

## CFD MODELLING OF A SECONDARY SETTLING TANKS: GENERALIZATION BASED ON DATABASE RELATIONS

ONDŘEJ ŠVANDA\*, JAROSLAV POLLERT

*Czech Technical University in Prague, Faculty of Civil Engineering, Department of Sanitary and Ecological Engineering, Thákurova 2077/7, Prague 6, Czech Republic*

\* corresponding author: [ondrej.svanda@cvut.cz](mailto:ondrej.svanda@cvut.cz)

**ABSTRACT.** The area of secondary settling tanks modelling using numerical methods has been quite extensively explored and researched by numerous authors and papers. These models utilize different approaches, from efforts to create a solely deterministic models to attempts to generalized or calibrated empirical models. Nevertheless, the processes are not easy to simulate due to the high complexity of the physics involving multiple phases, bio-chemical reactions and non-Newtonian fluids. Therefore, an additional effort should be focused on improving these models and to validate them against experimental measurements. This article is focused on creating a numerical model for settling tank optimization, which builds on the previous works and is then extended with newly obtained relations from vast experimental measuring using the database approach.

**KEYWORDS:** CFD modelling, secondary settling tank, sludge database.

### 1. INTRODUCTION

The field of numerical solutions of the Secondary Settling Tanks (SST) has been under the scope of many researchers and over the years, numerous different models have been developed in order to describe the driving physics.

The comprehensive summary of early works in SST modelling was done by Ekama [1] and was later extended by Samstag [2]. Firstly, he mentions the historically first attempts to use CFD for sedimentation purposes done by McCorquodale and his student using the method of Roache [3] and Patankar [4]. Later, Zhou & McCorquodale [5] used a standard k-ε turbulence model with the incorporation of solids transport and a settling model using double exponential equation of Takacs [6]. They concluded that the velocity pattern of the water-only flow is significantly different from the one containing solids.

A more advanced model was introduced by Griborio [7], who developed a model that included also flocculation and used the vorticity/stream function to model the fluid pressure correctly. The impact of flocculation in the centre-well design tank was studied in Griborio & McCorquodale [8], they stated that the influence of flocculation on the hydraulic performance is low. A recognizable author is De Clercq [9], who introduced a 2D model based on a commercial solver that took into account flocculation, solids transport, and density coupling with the Herschel Bulkley rheological model.

The possibilities of using a mixture model are well described in a PhD thesis by Burt [10], where the author tries to extensively validate and verify an extended drift flux model to be used in clarifier processes modelling. As a result, he points out that improved models are required for flocculent and discrete set-

ting, since those cannot be captured by the standard Takács settling function.

The general problem is to incorporate all 5 regimes of sedimentation into one framework, which leads to the need for a generalized sedimentation model. In the recent years, there have been several attempts to do so, Morse, Sickza, & Nielsen [10] or Ramin, et al. [11] who introduced an extension of Takacs' model for hindered settling to account for the compressive settling region. One of the most recent models is from Wimshurst & Burt [12], who modified the standard Takacs' settling equation to account for lower velocity compression settling, but does not properly account for the flocculant and discrete settling phase, as he points out in the paper. He also demonstrates a use of a response surface method to predict the behaviour under different conditions without the need to use a CFD model. This response surface is created by 64 CFD simulations of different conditions, but is not compared to any measured data to validate its accuracy outside the initial data.

The developed models differ by XD approach, the complexity of the physics taken into account and by the approach chosen. One type of the models is focused on discrete particle settling using different particle classes and modelling their kinematics, which does not capture the hindered phase correctly and seems not to be the correct path for a generalized sedimentation model for several reasons. The second type of models considers the sludge phase as monodisperse, which is beneficial for the hindered phase but struggles to correctly account for the flocculation and discrete particle sedimentation phase. But the recent research focuses on these models as they are continuously being improved. Nevertheless, what all these models share in common is that their performance

Properties recorded for every sample	External properties
Sampling – depth in the tank	SST inlet flow rate
Sampling – radial coordinate of the tank	SST outlet flow rate
Time and date	SST sludge removal flow rate
Temperature	SST inlet suspended solids concentration
Hindered sedimentation velocity	SST outlet suspended solids concentration
Viscosity	SST flocculant dosage
Sludge volume index	Weather (dry/rain)
Density	SST suspended solids concentration profile
Suspended solids concentration	
Flocs size distribution (small, medium, large)	
Microflocs	
Core consistency (compactness)	
Filament index	
Fragmentation	
Buoyancy	
Turbidity	

TABLE 1. Sludge sample properties and external properties recorded during experimental campaign.

decreases when used outside the sludge parameters they were calibrated on or require to obtain the sludge parameters for every settling tank they are trying to assess. Also, to this point, the CFD models are not validated against the real values in settling tanks during operation but rather against laboratory measured data, which is not optimal given the number of factors influencing the sedimentation.

This paper describes an attempt to create a generalized sedimentation model with a different approach from all previous works. It utilizes the Tacacs' sedimentation equation for the hindered settling, as it has been verified many times before, to provide good results for hindered settling phase, but modifies it by additional sub-models to account for the flocculation phase and floc breakups but more importantly, adds a modifying coefficient to the Tacacs' sedimentation curve to allow for an adjustment to different flow and sludge conditions as the sedimentation is influenced by numerous biological and chemical aspects that change the settleability of the sludge and cannot be described by a single parameter.

The novelty of this approach lies in the utilization of a big set of experimental data obtained over a long period of time. These data were put into a database in order to find relations between different influences, which allows to create a CFD model that can account for the sedimentation changes under different tank conditions. To be able to validate the model, a screening method for monitoring the suspended solids concentration distribution inside the settling tank was developed.

## 2. MATERIALS AND METHODS

The methodology consisted of several subsequent steps. First, the experimental data of the sludge properties of interest were gathered at the Central Waste Water

Treatment Plant in Prague (CWWTP) from two different SSTs. Subsequently, the measured data were evaluated partly on-situ and partly in the lab for a more complex sampling. For each sample, a report including all measured and calculated properties was made. Due to an extensive amount of data gathered over a period of two years, a database framework was created to process that data and to find sludge sedimentation dependencies, which were then used as an input for the CFD model.

For the purposes of running the tests in-situ, a temporary field lab was built next to the SSTs. It houses two settling columns for sedimentation tests, viscosimeter, sludge pump and other accessories.

There were total of 9 data gathering campaigns from April to October 2017 from SST DN1 and then from April to September 2018 from tank DN3. Specific data for the need of the numerical model were also measured in 2019. A total of 136 complex samplings were conducted. The extent of data analysed for each sample is summarized in Table 1.

One of the main tests was the settling column test conducted at the site. Two three-meter-high cylindrical columns with a diameter of 0.3 m were used. The sludge from different locations in the SST was pumped into the columns up to the height of 2.8 m using a standard submerged sludge pump. The height of the interface between the water and the sludge was recorded each 5 minutes for the entire length of the test taking 1 or 2 hours. The outcome from this test was the hindered settling velocity (HSV) taken as the slope of the curve linear part (m/h). Later in the CTU lab, spectrophotometry was used to obtain the concentration of extracellular polymers (carbohydrates, proteins and humic substances). The suspended solids concentration was measured gravimetrically.

Rheological properties of the samples were measured using the rotary viscometer Rheometer RC20.

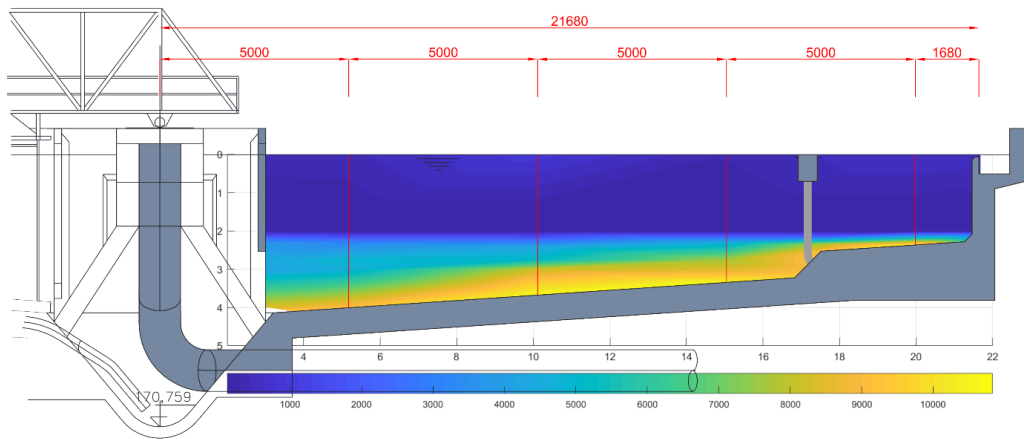


FIGURE 1. Distribution of suspended solids concentration in the SST (mg/l) – rainless flow.

The tests were conducted in a cylinder/cylinder setup suitable for non-Newtonian fluids. The strain rate range was chosen to be  $0\text{--}1000\text{ s}^{-1}$  during the tests in 2017 and then changed to  $3.5\text{--}500\text{ s}^{-1}$  during 2018. The overall time of the test was 300 s with the resolution of 50 values per test. The postprocessing of the data was done in Rheotec 3000, v2.0. The dynamic viscosity was calculated as:

$$\mu = \frac{\tau}{\frac{\partial u}{\partial y}}, \quad (1)$$

where  $\mu$  is dynamic viscosity ( $\text{Pa} \cdot \text{s}$ ),  $\tau$  is shear stress and  $\frac{\partial u}{\partial y}$  is the strain rate.

The maximum strain rate in the SST obtained from a CFD simulation was around  $20\text{ s}^{-1}$ , meaning that the resolution from the Rheometer RC20 was not sufficient for analysing the sludge in the SST as there was only 1 value between 0 and  $20\text{ s}^{-1}$ . Changing the maximum test strain rate and/or sample resolution did not lead to usable results with the Rheometer RC20. Consequently, in 2019, a new viscometer Brookfield DV2TLV was obtained in order to measure the viscosity in the interested range of  $0\text{--}20\text{ s}^{-1}$ .

The density of the sludge was measured using a 100 ml pycnometer. The weight of a dry pycnometer was recorded and then it was filled with the sample and closed. The redundant sample overflowed through a capillary and its weight was measured. The density was then calculated from the weight difference of a dry and full pycnometer. Also, the temperature of the sample was recorded using WTW Multi 3430 multimeter.

Sludge volume index (SVI) was determined as a specific volume of activated sludge after 30 minutes of settling in a 1 l container related to the suspended solid concentration.

$$\text{SVI} = \frac{V_{30}}{X}, \quad (2)$$

where  $V_{30}$  is the settled sludge volume and  $X$  is the suspended solids concentration.

The concentration of suspended solids was measured gravimetrically according to Horáková et al. [13].

As a filter, Pragopor nitrocellulose  $0.4\text{ }\mu\text{m}$  was used, pre-dried at  $105\text{ }^\circ\text{C}$ . The filtered volume was chosen based on the suspended solids concentration. It ranged between 5–20 ml for sludge samples, 50 ml for supernatant and 100 ml for the water outflow.

## 2.1. SLUDGE CONCENTRATION PROFILE

For the numerical model validation, it is important to capture the distribution and depth of the sludge blanket. For that purpose, an innovative approach was developed [14]. It is based on the suspended solids concentration measuring using the Cerlic Multitracker and then postprocessing the data in Matlab to visualize the concentrations in the SST.

The handheld multitracker consists of a probe connected to the device through a several-meter-long cable. As the probe is being submerged into the tank to the bottom, it continuously records the suspended solids concentration creating a vertical concentration profile.

This profile was measured at the SST at the radial distance of 3 meters from the tank's centre and then at each 2 m increment until the outer wall of the SST, with the last profile being taken at the radial distance of 21 m. These data were then assembled in Matlab to create a 2D concentration map (Figure 1). It vividly displays the position of the sludge blanket and provides more insight into the state of the sludge in the tank during different events such as rain flow. It serves as a main validation tool to compare the CFD model results with, as these distributions can be taken at any moment to validate different flow scenarios and conditions.

## 2.2. SLUDGE PROPERTIES DATABASE

To consolidate the big amount of data obtained during the campaigns, a database system was developed. For that purpose, a commercial software Microsoft Access was used as a platform. Developing the database system was both beneficial and necessary from several aspects:

- ability to sort and show all properties and values from a certain sample,
- possibility to easily compare samples and to find relations between properties,
- ability to categorize and to create sludge groups based on the settling properties.

Each sample underwent several different tests. The settling column test and viscosity measuring was done in-situ, where microscopic test, sludge volume index, ECPs and densities were analysed in the CTU lab. On top of that, external parameters such as SST inlet and outlet flows and concentrations, flocculant dosage and weather information needed to be included as well. For that purpose, each sampling was given an ID through which all the tests can be connected together in the database. Choosing a certain sampling ID brings all the parameters associated with that sampling in a well-arranged matter. Plotting the properties from all samplings at once enabled to identify wrong data and error measurements and to exclude them from the database in order not to influence the relations.

Creating the database required an extensive amount of man hours and thus was developed with a cooperation of a small team who went through the input data a cleared them from any corrupted measurements, wrong readings and other misplaced data.

### 2.3. CFD MODEL DEVELOPMENT

The framework on which the numerical model is built is the commercial CFD software Ansys Fluent. It is not the goal of this work to develop a new CFD code from scratch but to extend the ability of a widely used CFD code to simulate the specific behaviour of sludge in SSTs. That enables an easy deployment of the sludge settling model to any user with the Ansys Software package. The Ansys software package provides all the necessary tools for creating geometry, meshing, post-processing and already implements transient implicit solver, multi-phase models and common turbulence models.

The CFD sedimentation model is implemented through utilization of user defined functions (UDFs) to handle the flocculation, sedimentation and rheology of the sludge. This model can be easily adjusted through parameters to respect different sludge types and behaviour which extends its usage to be applied at any settling tank beyond the experimental one.

The developed numerical model consists of several sub-models, each handling different part of the sludge behaviour:

- flocculation sub-model handles the initial phase of the settling process, the flocculation and particle breakup,
- sedimentation sub-model is responsible for hindered zone and compress zone sedimentation,

- rheology sub-model is based on the non-Newtonian characteristics of the sludge.

#### 2.3.1. RHEOLOGY

The purpose of the rheology sub-model is to find a relation between suspended solids concentration and strain rate. In the CFD model, both the strain rate and concentration are known so a viscosity can be calculated and assigned accordingly to each cell.

A total of 41 samples were analysed using the viscometer which outputs the relation between strain rate and shear stress. Using the well-known equation, the apparent viscosity was calculated:

$$\mu_m = \frac{\tau}{\dot{\gamma}}. \quad (3)$$

The data showed a good correlation with the Casson sludge type, that is described by the following equation:

$$\tau^{\frac{1}{2}} = \tau_0^{\frac{1}{2}} + \eta_{\infty}^{\frac{1}{2}} \cdot \dot{\gamma}^{\frac{1}{2}}, \quad (4)$$

where  $\tau_0$  is the Casson yield stress that needs to be overcome at zero shear rate and  $\eta_{\infty}$  is the Casson plastic viscosity. These parameters differ for each sample based on the solids' concentration, so we can obtain the function from a regression analysis of the data. The selected data to extract the dependency are the curves with  $c = 4.9 \text{ g/l}$  and  $c = 13.5 \text{ g/l}$  to capture both the low and high concentration profiles.

From the regression of the data the  $\tau_0$  parameter shows a linear dependency on the solids concentration that can be described as:

$$\tau_0 = 6.35 \cdot 10^{-2} \cdot c - 1.58 \cdot 10^{-1}. \quad (5)$$

Also, the  $\eta_{\infty}$  can be described using a linear function:

$$\eta_{\infty} = 7.51 \cdot 10^{-5} \cdot c + 1.85 \cdot 10^{-4}. \quad (6)$$

Eventually, we can create a viscosity function based on the solids concentration:

$$\tau^{1/2} = (6.35 \cdot 10^{-2} \cdot c - 1.58 \cdot 10^{-1})^{1/2} + (7.51 \cdot 10^{-5} \cdot c + 1.85 \cdot 10^{-4})^{1/2} \cdot \dot{\gamma}^{1/2}. \quad (7)$$

In the Figure 2, the aforementioned function is plotted against experimental data. One is constructed for  $c = 4.9 \text{ g/l}$  with  $\tau_0 = 0.15$  and  $\eta_{\infty} = 5.5 \cdot 10^{-4}$  to show low solids concentration region fitting and one for  $c = 13.5 \text{ g/l}$  with  $\tau_0 = 0.7$  and  $\eta_{\infty} = 1.2 \cdot 10^{-3}$  to show high solids concentration fitting. Only some of the sampling data are shown for better clarity.

#### 2.3.2. SEDIMENTATION

Overall, 108 samples were measured using the settling columns. However, 20 of the samples did not create a sludge-water interface and were therefore omitted from the data which is usually the reason for suspended solids concentration over  $14 \text{ g/l}$ .

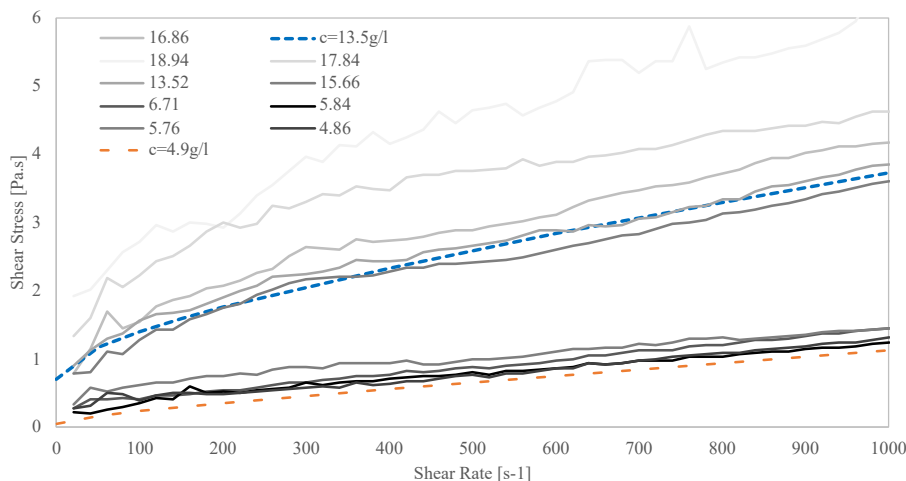


FIGURE 2. Fitted Casson sludge type rheology model.

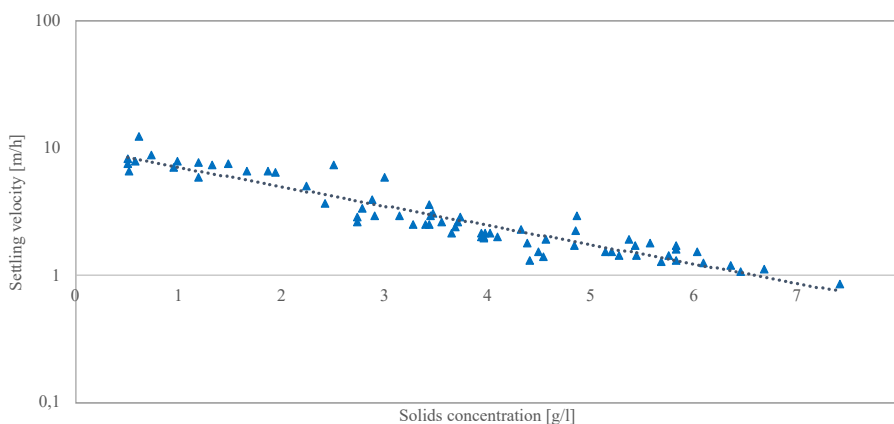


FIGURE 3. Dependency of settling velocity on solids concentration.

$V_0$ [m/h]	$r_h$ [m <sup>3</sup> /kg]	$X_{min}$ [m/h]	$r_p$ [m <sup>3</sup> /kg]
10.08	0.35	0.008	3.5

TABLE 2. Obtained coefficients for the Takacs'-Vesilind settling curve.

The sedimentation sub-model origins from the well-known Takacs-Vesilind model:

$$V_s = V_0 e^{(-r_H \cdot (X - X_{min}))} - V_0 e^{(-r_p \cdot (X - X_{min}))}, \quad (8)$$

where  $V_0$  is the maximum settling velocity,  $X_{min}$  is the minimum solids concentration at which settling occurs,  $r_H$  is a parameter describing the hindered zone and  $r_p$  is a parameter characterizing the low concentration settling. These parameters can be deduced from the batch column test data by linear regression same as the Vesilind parameters.

The settling velocity against suspended solids concentration was plotted on a natural log to linear scale. The gradient of the slope and the intercept of the curve are the  $V_0$  and  $r_H$  coefficient respectively as shown in Figure 3.

From the regression the  $V_0 = 10.08$  m/h and  $r_H = 0.35$  m<sup>3</sup>/kg. The  $X_{min}$  parameter was measured by

using decantation and resulted in  $8 \cdot 10^{-3}$  m<sup>3</sup>/kg. The last parameter  $r_p$  is generally considered to be a one order of magnitude larger than  $r_h$ , thus  $r_p = 3.5$  m<sup>3</sup>/kg. The summary of the coefficients is presented in Table 2.

It is apparent from the plot that the curve does not perfectly copy the shape of the source data. The settling velocity of the samples with low suspended solids concentration of  $x < 2$  g/l are undervalued where the velocity of the samples with higher concentration of  $x > 3$  g/l are slightly overvalued. The main reason for this is the fact, that the samples were taken over a long period of time (almost 2 years) and although they all come from a single WWTP, the properties of the sludge and especially the settleability may vary depending on the actual condition under which the samples were taken and thus creating a significant variance. This is very important to notice as this is actually the cumber stone of sludge settling models – they are fitted on very limited set of data representing usually only one flow condition.

It becomes apparent from the Figure 4, that a single averaged settling curve cannot enclose all the different sludge conditions and differentiate between well settling and badly settling sludge relatively to the suspended solids concentration.

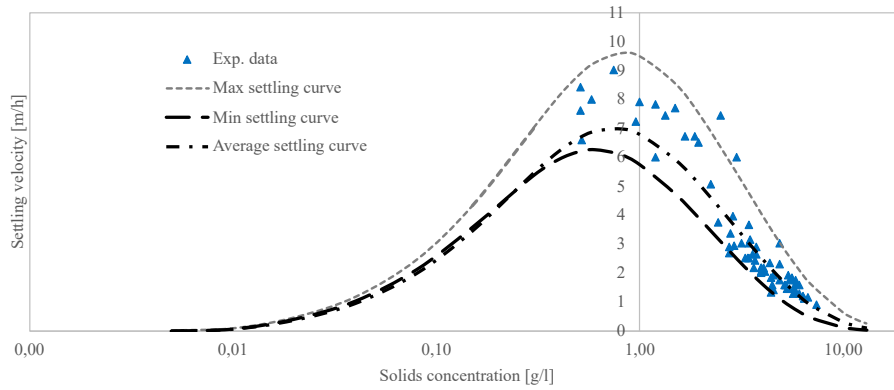


FIGURE 4. Envelope of the sludge settling curves.

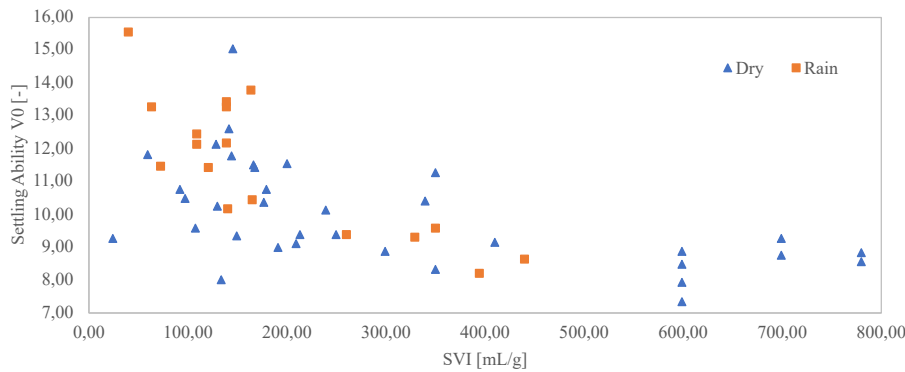


FIGURE 5. Relation between the sludge settling ability and SVI.

In order to be able to compensate the settling curves for different condition without the need to rerun the expensive batch settling measurement every time, an envelope is created to mark the maximum and minimum boundaries. That produces two new sets of settling curves as can be seen in Figure 4.

It is apparent from the range of min and max curves, that the settling velocity for the same sludge solids concentration may differ significantly. That corresponds to the fact, that there are other factors with a strong influence on the settleability of the sludge.

The settling curves are based on the ZSV which is considered to be a lumped parameter that inherently embeds sludge morphological, physical and chemical factors. Given the fact that a sludge property database was created during the campaigns, it is possible to try to find other relations between sludge settleability and other factors such as SVI, rain conditions, filament index, flocculant and coagulant dosage or retention time.

After investigation the relation between settleability and other factors, it turned out that from the gather data, there is no statistical dependency for rain, flocculant dosage, coagulant dosage and not enough data to asses the filament index. On the other hand, the SVI shows a logarithmic correlation of the data. Low SVI results in better settling performance and vice versa which corresponds to the general experience [15]. This correlation is valid for both dry and rain samples.

Now we can transform the Y-axis into a  $V_0$  Correction Coefficient and add another parameter called  $r_H$  Correction Coefficient. These coefficients will serve as modifiers to the original Vesilind-Takacs exponential function to adjust the settling curve and we can rewrite the equation as follows:

$$V_s = 10.08 \cdot V_{0c} e^{(-0.35 \cdot r_{Hc} \cdot (X - 0.008))} - 10.08 \cdot V_{0c} e^{(-3.5 \cdot r_{Hc} \cdot (X - 0.008))} \quad (9)$$

The dependency of the coefficients can be seen in Figure 6.

The ultimate benefit of this modified equation is that we can now construct a custom settling curve based only on a suspended solids concentration, flow rate and SVI for any sample. That means that the numerous samples laboratory batch settling tests required every time when we want to run a numerical model simulation can now be completely avoided. That significantly simplifies the preparation work to run a CFD simulation of the SST and more importantly, it expands the usage of CFD settling model outside the batch test specific WWTP.

The aforementioned models were converted into C language code and were implemented into the Ansys Fluent CFD solver using User Defined Functions. The simulation was run in 3D using  $\frac{1}{4}$  of the tank and periodicity.

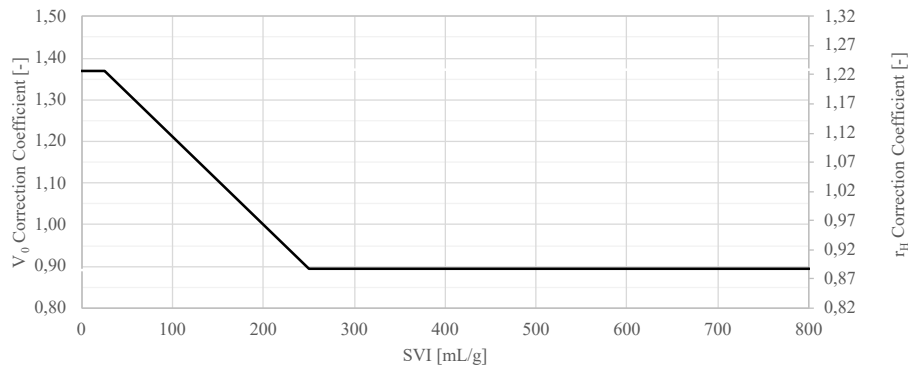
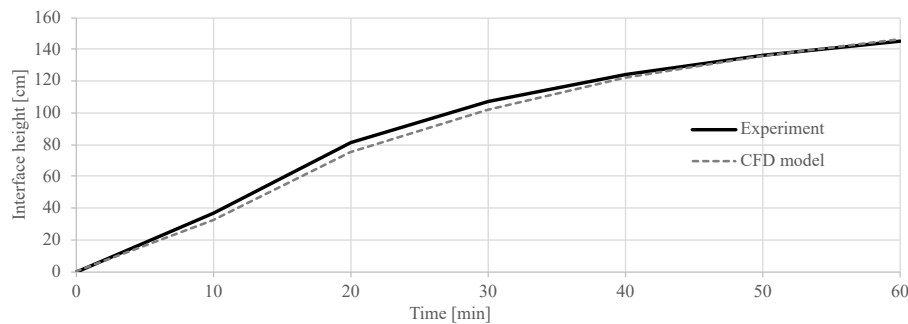
FIGURE 6.  $V_{0c}$  and  $r_{Hc}$  correction coefficient dependency on SVI.

FIGURE 7. Results of sludge water interface evolution.

### 3. RESULTS AND DISCUSSION

First validation was done using the recorded batch settling column test where the water-sludge interface is of an interest. The column has a height of 3 m and diameter of 0.3 m. Initial suspended solids concentration was 5.7 g/l. As it can be seen from the Figure 7, the evolution of the interface is similar between CFD and experiment.

The 3D tank validation was done at settling tank DN3 located at the Prague WWTP within the old treatment plant. The radius of the tank is 21 m and depths are 5 m at the sludge removal pit and 2.1 m at the outer rim. The influent is a pipe located traditionally in the centre area. The inlet zone is bounded by 8 pillars supporting metal plates. The outlet area is located 17 m from the centre and consists of two circular weirs.

The geometry of the tank has a cylindrical periodicity and therefore only  $\frac{1}{4}$  of the geometry was modelled. The inlet is considered to be a mass flow inlet and atmospheric pressure is setup at the outlet. Sludge removal is modelled as mass flow outlet. The side walls of the model are modelled as periodic to capture the symmetry. Top boundary that represents water-air interface is modelled as symmetry boundary condition – it ensures a non-zero velocity at the boundary.

For the tank DN3, a dry conditions scenario was simulated and compared to the experimental measurements. The flow rate  $0.635 \text{ m}^3/\text{s}$  represents the standard flow at the tank during normal conditions and was measured on 16th June 2016. The SVI at

the tank inlet was 55 mL/g, which corresponds to the  $V_{0c} = 1.31$  and  $r_{Hc} = 1.18$ .

The comparison of the suspended solids concentration between CFD and experiment can be seen on Figure 8. It is clear that the CFD model shows a good match with the experiment. Right after the inlet zone, there is a rising sludge eddy which is well-captured by the model. Also, the sludge blanket height matches the experiment.

Another validation was done on a tank DN1 which has a different inlet zone. The rain flow from 16th April 2018 was chosen and is represented by the  $0.87 \text{ m}^3/\text{s}$  flow rate and the concentration of suspended solids  $c = 3.3 \text{ g/l}$ . The SVI was measured 270 mL/g which corresponds to the correction coefficients of  $V_{0c} = 0.9$  and  $r_{Hc} = 0.89$ .

From the results of the rain event, the experiment shows an area of an increased blanket height after the inlet zone. The same phenomena can be seen from the CFD results, even though the peak is more apparent. Also, the overall sludge blanket height matches well between CFD and experimental data. The concentration of suspended solids is slightly over predicted by the model which might be caused by the fact, that during the rain events, the sludge properties vary quickly and the measured SVI at the moment might not have corresponded to the sludge SVI already in the tank because the retention time. That leads to the question of when to measure the SVI during the rain events to realistically capture the tank average and more effort should be put into this matter.

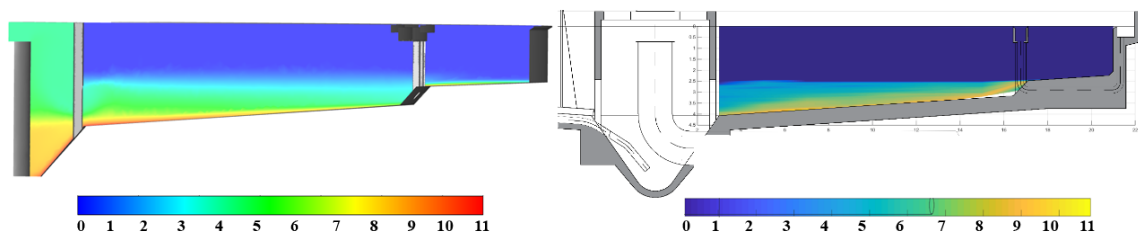


FIGURE 8. Comparison of the sludge blanket in DN3 between CFD model (left) and experiment (right).

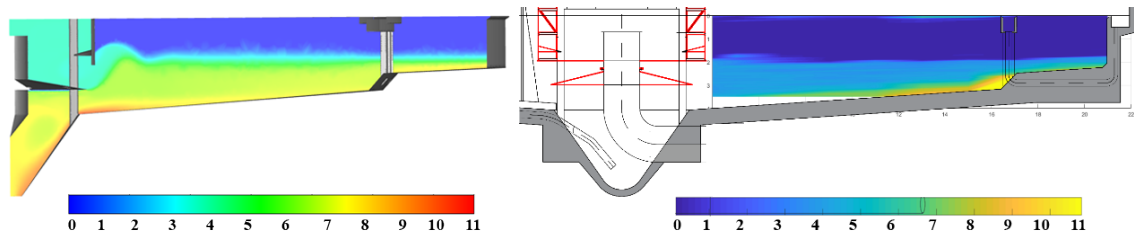


FIGURE 9. Comparison of the sludge blanket in DN1 between CFD model (left) and experiment (right).

The aim of this paper was an attempt to create a CFD model for secondary settling tanks which would be calibrated on a data obtained through a measuring campaign but also to try to generalize the model enough so it would be possible to use it on different tanks with different type of sludge. Based on a database data processing a new coefficient was used to extend the Takacs settling curve in order to compensate for better or worse settling sludges based on their SVI. That way it is possible to adjust the settling model based on an inlet flow rate, suspended solids concentration and SVI.

Further work should be aimed to test the model against different settling tanks and compare its performance. Also, additional work should be done to better the compression settling model which might lead to more accurate suspended solids distribution at the tank bottom.

#### ACKNOWLEDGEMENTS

The published results were achieved under the grant TAČR TE02000077 Smart Regions – Buildings and Settlements Information Modelling, Technology and Infrastructure for sustainable Development.

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