dimensionless values. The most significant numbers determinate the flow behavior for different basic conditions.

Euler number: $Eu = \frac{p}{\rho c^2}$

The Euler number describes the ratio of pressure to inertia forces.

Froude number: $Fr = \frac{c}{\sqrt{gD}}$

The Froude number is the ratio of inertia and gravitational forces.

Weber number: $We = c\sqrt{\frac{\rho l}{\sigma}}$

The Weber number describes flow conditions under surface stress effects.

Reynolds number: $Re = \frac{cd}{\nu}$

The Reynolds number gives a measure of the ratio of inertial forces to viscous forces.

Froude number and Reynolds number are the most significant similarity figures concerning physical model investigations. Flow mainly influenced by friction, such as flow through closed pipes or covered sections, is characterized by the Reynolds number.

Froude number must be equal for model and prototype structure, if gravity is the dominating force of the main flow. This involves all free surface flow.

Due to physical reasons, it is not possible to have equal Reynolds and Froude number at the same time, except for the trivial case of modeling in scale 1:1. Almost all intake structures are of free surface type. Thus the Froude law ($F_{MODEL}=F_{PROTOTYPE}$) has to be applied, while the Reynolds number cannot be neglected ($Re>Re_{crit}$).

Vortex formations are classified by different energy levels. With increasing strength, the vortex core emerges more defined. George Hecker from the Alden Research Laboratory (ARL) /2/ sections vortex formations into two groups: free surface and sub-surface boundary-attached vortices. Vortex classification is shown slightly modified in the following figures.

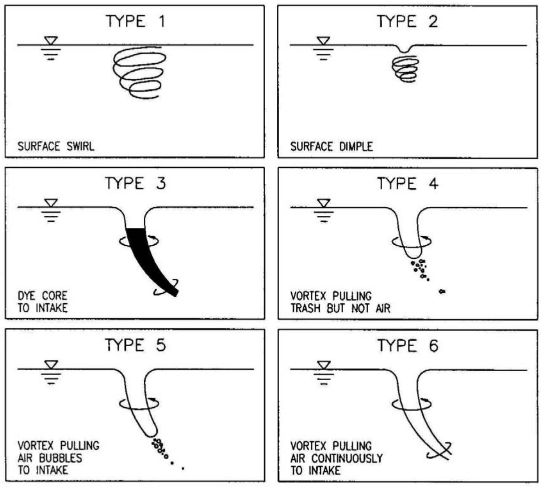


Figure 3: Classification of free-surface vortices

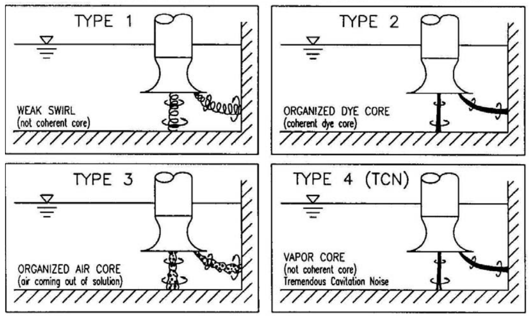


Figure 4: Classification of sub-surface boundary attached vortices

Free surface vortices are sectioned into six types:

Type 1: weak rotation of fluid at surface
Type 2: weak rotation with a dimple in the surface swirl
Type 3: dye core vortex - to be detected only by visualization
Type 4: vortex pulling trash from surface downwards
Type 5: vortex pulling air bubbles from surface, at times air bubbles entering the inlet nozzle
Type 6: constant air entraining vortex

According state of the art criteria, only free surface vortices of type 1 and 2 are accepted.

Boundary-attached subsurface vortices are classified into four types, although the ARL distinguishes between three types. Type 4 (TCN-type) had been detected at TU Kaiserslautern and classified and appended to the excising Hecker scale /2/:

Type 1: vortex visible with dye, but not coherent
Type 2: coherent swirl
Type 3: visible through air coming out of solution
Type 4: visible through a vapour core, coming out of the fluid

According state of the art criteria, no boundary-attached subsurface vortex is accepted.

Pre-rotating approach flow can influence the pump performance directly. The characteristic curve shifts towards higher flow rates or higher charge head, depending on the rotating direction of the impeller. Thus pre-rotation above specified limits can lead to changed operating data of pumping stations and thereby influence interfaced processes downstream the affected pumps.

Pre-rotation can be detected by installing a vortimeter at the elevation of the impeller inside the pump column. This is a common approach to evaluate the direction and the strength of rotational flow around the axis of the suction pipe.
A vortimeter itself consists of a four blade, zero-pitched propeller, which extends over a diameter of 95% of the pump column diameter. Angular velocity is calculated by counting revolutions per unit time. The swirl angle Θ is computed by following formula:

$$\Theta = \arctan\frac{v_b}{v_a} \quad [°].$$

Common guidelines recommend not to exceed 5 degrees of swirl angle. /3/

High mechanical load of the pump shaft and bearing sections can result from unequal and nonsymmetrical charging of the impeller. Furthermore clearance gap cavitation, torsion and bending oscillation and unsteady axial forces getting forced in consequence /4/.
By this means, variation of pump throat velocity should be limited to 10% around mean velocity. Maximum deviation in circumferential direction is limited to ± 5% of mean velocity of corresponding circle.

Velocities are measured at 25 positions inside the pump column at impeller elevation. Measure points are the intersections of eight lines and three concentric rings plus center point. A differential pressure tube is suited to measure local velocities.

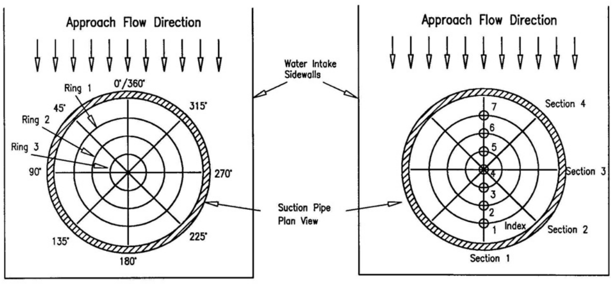


Figure 5: Definition of measure locations at impeller elevation

In summary, model test results are evaluated with following main performance criteria:

1. Vortices:

- Free surface vortices max. type 2
- No sub-surface vortices

2.Pre-rotation

- Swirl angle Θ ≤ 5°

3. Velocity distribution:

- Circumferential ≤ 5%
- Radial ≤ 10%

All model investigations described in this paper were accomplished at different wet pit test rigs. Model structures were made of Plexiglas, plastics and steel.

NUMERICAL ANALYSIS

Although numerical analysis is adopted as a complementary method to evaluate and to optimize approach flow conditions of intake structures, no common standard specifies evaluation criteria for numerical methods. Thus performance criteria, as described for physical model investigations, cannot be fully transferred to numerical approaches.

Pre-rotation can only be estimated with results of a numerical analysis. Usually the rotation direction can be identified, while the strength cannot be determinate. Therefore, for this criteria the results of model tests are more transferable.

Flow distributions at impeller elevation can be displayed as velocity or pressure contour plots. Compared with analyzed results of model investigations, contour plots give an immediate impression of the distribution. While measured values of model investigations typically are mean values, contour plots for CFD calculations, if they are solved unsteady, are snap-shots of the current flow time. For a detailed conclusion the flow behavior need to be observed for a sufficient time period.

The following figures show velocity distributions for a covered intake structure. Results of the model test, as well as two contour plots at two different time steps, are shown.

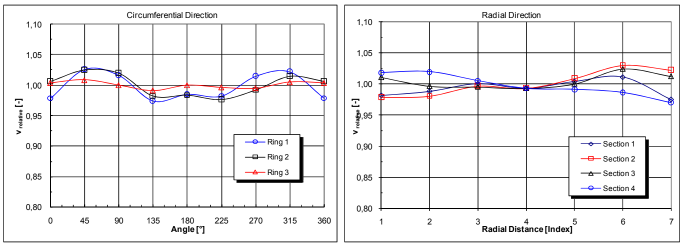
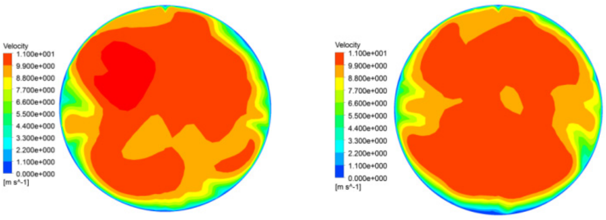


Figure 6: Velocity profiles (model test)



a b

Figure 7: Velocity distributions at different flow time (a=1.00s, b=2.00s)

Free surface and boundary-attached subsurface vortices can be reproduced in model tests, an adequate similarity method assumed. Using numerical methods, boundary conditions have to be reviewed, to minimize the complexity of an calculation and, by that, to reduce the time and cost factor. Primarily a detailed calculation of free surface flow is very computer power intensive. So in a first step, this term should be eased. By applying a fixed surface instead of using a multiphase model, the calculation time to reach periodicity can be reduced drastically. In some cases a calculation with fixed surface can be seven times quicker than one with a separate air and water phase /5/.
Additionally a fixed surface should be set frictionless. In this way, optimized basic conditions for potential vortex formations can be adjusted. With results of investigated prototype structures and model investigations it could be verified, that a calm surface flow, with a low shear rate between the single phases, abet the occurrence of free surface vortices of all kind. The other way round, a turbulent or rough surface as well as the entrainment of friction (e.g. installation of a cover plate) can reduce the strength of a vortex to zero.

Among others, two methods in visualizing vortex formations in numerical methods are in common use:

Streamlines: Curves, that are instantaneously tangent to the velocity vector of the flow.

Q-criterion: Description of a vortex as an area, where the Euclidean norm of the rotation tensor Ω is larger than the one of the shear stress tensor S.

$$Q = \frac{1}{2}\left(|\Omega|^2 - |S|^2\right) > 0$$

To illustrate vortex formations with the use of Q-criterion, the results should be normalized with a typical velocity U and a typical length L.

$$Q_0 = \frac{Q}{(U/L)^2} > 0$$

In the following example (V1), these two methods are adopted for a free surface vortex of type 4, caused by separation flow at an inlet hub.
The vortex system occurred at the inlet section of a cooling water approach flow channel. The water enters the section with a cross flow of 50° and gets accelerated beneath an installed baffle wall.

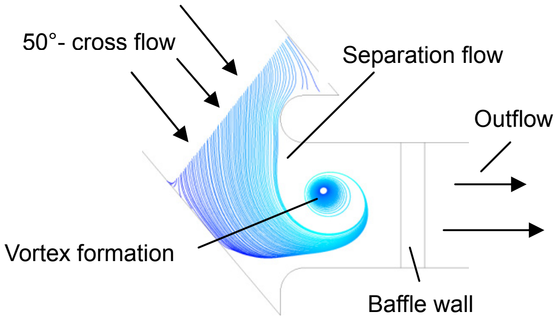


Figure 8: Scheme of a flow problem caused by separation flow at a hub (example V1)

In a physical model investigation the separation flow and the vortex formation could be reproduced.

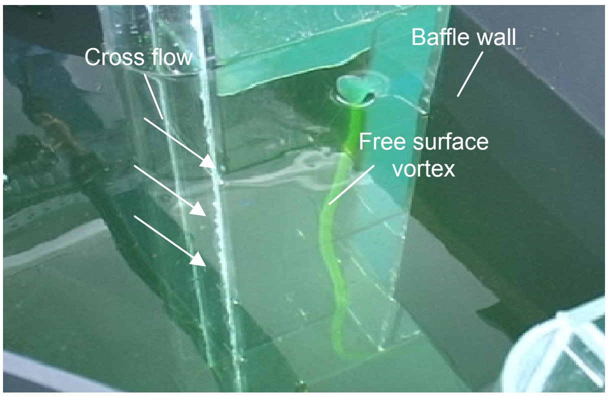


Figure 9: Free surface vortex (type 4) (model test V1)

All calculations mentioned in this work were carried out with a finite volume approach (3D RANS). As standard turbulence model the k-ω SST was used. All calculations were done transient for a sufficient time period. Grids were generated structured, as far as possible. For all layouts mesh sizes larger than 3.5 million nodes were used. Free surfaces were modeled as frictionless and fixed walls. All variations of this basic conditions will be specified.

Post-processing of the cross-flow problem was done by visualizing the vortex system with streamlines, starting in the direct area of the vortex center, and Q-criterion isosurfaces, normalized with different values ($(U/L)^2$).

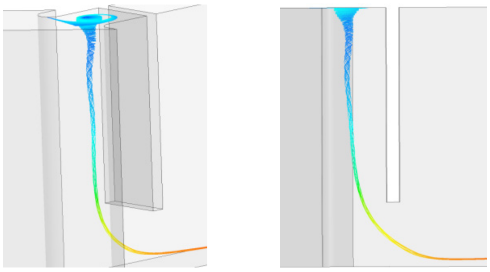


Figure 10: Free surface vortex visualized by streamlines (V1)

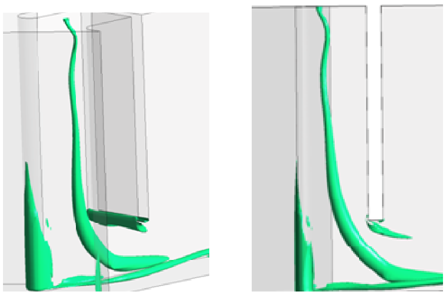


Figure 11: Free surface vortex visualized by isosurfaces (Q-criterion) (V1)

By visualizing with streamlines, the vortex core can be reproduced very well. Even the contour of the surface dimple in the center of the vortex can be brought out with the run of streamlines, although no free surface effects are modeled.

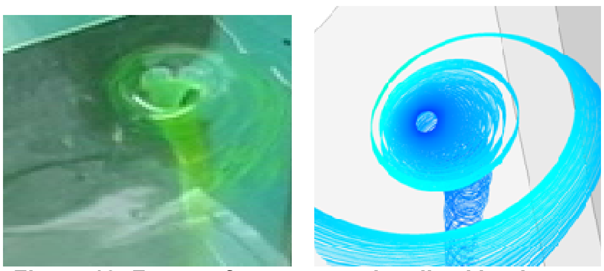


Figure 13: Free surface vortex, visualized by dye (model test) and streamlines (CFD)

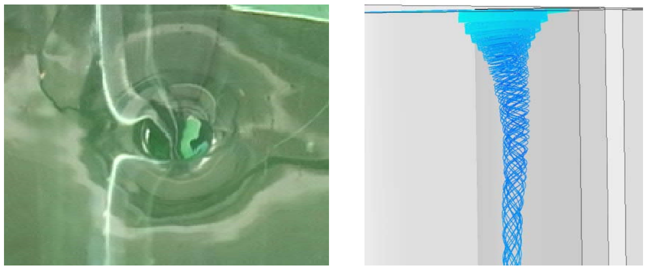
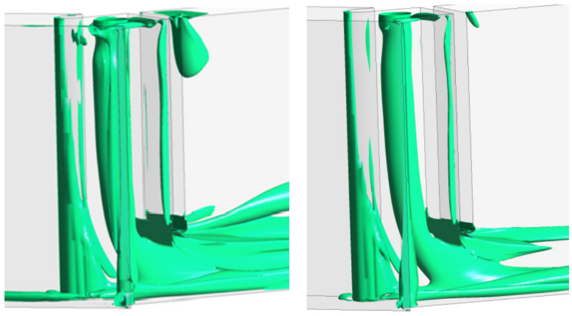
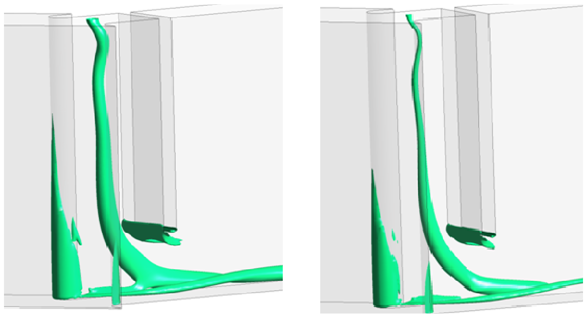


Figure 13: Free surface dimple (model test) and dimple shape, visualized by streamlines

To exert this method in a optimum way, it is necessary to know where the vortex formations occur inside the intake structure. To find potential vortex systems, it is useful to check the flow field with Q-criterion isosurfaces for various normalizations. The strength of detected rotational areas increases with an increasing normalization value.



a b



c d

Figure 14: Various normalizations of Q-criterion isosurfaces (a=0.01s^{-2}, b=0.1s^{-2}, c=1.0s^{-2}, d=1.6s^{-2})

With a normalization value of $0.01s^{-2}$ almost all estimated areas of separation flow are illustrated with isosurfaces. A normalization with $1.6s^{-2}$ leads to a result, where only the most significant sections, such as the vortex core and the separation flow at the hub and the edge of the baffle wall, are visible.

In this way, zones of critical flow, containing vortex formations, can be detected in a very simple and effective way. Based on Q-criterion information, causes for insufficient flow can be evaluated by using streamlines, contour plots and various isosurfaces.

OPTIMIZATION OF APPROACH FLOW

In the first part of this work, different approaches of physical model investigations and numerical analysis of intake flow for vertical pump systems were presented. The following section contains examples of characterization and optimization of insufficient approach flow for different structures. All described investigations were done at the institute of fluid mechanics and fluid machinery (SAM), TU Kaiserslautern, Germany.

Due to dimensional and fabrication tolerances of intake structures and their components, e.g. shortened ranges, reduced wall or floor clearances, the approach flow for vertical pump systems is never completely symmetrical on-site. The same effect can be described in physical model investigations. These very slight distortions of the flow have no direct influence on the pump performance. However, the progression of vortex formations can be influenced in the way that their occurrence alternates in time and position.

As an example, following structure (V2) was investigated by numerical analysis and physical model investigations /6/.

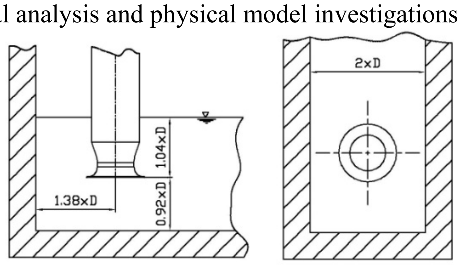


Figure 15: Dimensions, referred to bell diameter D (example V2)

In the model test, free surface vortices up to type 6 occurred in the area between pump and back wall. They switched their position unsteady, while emerging or subsiding.

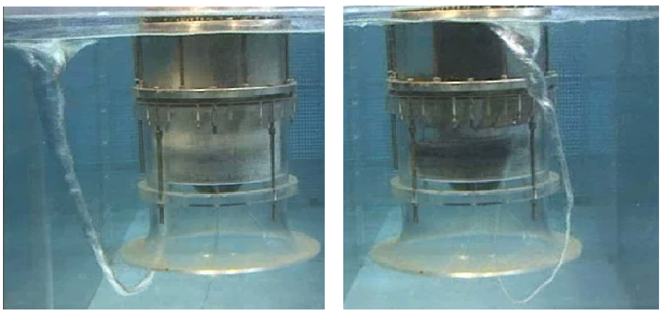


Figure 16: Free surface vortices (type 6) in different positions (V2)

From time to time, two vortices with different strength could be detected.

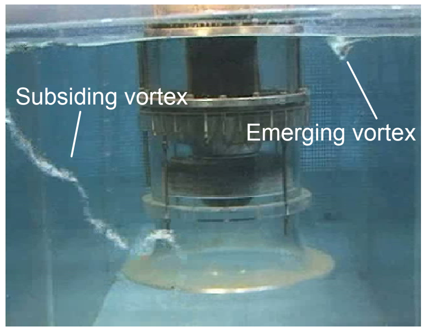


Figure 17: Appearance of subsiding and emerging free surface vortices at the same time

The appearance of two vortices at the same time is in correspondence with the results of the numerical analysis, where always one symmetrical pair of free surface vortices could be visualized by the methods described above. Even with unsteady calculations and various changes of time steps, no flow distribution leading to only one single vortex could be detected.

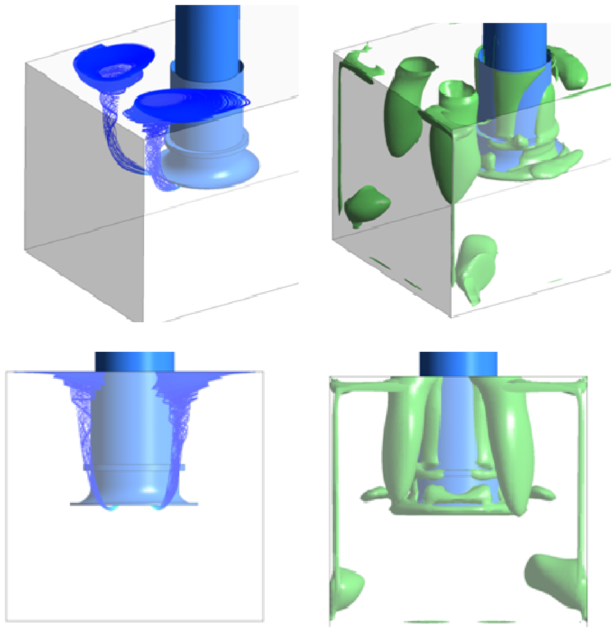


Figure 18: Visualization of symmetrical free surface vortices by streamlines and isosurfaces (Q-criteria) (V2)

The calculated results are conform with the common theory concerning vortex formations. Deviations from the results of the model tests are presumably generated by unsymmetrical flow, due to dimensional tolerances and slightly differing inflow conditions. Calculations normally have homogeneous inlet conditions and dimensional tolerances, that have no effect on the flow conditions.

All these differences have to be considered, when numerical analysis of intake structures are evaluated. Due to mostly unsteady changes of position and strength, especially of free surface vortices, it is not always possible to reproduce these vortex systems in the calculation exactly. But normally this is not even necessary, because only the information of the occurrence and the activator of the vortices is of note.

The splitting of a vortex into two symmetrical systems leads also to a split of the energy content with the effect, that the significance of the Q-criteria is lowered. In the previous example (V2), this consequence did not affect the results perceptible, due to a high energy content of the free surface vortices (type 6). But with a decreasing vortex energy level, the adoption of the Q-criteria becomes more difficult.

The following example (V3) shows a free surface vortex problem inside a covered intake chamber.

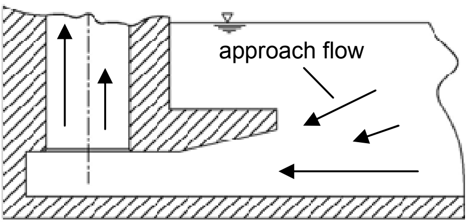


Figure 19: Covered pump sump (V3)

In front of the slopy inlet, free surface vortices up to type 3 occurred. On-site, it could be detected, that the vortex systems only appears at one side of the inlet. Also in physical model investigations /7/, a vortex emerged at only one side of the structure.

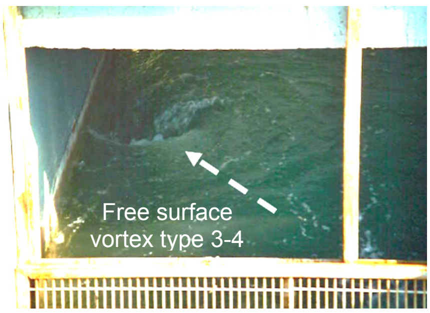


Figure 20: Free surface vortex inside a prototype structure (V2)

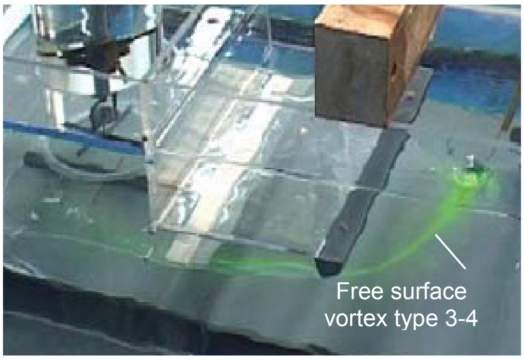


Figure 21: Free surface vortex (type 3-4) (model test V3)

Due to the effects described before, in the attendant numerical analysis, two symmetrical vortices occurred. As described, the energy content of the vortex, detected in the prototype and the model, was split up into two equal sections. As a consequence, evaluation of the calculation with Q-criterion isosurfaces did not lead to sufficient results. No adequate normalization could be adjusted, to reproduce a rotational section in front of the inlet. Only separation flow at the edges of the cover plate and the inlet nozzle could be visualized. The working principle of the used method can be verified by the occurrence of a floor-attached sub-surface vortex underneath the pump. Here, the energy content was not portioned, so that the whole vortex core could be reproduced, similar to example V1.

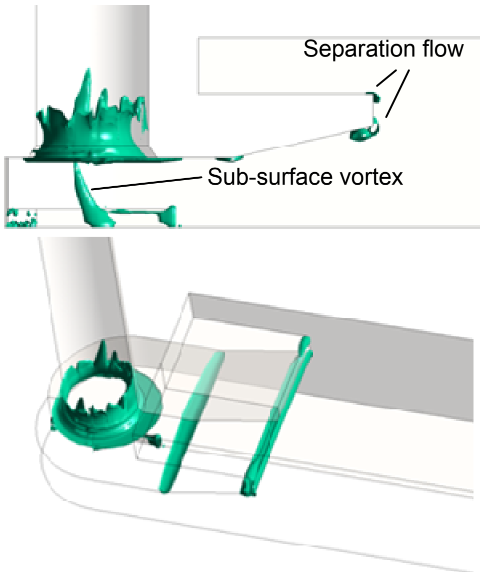


Figure 22: Isosurfaces (Q-criterion) (V3)

By using streamlines, the vortex systems could be visualized. Streamlines follow the rotational run along the vortex contour, starting at calm surface. Although free surface effects are not calculated, basic characteristics of free surface vortex systems could be reproduced, as in previous examples.

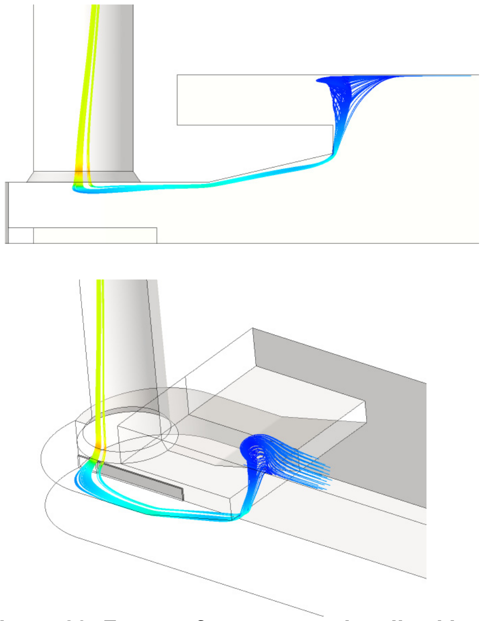


Figure 23: Free surface vortex, visualized by streamlines (V1)

For the purpose of using streamlines, it is necessary to know, where a potential vortex formation area is located. Otherwise the massive use of streamlines can produce interactions, that lead to insufficient conclusions.

Installing a baffle plate in front of a free surface vortex system is a common approach to optimize free surface problems. In this way, surface flow gets troubled. The insertion of friction leads to separation flow, that deflects the flow towards the surface. This effect (pulsation of the surface flow) disrupts developing vortex formations. Depending on the immersion depth and the vortex core clearance, vortices can be avoided. However, an oversized immersion depth leads to vortex formations in front of the baffle plate. In this case, the surface clearance of the separation flow at the baffle edge is too large. Flow in front of the plate gets accelerated and vortex formations get initialized, by rotational corner flow. Within model investigations, an optimized immersion depth can be adjusted.

In the model investigation of example V3, a baffle plate was fixed on the existing bar screen. By adjusting the immersion depth, the vortex problem could be optimized. An application of the improvement on-site led to an optimized approach flow with no free surface vortex occurring. The approach flow hits the plate and gets accelerated below. Behind, the flow circulates. The shear stress between the different flow patterns proceeds in opposite direction to the vertical progress of the vortex. Together with an unsteady surface, the emergence of a free surface vortex can be inhibited.

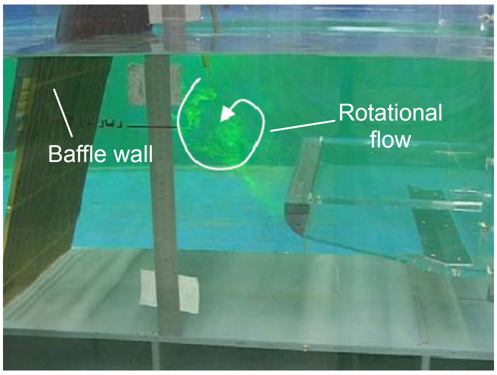


Figure 24: Rotating flow behind a baffle wall (V3)

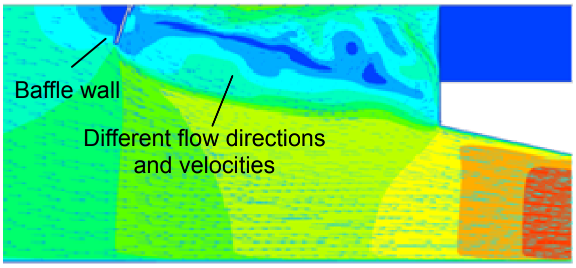


Figure 25: Velocity distribution behind a curtain wall - shear stress caused by opposite flow patterns

This example shows that it is possible to optimize free surface flow problems without considering a free surface in the numerical model. Hydraulic effects of an improvement can be verified by physical model tests. Corresponding results are in good accordance with results of the CFD-calculations.

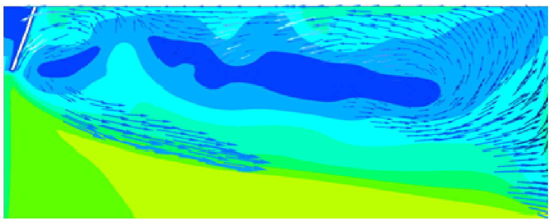


Figure 26: Rotational and separation flow behind a baffle wall (V3)

SUMMARY

Evaluation, optimization and documentation of approach flow for vertical pump systems is normally done by physical model investigations. So far, it is the best tool of prediction. However, computational analysis can be more and more adopted in this work field. While common standards contain detailed specifications for model test, no recommendations for performing and evaluating numerical analysis of intake flow are given.

In this work, various intake structures for vertical pump systems, all having approach flow conditions not in compliance with state of the art acceptance criteria, were presented. For all examples, physical model investigations and numerical computational analysis of different kinds were done. Focusing on the occurrence of free surface vortices, methods of reproducing free surfaces vortices with numerical approaches were presented and evaluated.

For all investigated cases, it could be verified that free surface effects can be neglected, when the free surface is modeled as fixed and frictionless wall. Using isosurfaces (Q-criterion) with adequate normalizations and streamlines, free surface vortices could be reproduced with numerical analysis. All results were in accordance with model test results and prototype data.

As a further result, it could be shown that some kind of unsteady vortices - vortices that switched position and strength in prototype and model tests - are displayed as two symmetrical vortices in computational calculations. In this cases, the effectiveness of energy based evaluation criteria (e.g. Q-criteria) is more and more reduced with a decreasing vortex strength. Therefore, they cannot be used generally.

Additionally, an optimization of a free surface vortex problem, by installing a baffle wall, was verified with model tests and CFD results.

Referring to the results of this report, model investigations remain essential in the process of evaluating approach flow for vertical pump systems. But numerical approaches can be a very efficient support, even for optimization of free surface problems. Although an implementation of a fixed and frictionless surface is an direct intervention in the free surface flow, reproducibility of free surface vortex formations with numerical analysis can be confirmed.

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