Prediction of transport capability of intake vortices based on a hybrid modelling strategy

Prévision de la capacité de transport des vortex d'admission sur la base d'une stratégie de modélisation hybride

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RÉSUMÉ

Sur la base d'une stratégie de modélisation hybride, un modèle de prévision a été développé qui permet d'évaluer la capacité de transport des tourbillons d'admission sur la base d'une probabilité calculée pour différents solides flottants. Les paramètres caractéristiques du champ d'écoulement des tourbillons, dérivés de simulations numériques, servent d'entrée du modèle.

Comme la modélisation de solides flottants de grande taille dans une simulation numérique est très complexe, une stratégie de modélisation hybride a été appliquée. Ces stratégies combinent des expériences dans un modèle physique à petite échelle avec les résultats d'une simulation hydronumérique. Une régression logistique établit une causalité entre le transport de matière flottante observé dans le modèle physique, d'une part, et les forces d'écoulement, calculées à des sphères virtuelles dans le modèle hydronumérique, d'autre part.

ABSTRACT

Using a hybrid modelling strategy, a prediction model was developed which allows an evaluation of the transport capability of intake vortices based on a calculated probability for various floating solids. Characteristic parameters of the vortex flow field, derived from numerical simulations, serve as model input.

Since the modelling of large floating solids in a numerical simulation is very complex, a hybrid modelling strategy was applied. This strategy combines experiments in a small scaled physical model with the results of hydronumerical simulations. A logistic regression establishes a causality between the transport of floating solids observed in the physical model on the one hand and the flow forces, calculated on virtual spheres in the hydronumerical model, on the other hand.

KEYWORDS

hybrid modelling, intake vortex, numerical simulation, prediction model, transport capability

1 INTRODUCTION

From a certain level of strength, intake vortices are able to transport floating solids - and this level is lower than required for the transport of air. The strength of an inlet vortex depends not only on the geometric boundary conditions (e.g. asymmetries), but also on the hydraulic boundary conditions defined by the flow rate and the water level above the intake.

Scientific studies of vortex formations were mostly carried out in the context of pump-intake configurations in which air entrainment can cause a discharge reduction, vibrations, noises and even mechanical damage. However, significantly fewer investigations are dealing with the transport of floating solids via intake vortices. Therefore, there is a lack of knowledge about the correlations between the characteristics of the vortex flow and the transport capability.

However, a direct observation and analysis of the transport of floating solids in the numerical model is not practicable. On the one hand, vortex phenomena are extremely complex due to their transient behaviour and a highly three-dimensional nature. This imposes high demands on the numerical model used. On the other hand, the software ANSYS Fluent does not provide the option to include large floating solids reliably in the numerical model (At the time of the research project). Therefore, a hybrid modelling is carried out by a combination of experimental model experiments and a hydronumerical model.

The transport of different floating solids was observed in the physical model. Using the numerical model, the flow forces at virtual spheres in the numerically modelled vortex flow were computed. Regression analyses were carried out to develop the so-called hydronumeric-empirical prediction model. The regression establishes a causality between the vortex flow calculated in the hydronumerical model and the observed floating solid transport in the physical model.

2 MATERIALS AND METHODS

Physical Model

In this investigation a small-scale physical model (scale 1:5) was used. Figure 1 shows a schematic illustration of the physical model.

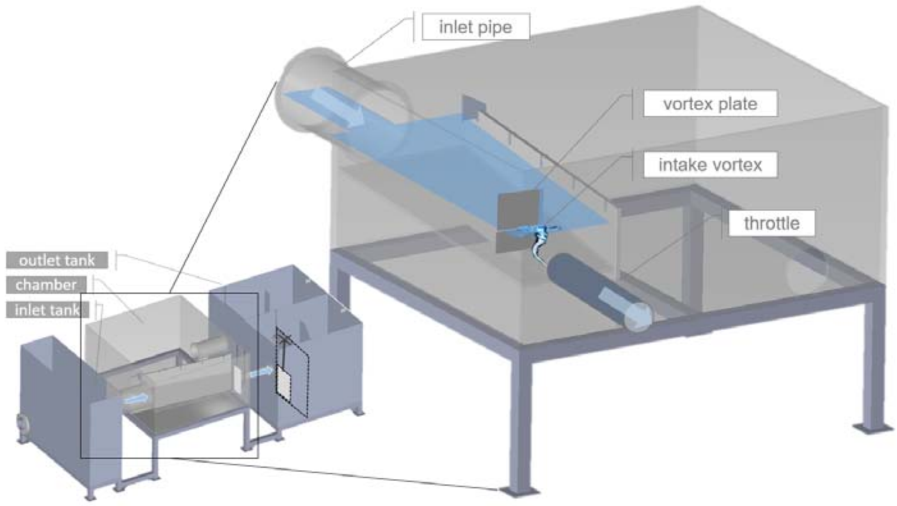

Figure 1: Configuration of the small-scale physical model (1:5) of the overflow structure (Vosswinkel 2017)

The chamber is 1.16 m long, 0.33 m high and is made of acrylic glass. The vortex plate is attached to the side wall of the chamber. This vortex plate is designed to reinforce and stabilize the intake vortex induced by the inflow into the throttle.

By regulating the downstream water level (h_u) in the outlet tank, the flow rate (Q) and the water level in the chamber (h_o) can be regulated independently of each other. A total of 26 different combinations of water level (h_o, from 0.06 m to 0.31 m) and flow rate (Q, from 2.0 l/s to 9.7 l/s) were investigated in the physical model. The so-called intake Froude-number Fr_E (-) is used to describe the hydraulic boundary conditions: $Fr_E = \frac{v}{\sqrt{g * h_0}}$ (-); *with: g = gravity ($m^3 * kg^{-1} * s^{-2}$); v = intake velocity (m/s); h_o = water level (chamber) (m).*

Floating Solids

A total of 19 spherical floating solids were tested. These are distinguished in terms of their different combinations of density and size. An important characteristic of floating solids is the difference between the buoyancy force F_A (N) and the gravity force of a particle F_G(N). This residual buoyancy force F_{Rest} (N) needs to be overcome by the flow in order to transport the floating solids downwards to the intake. The residual buoyancy force is calculated by the following formula: $F_{Rest} = (F_A - F_G)$ *(N).*

Transport Capability

All floating solids are added individually into the sphere of influence of all vortices by hand. A quality criteria G_W (-) is defined which allows a comparison of the transport capability of the vortices regarding the 19 floating solids used here. For this purpose, the number of solids transported into the throttle is counted ($n_{P,transported}$ (-)) and compared to the total number of used solids ($n_{P,total}$ (-)): $G_W = \frac{n_{P,transported}}{n_{P,total}} * 100$ *(-)*

Numerical Model

Despite the unsteadiness of intake vortices, a steady-state simulation reproduces the intake vortices with good accuracy. An Omega RSM turbulence model is preferable compared to a k-ε RNG turbulence model. The resolution of the numerical mesh was determined in a preliminary study. A VOF model was used to compute the free water surface.

3 RESULTS AND DISCUSSION

Forces on virtual spheres

Using a simplified theoretical model, the vertical components of the flow forces acting on the virtual spheres in the flow are calculated. Since the flow forces increase downwards along the vortex rotation axis, the critical point for the transport of floating solids lies directly below the dimpel.

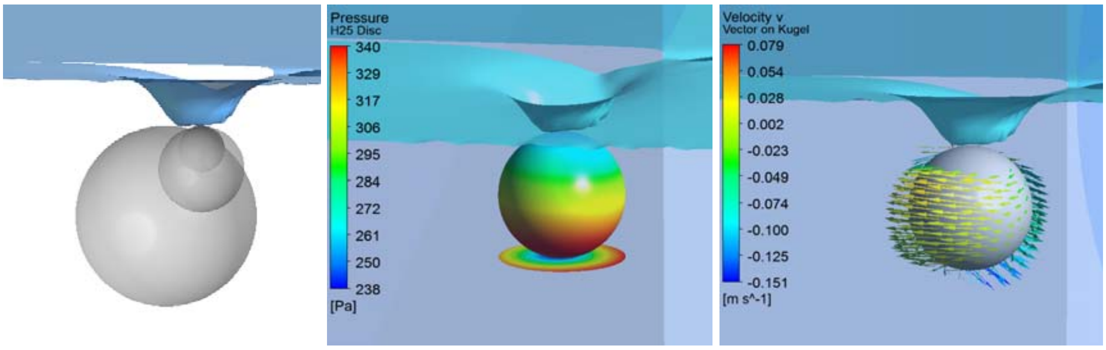

Figure 2: Left: Positioning of the virtual spheres (different diameters) in the numerical simulation; Right: forces on virtual spheres in the numerical model (Vosswinkel 2017)

The vertical components of the following flow forces $F_{Ström}$ were calculated for each of these spheres using equations (1) to (4):

inertial force: $$F_{inert,NUM} = v^2 * \rho_F * A_{Proj} * c_W \quad (N) \tag{1}$$

pressure force: $$F_{press,NUM} = F_A - \iint p \, dO_y \ (N) \tag{2}$$

friction force: $$F_{fric,NUM} = \nu * \rho_F * O * \frac{\Delta v}{d_K/2} \quad (N) \tag{3}$$

turbulence force: $$F_{turb,NUM} = \rho \iint \overline{v'^2} \, dO_y + \rho \iint \overline{u'v'} \, dO_y + \rho \iint \overline{v'w'} \, dO_y \quad (N) \tag{4}$$

with: p = pressure (Pa); ρ_F = density fluid (kg/m³); u, v, w = velocity components (m/s); x, y, z = coordinates (-); A_{Proj} = projection surface of the sphere (m²); ν = kinematic viscosity (m²/s); O = surface of the sphere (m²); c_W = drag coefficient, here generalised = 0.45 (-); Δv = velocity difference (m/s); d_K = sphere diameter (m); $\overline{v'^2}, \overline{u'v'}, \overline{u'w'}$ = turbulent stresses (N/m²)

Regression Model

The inertial force $F_{inert,NUM}$ and the pressure force $F_{press,NUM}$ as well as the residual buoyancy force of the floating solids $F_{Rest,NUM}$ were used as independent variables. The turbulence force $F_{turb,NUM}$ and the friction force $F_{fric,NUM}$ on the other hand, were excluded because of their minor significance. As a dependent variable, the result of the observation of the transport of floating solids in the experiment is included in the regression. Thus, the logistic regression is based on a total of 26 cases x 19 floating solids = 304 observations. Table ***1*** shows the coefficients of the regression function (HEMP_KR) and the statistical evaluation.

Table 1: Coefficients of the regression function (HEMP_KR) and the statistical evaluation

	coefficents	standard error	Wald z-value	p-value	
b_0 (Intercept)	2.23	0.28	8.00	1.25E-15	***
b_1 F_{REST}	-121.47	16.43	-7.39	1.43E-13	***
b_2 F_{inert}	99.39	17.32	5.74	9.59E-09	***
b_3 F_{press}	-36.44	44.06	-0.83	0.408	

The correlation classification rate is 86% and is rated as good. This confirms the representation of the solution field of the calculated quality criteria $G_{W,HEMP\_KR}$ as a function of the boundary conditions Fr_E and h_o/d in comparison to the experiment in the physical model in Figure 4 41.

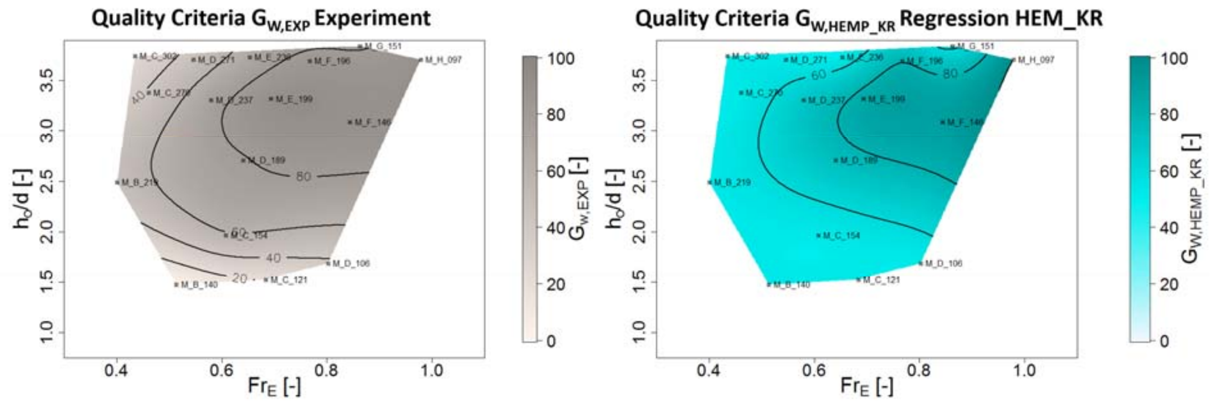

Figure 3: Comparison of the transport capability of the vortices presented as quality criteria G_W [-] depending on the boundary conditions Fr_E [-] and h_o/d [N] between experiment (left) and HEMP_KR (right) (Vosswinkel 2017)

4 CONCLUSIONS

A direct numerical simulation of large floating solids in a vortex flow is not easily possible in the numerical model. Therefore, a prediction model for the estimation of the transport of floating solids via intake vortices was developed using a hybrid modelling strategy. The future application of the developed prediction model requires the following steps:

- Performing the hydronumerical simulation of the vortex flow

- Calculation of the forces from the vortex flow

- Insertion of forces and particle properties (FRest) into the prediction model

Result: Transport probability for a defined floating solid.

LIST OF REFERENCES

Vosswinkel, N. (2017): Transport von Einlaufwirbeln (Transport capability of intake vortices). Bd. 21, Aachen: University of Wuppertal.