# Memo

| **Date** | **Our reference** | **Number of pages** |
|---|---|---|
| March 4, 2019 | 11201789-000-HYE-0002 | 14 |
| **Contact person** | **Direct number** | **E-mail** |
| Tom O'Mahoney | +31(0)88 335 7206 | Tom.OMahoney@deltares.nl |

**Subject**
Summary of reserach results of Euler-Euler CFD models of a bubblescreen

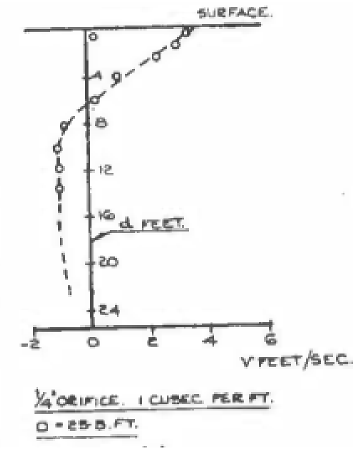
---

## Introduction

Deltares has been involved for many decades in research into bubble screens for the purpose of mitigation of salt intrusion at shipping locks. The early research in the 60s and 70s by Delft Hydraulics and the Waterloopkundig Laboratorium was pioneering in this technology and research into its application in the field. In the last decade research was been restarted and from the beginning [1] Computational Fluid Dynamics models have been used to try to understand the flow fields generated. This memo gives a short summary of the current state of validation of CFD models at Deltares used for this purpose.

## Available validation data

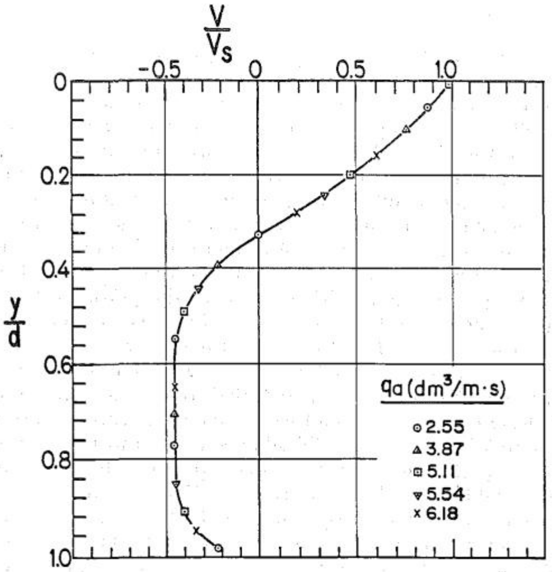
Early research was performed via field experiments although flow fields were never measured. The earliest measured flow field was from Bulson [2], in the absence of density differences and also in the field with a depth of 10 m. There are several cases in Bulson for which a single vertical profile is measured at a distance of one depth away from the axis of the bubble screen. At this point, it is asserted, the flow speed at the surface has reached a steady maximum value. An empirical relation of the maximum surface flow velocity at this location as a function of air flow rate in the bubble screen was developed.



$$V_{\max,1} = 1.46\left(g q_a\right)^{1/3}\left(1 + H / H_0\right)^{-1/3}$$

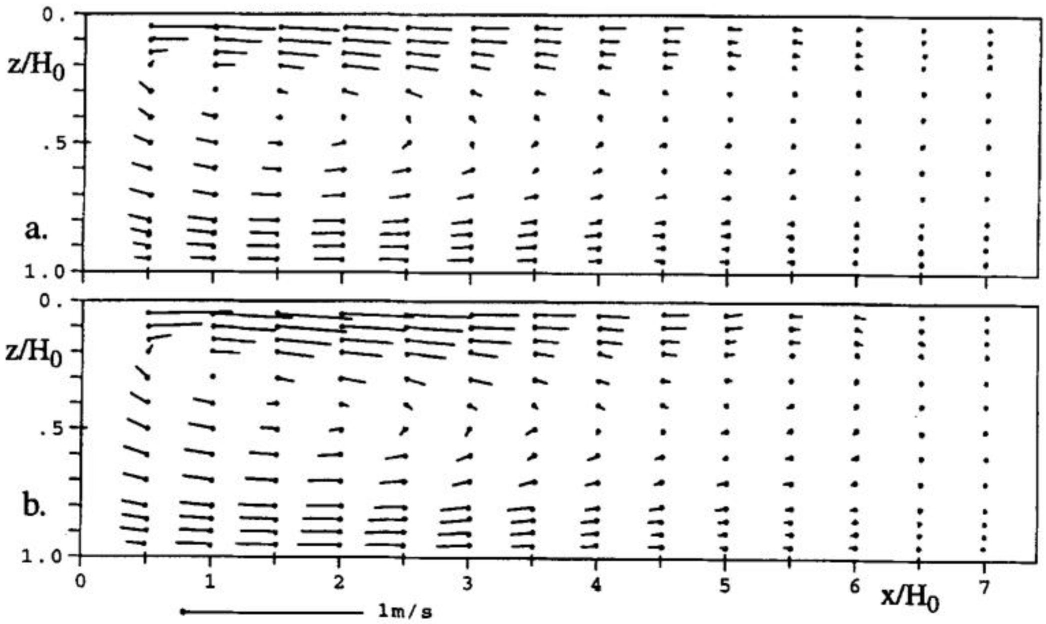
Example profile results from Bulson [2] and empirical relation

The next known measurements of flow fields for bubble screens are from lab experiments [3]. The flume used for the experiment was 46 cm wide, 3.7 m in length and for water depths between 30 cm and 90 cm. Profiles at several locations way from the axis of the screen were measured, from one half of the depth away up to 3.6 times the depth. These experiments are still the most extensive known set of measurements in the lab, covering multiple flume dimensions, depths, air flow rate, measurements at different locations and also a study of different manifold types.



Example flow results from Wen and Torrest [3]

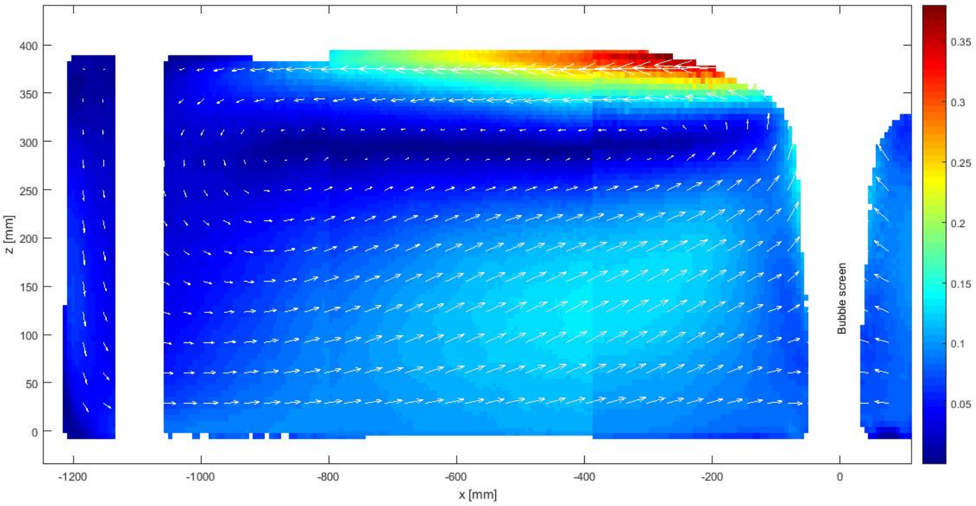
Experiments have also been performed by Ries and Fannelop [4] but the manner in which the data is presented in the paper makes it impossible to extract quantitative data for the purpose of CFD validation without contacting the authors directly. This paper has thus far not been used for CFD validation.



Example of flow field as presented by Riess and Fannelop [4]

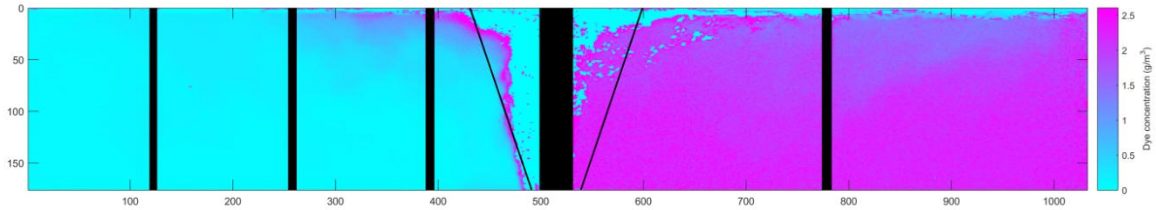
When Deltares started research into bubble screens in the ‘modern’ era some lab experiments were also made although these were meant to support the main field experiments which formed the bulk of the research. These lab experiments included measurements of density flows without bubble screens, but also some of bubble screens in the absence of density differences [1]. They were performed by Dick Mastbergen. Flow field measurements were not extensive. Attempts were made to measure velocities at three point locations, one of which was at the surface but the variation on the reported measured values is very high. Measurements of density were also made but not during a test with the bubble screen, only at the end of the test (90 s) to calculate the average salt concentration. This enables an assessment of the effectiveness of the bubble screen for mitigation of salt intrusion. The results are reported as a reduction factor, which gives a single number as a measure of the amount of salt which has entered the lock over a given time. It is therefore a bulk parameter. As far as it is known these were the first laboratory tests of the bubble screen with a density difference. The results are also summarised in a journal paper [5].

The most recent experiments in the lab have also been performed by Deltares [6] by Pepijn van der Ven and Gosse Oldenziel (with input from a variety of students). These involved two sets of experiments: one set whereby Particle Image Velocimetry (PIV) was used to measure detailed flow fields for a bubble screen without density differences; and, a second set where dye was used to measure mixing from one side to the other of a screen with and without density differences. The second set of experiments has yet to be published and is currently only available in a student internship report. The experiment was made in a flume 50 cm wide and 2.4 m long with a water depth of 40 cm, so comparable with the tests of Wen and Torrest [3]. A smaller range of conditions were measured than for the previous experiments with only 3 air flow rates used. Two different spargers were tested.

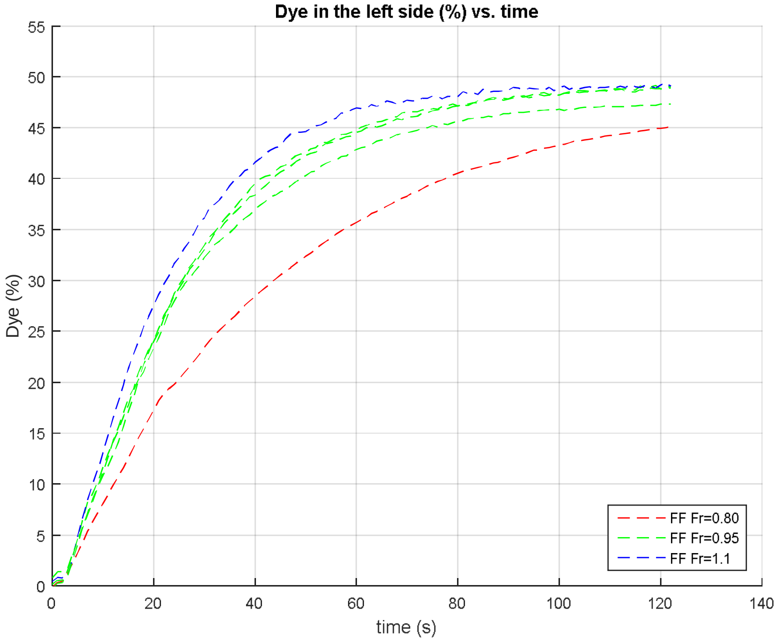


Example flow field from the PIV measurements [6]

The dye experiments give detailed concentration measurements throughout the entire tank which allow for a high resolution analysis of the mixing process (although not in the bubble screen itself). This also allows for a temporal processing of the data so that the effectiveness of the screen as a function of time can be presented (see Figure below). One unfortunate failing of this set of experiments is that the range of flow rates was chosen in an attempt to encompass the point of maximum efficient of the bubble screen (Froude air numbers ranging from 0.8 -1.1 where the empirical minimum is often found at a Froude number of 1, that is to say that for rising air flow rates above Fr_a = 1 the effectiveness falls and for falling air flow rates below Fr_a = 1 the effectiveness also falls). However the results of the experiments show falling effectiveness for rising air flow rates from Froude air numbers of 0.8 – 1.1, so it is not obvious that the point of maximum efficiency is captured in this test series (although it still could be). This is an unfortunate shortfall in the performed experiments.



Example output from the experiments with the dye

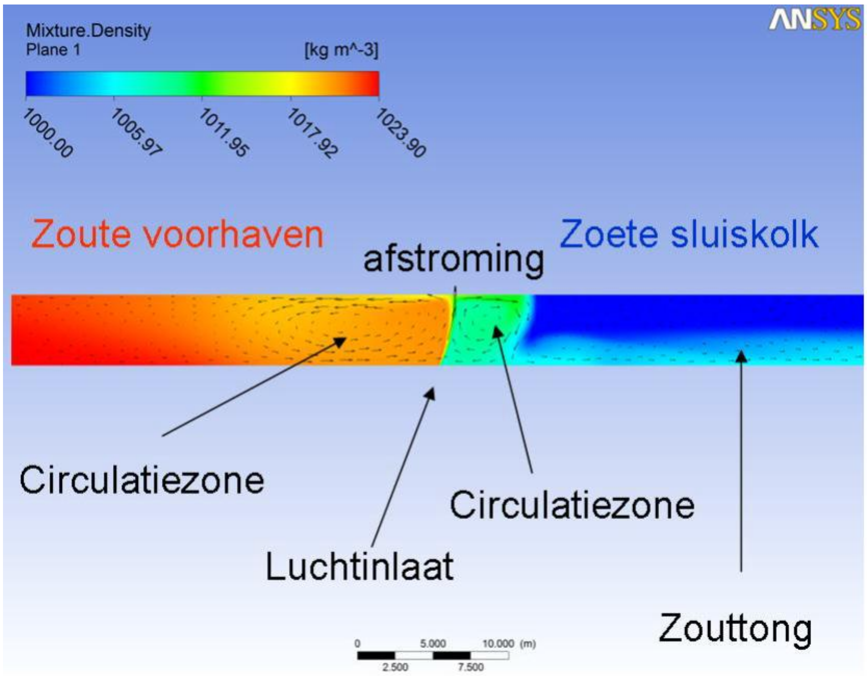


Results of effectiveness of the bubble screen in time

## CFD validation work at Deltares

Work of Geert Keetels

The first CFD work on bubble screens at Deltares was performed by Geert Keetels [1] in a 2D CFX model as part of the larger project to develop salt intrusion measures for the Volkerak locks. The model used a Euler-Euler multiphase model for the water bubble interaction. This solves two separate sets of momentum equations for each phase. They are coupled by extra force source terms which are function of the volume fractions and relative velocities of each phase in each cell (as well as other constants like the bubble size). There is therefore a volume fraction of water and a volume fraction of air in each cell.



Example density concentration contour plot of a bubble screen showing qualitative reasonable results

The validation of the model was limited. Comparisons were made with the empirical relation of surface velocity of Bulson and with the experiments made in the project itself, which created limited data for validation of CFD. This comparison is shown in the following table from the report. This comparison is for a bubble screen without density differences. Clearly the experiments showed a large variation in the quantity of interest but an average value is not reported. This table also shows that an analysis of different turbulence models was made (in the report a much larger list of tested models is reported and in the project folder itself it can be noted that an even broader sensitivity study was attempted). A mesh sensitivity study is also included with the smallest cell sizes of 1.4mm used.

| | Proef 1 | Bulson (1961) | RNG | Standaard |
|---|---|---|---|---|
| x=H, z=H | 0.30-0.50 | 0.45 | 0.45 | 0.35 |
| x=0.25, z=0.26 | 0.20-0.40 | nvt | 0.30 | 0.25 |
| X=0.28, z=0.01 | 0.15-0.25 | nvt | 0.18 | 0.18 |

Comparison of CFX model with Bulson and lab experiments of Mastbergen

The comparison with the empirical relation of Bulson was also made for the simulations on a prototype scale (see table below). These simulations also included a much longer geometry so that the recirculation zones on either side of the bubble screen could develop without interference of the end walls (which is often unavoidable for lab scale experiments). It is not reported what cell size was used for the prototype simulations.

| Luchtdebiet | Vmax,1 | CFX | Variatie | Afmeting circulatiezone |
|---|---|---|---|---|
| 1400 Nl/s | 1.3 m/s | 1.6 m/s | 0.6 m/s | 7 H |
| 700 Nl/s | 1.0 m/s | 1.2 m/s | 0.4 m/s | 5 H |
| 400 Nl/s | 0.9 m/s | 0.9 m/s | 0.2 m/s | 5 H |

Comparison of CFX model with Bulson at prototype scale

The final comparison of the model was made with the lab experiments where both bubble screen and density differences were included. These experiments limited the measured quantity to the bulk parameter of reduction factor measured only at the end of the experiment. The comparison is below (rhoog indicates that the finest grid is used). Clearly there is quite some sensitivity to the used turbulence model.

| | Zout massa | Reductiefactor |
|---|---|---|
| Laboratorium alleen bellenscherm | 0.040 kg/s | 0.19 |
| RNG-k-ε_rhoog | 0.042 kg/s | 0.20 |
| k-ε_rhoog | 0.033 kg/s | 0.16 |

Comparison of CFX model with lab experiments of the reduction factor

## Work of Mike van Meerkerk

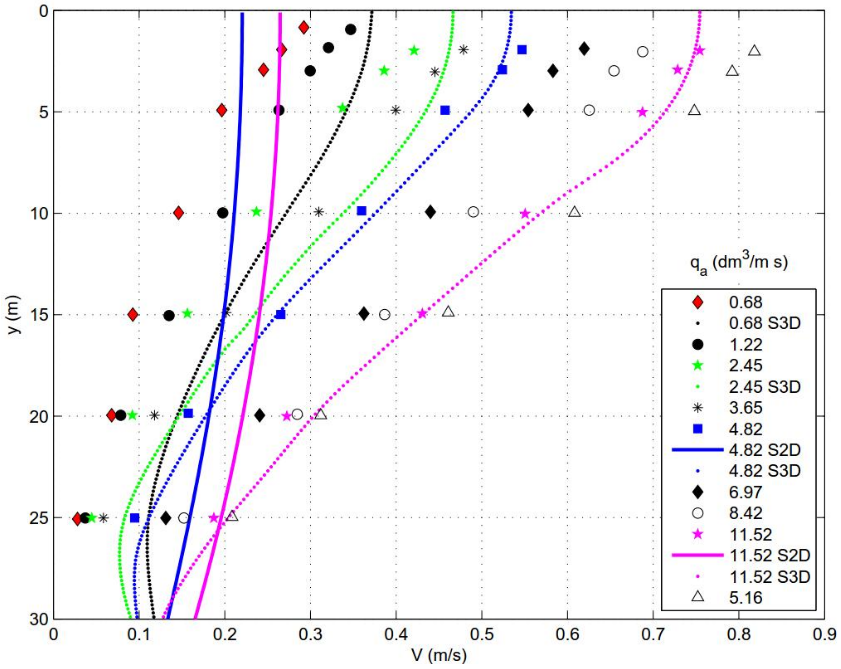
A more robust and detailed validation of an Euler-Euler CFD model was attempted by Mike van Meerkerk [7] during his internship at Deltares (supervised by Tom O'Mahoney). This work was conducted after Deltares made the switch of CFD packages from CFX to Star-CCM+ so that model was first transferred into the new software. In principle, the two codes should provide the same or similar performance as the physical models used and not the details of the numerical solving of the equations are the most important factors. However, a different performance of the two codes cannot be completely ruled out and direct comparison has never been made.

Mike conducted his validation on the data from Wen and Torrest [3] as this is the most extensive data set available in the literature on labscale. This research also included simulations of the original Bulson experiments.

The sensitivity study in this work concentrated on the multiphase model and not the turbulence model. The turbulence model was chosen to correspond with the best performing model from the work of Keetels, although some choices concerning the coupling of turbulence in the air phase may not be the same. The used models are well reported in the work of Mike but less so in the work of Keetels (although this information is recoverable from the model files). Mike also did tests on a 2D model (axisymmetric in flume breadth) and 3D models.

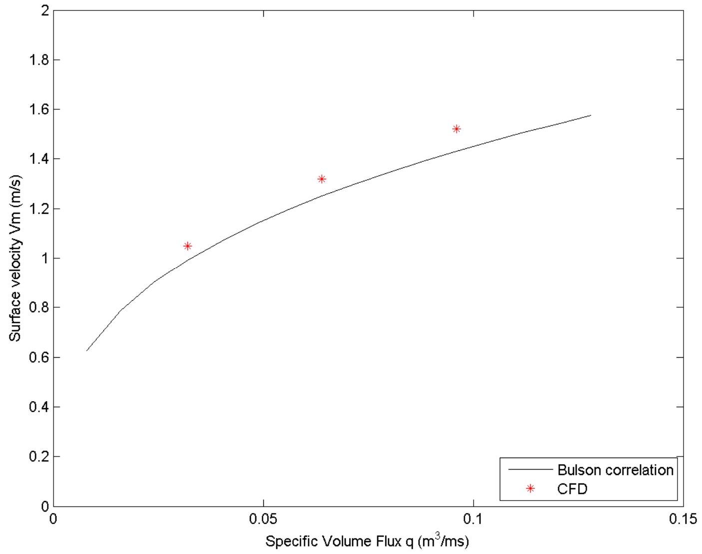
For the labscale Mike achieved very good agreement with the measured profiles high in the water column for the 3D simulations. Comparisons were not made lower down in the water column (these were not reported in the paper of Wen and Torrest for all flow rates). The comparison of the 2D results with the experiments is very bad which is not consistent with the good results achieved by Keetels in a 2D model. Even in 3D the agreement for low flow rates was less good. Because this was a student internship and the simulations are computationally expensive the question still remains if the simulations were fully converged. The simulations have only been run for 30 s of physical time and although 10 s is often enough for the bubbles to reach the surface plots from the simulations show that some parameters are still changing at the moment of post-processing. The 2D simulations are clearly converged, these are much less computationally expensive.

Mike used a mesh of 2 mm size near the inlet (comparable with that of Keetels) but with a very large aspect ratio in the breadth for the 3D simulations. Still the agreement with the 3D simulations is considered very good.



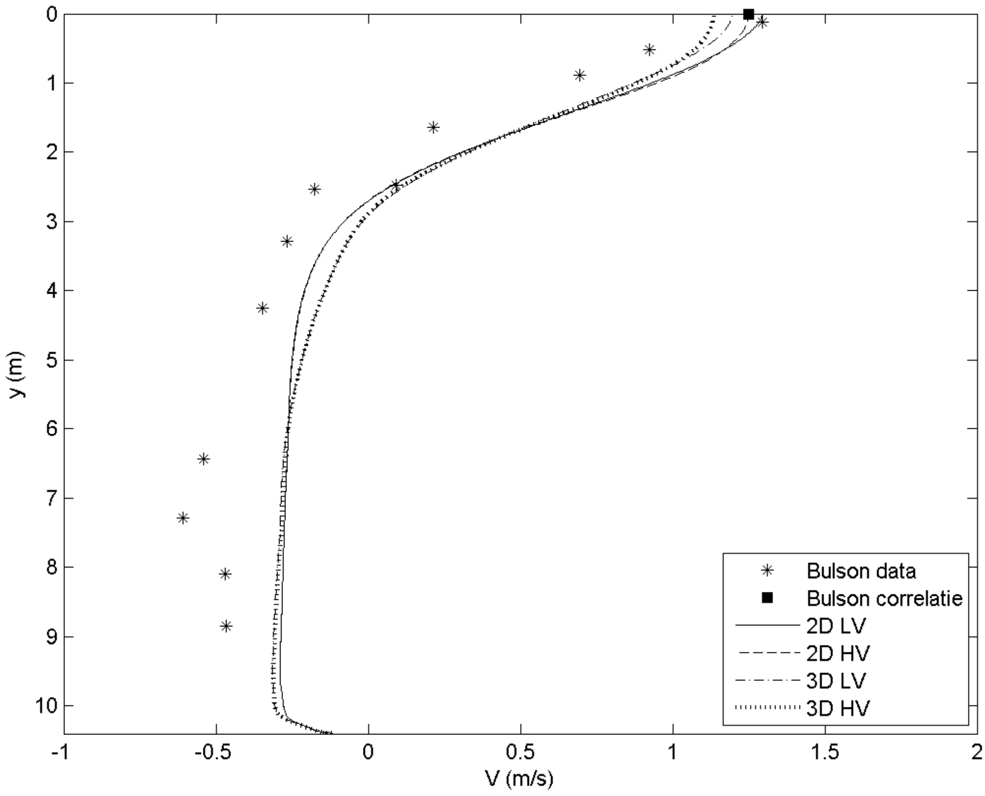
Example comparison of CFD model with data from Wen and Torrest

Simulations were also made of the prototype scale for the Bulson case but they were limited mostly to 2D simulations. A couple of 3D simulations were made. The reasoning was that the wall effects in this case would be much less and that therefore 2D simulations may give sufficiently good results. A comparison was made between the CFD and the empirical relation of Bulson for surface velocities.



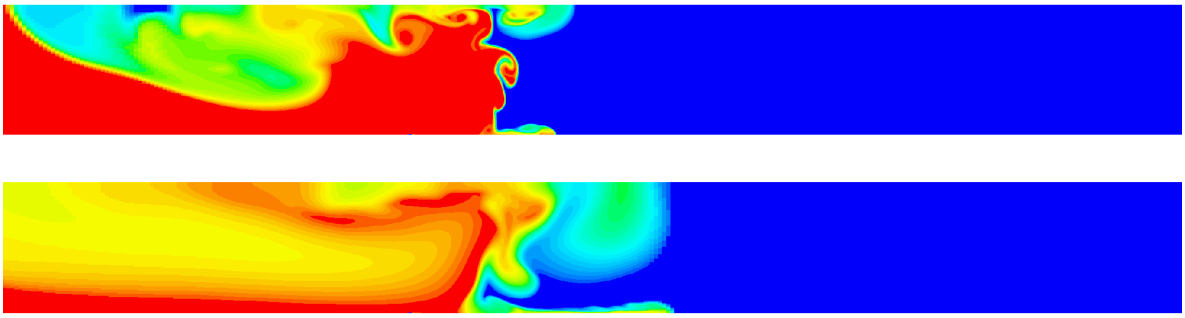
Comparison of 2D CFD simulations of the empirical relation of the Bulson experiments (at the scale of the original experiments)

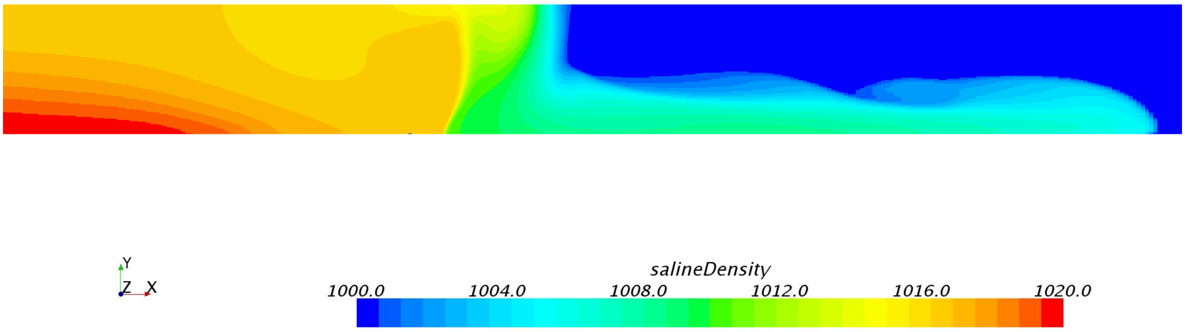
Mike also compared the flow profile from the CFD with that from the original Bulson paper. In the figure below both 2D and 3D simulations are shown. The mesh size was 1.25 cm near the inlet and the depth 10 m. The suffices LV and HV indicate whether the turbulent viscosity in the simulations was limited to a low value (LV) or a high value (HV). This has a small effect on the results and especially near the surface. This work shows indeed that at prototype scale (and more specifically for cases where the water depth is much less than the breadth) a 2D Euler-Euler model may perform as well as the 3D model. Similarly, it shows that a good agreement at the surface does not necessarily imply a good agreement elsewhere in the water column. This will likely be important if the model is used for the prediction of mixing of salt and fresh water over the entire depth.



## Extension of the work of Mike van Meerkerk by Tom O'Mahoney

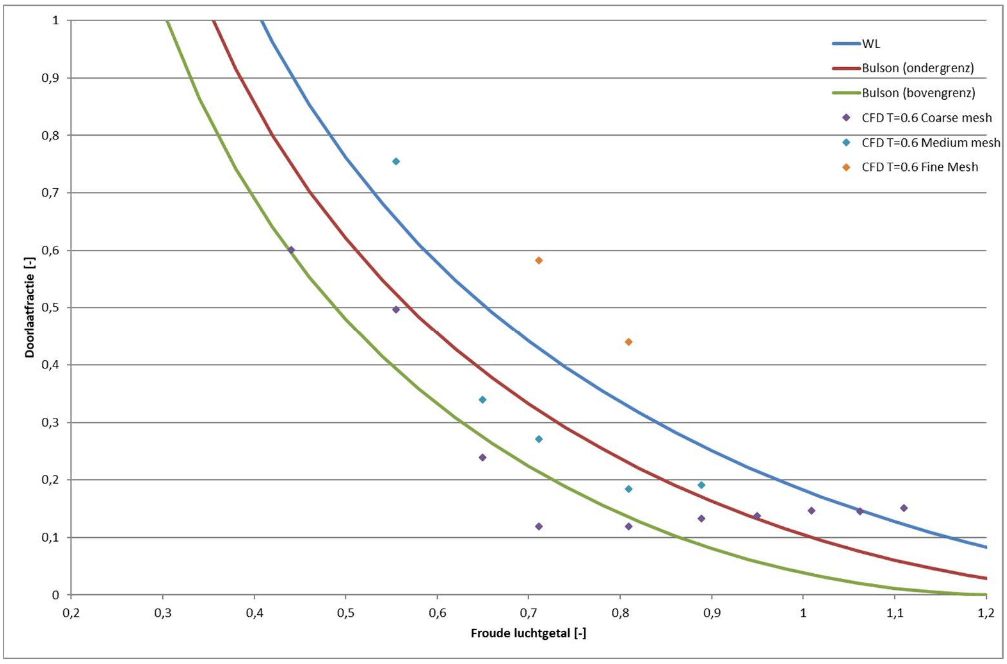
Subsequent to the modelling work of Mike van Meerkerk, which produced results that gave confidence that the model was sufficiently validated for the bubble screen without density differences the model was used in a case with density differences. These simulations were performed by Tom O'Mahoney and were not a part of any project. However, the dimensions used were chosen to correspond to the dimensions of the Krammer commercial locks (a depth of approximately 6.5 m). Again the size of the mesh at the bubble screen inlet was 1.25 cm. The figure below shows the development of the current at the start of the process and shows that the qualitative picture in the quasi steady situation is similar to that of the CFX model of Keetels.





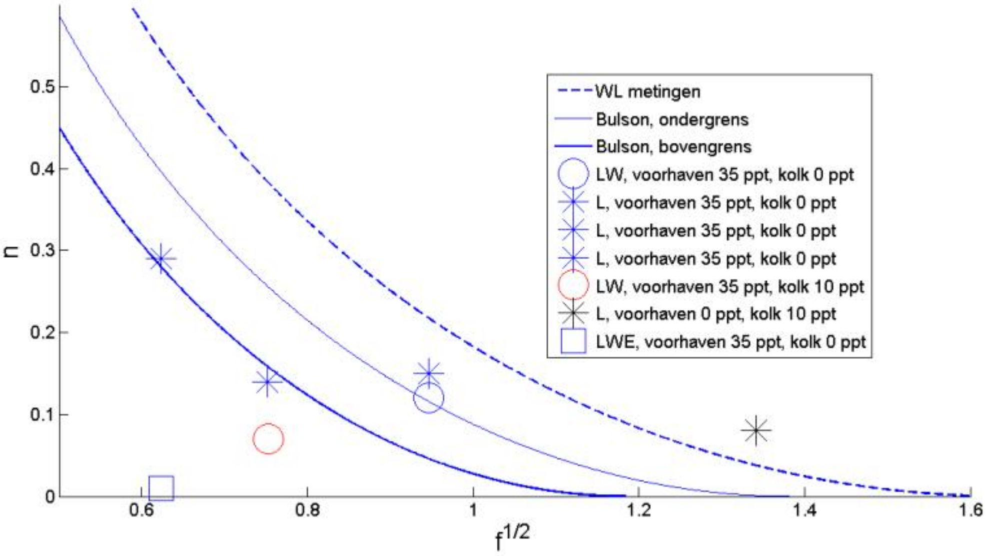
Example output from the 2D simulations of the Krammer lock

For a comparison with the measurements the reduction factor was calculated. This is a bulk parameter of the proportion of exchange which has occurred at a given moment relative to a situation where no mitigation measure is present. In the following figure the reduction factor has been calculated at T=0.6 which means 60% of the time for a full exchange in an unprotected scenario (salt wedge to the end of the lock, reflect, and back to the active gate). Bulson and the Waterloopkundig Laboratorium gave relations for this moment as well as at T=1.



Comparison of CFD and experimental relations for reduction factor – grid sensitivity

The figure shows the CFD results for different mesh sizes. The finest mesh is the 1.25 cm mesh at the inlet and the medium and coarse are respectively 2 times and 4 times coarser. A wide range of air flow rates was simulated. As can be seen, there is a lot of grid sensitivity and it is clear that at the finest mesh no grid independent solution has been found. It is also clear that the solution is not reaching an asymptote of a grid independent solution. The results for a medium mesh seem promising however so it can easily be imagined that if only simulations on the medium mesh were run that a conclusion would be drawn that the model performs well. Given the results for the fine mesh it can be seen that the agreement is coincidental.

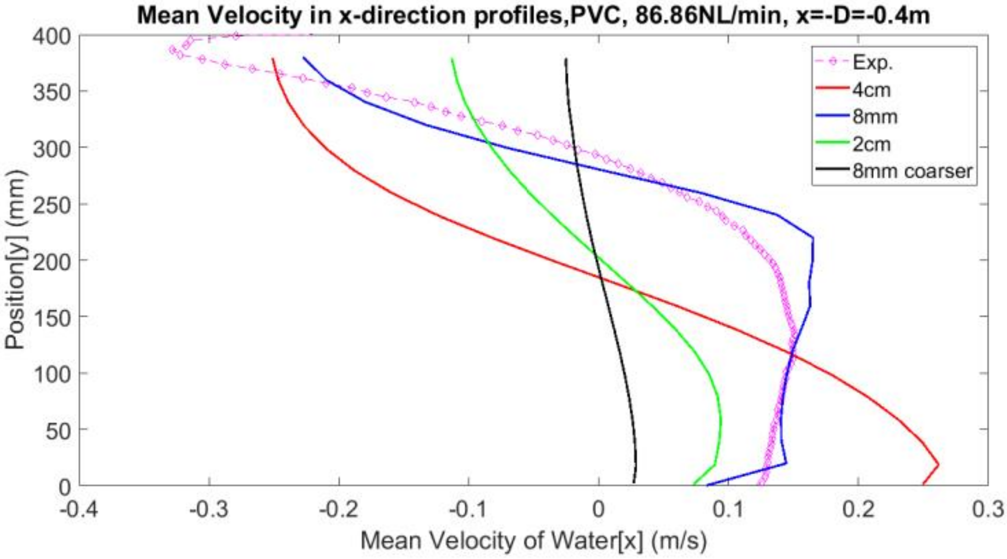


Comparison of CFD and experimental relations for reduction factor – from Keetels

A similar plot was made by Keetels for simulations on the scale of the Stevin locks (approx.. 4 m deep). Again the relations of Bulson and the Waterloopkundig Laboratorium are plotted against CFD results. In this comparison the reduction factor at T=1 is taken. Simulations are also made for a combination of a bubble screen with a water screen (LW) and with a leeking ebb gate (LWE). Simulations with only a bubble screen are marked with L. No sensitivity of these results to changes in grid or turbulence models were attempted.

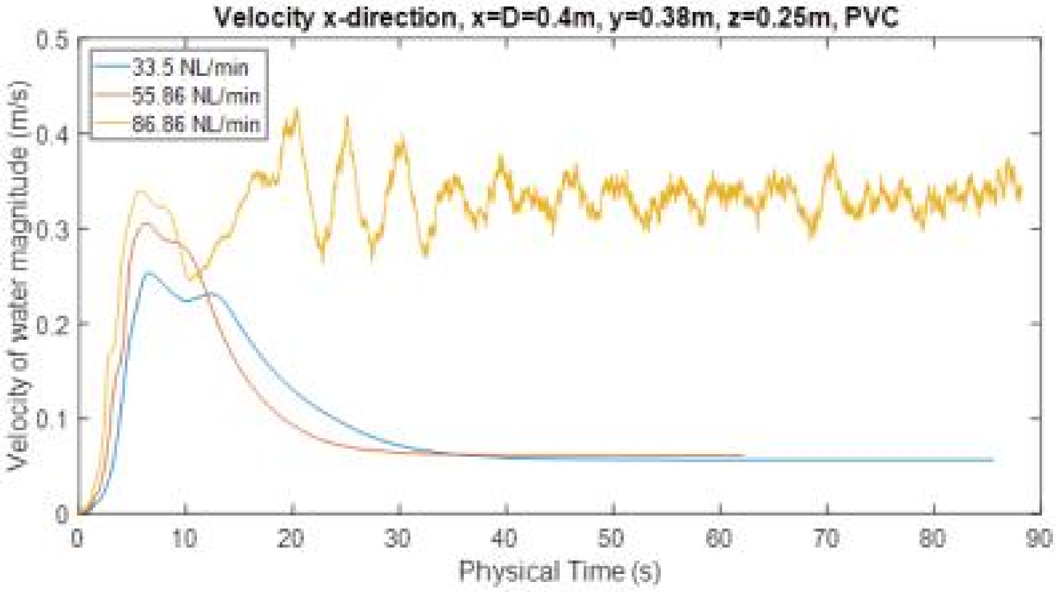
## Work of Lina Nikolaidou

In a student internship of Lina Nikolaidou the first comparisons of CFD with the recent Deltares experiments of Pepijn van der Ven were made. Due to the short length of her internship Lina was only able to make a comparison with a situation without density difference. It was expected that she would be able to confirm the conclusion of Mike van Meerkerk that an Euler-Euler model could achieve good agreement of velocity profiles. However, owing to slightly different test conditions between the Wen and Torrest case (which Mike used) and the tests of Deltares, Lina had difficulty in defining an inlet condition which was consistent with the model of Mike. She found a large dependence of the results on the size of the inlet (more relevantly on the speed of the bubbles at the inlet). Her main result can be seen in the figure below. Lina used the same model settings as Mike van Meerkerk and a comparable mesh size (1 mm instead of 2 mm and large aspect ratio of the cells relative to the breath).



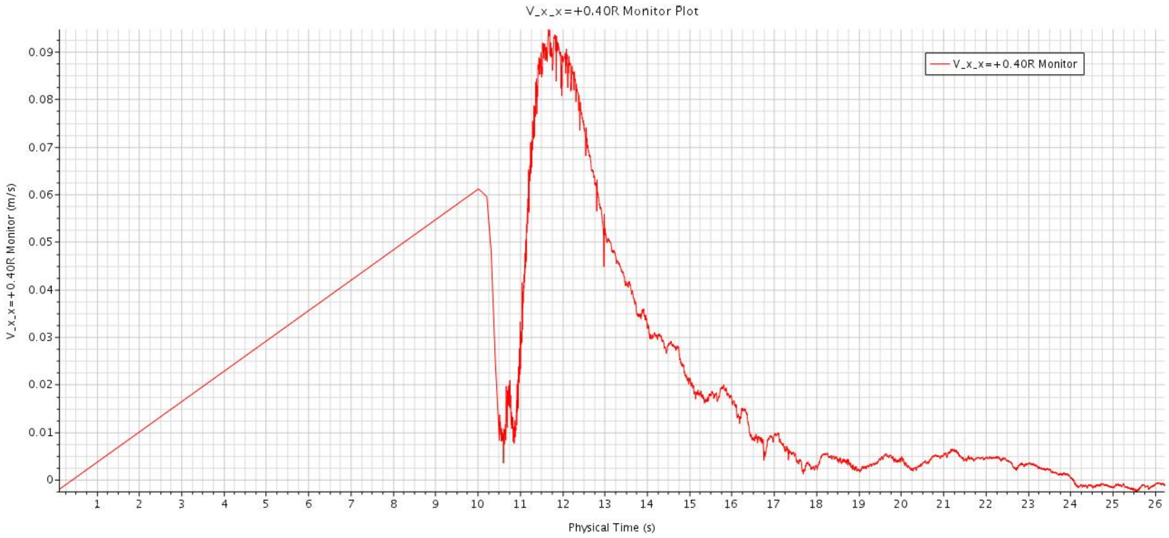
Example comparison of CFD model with data from Deltares – Pepijn van der Ven – from the work of Lina Nikolaidou

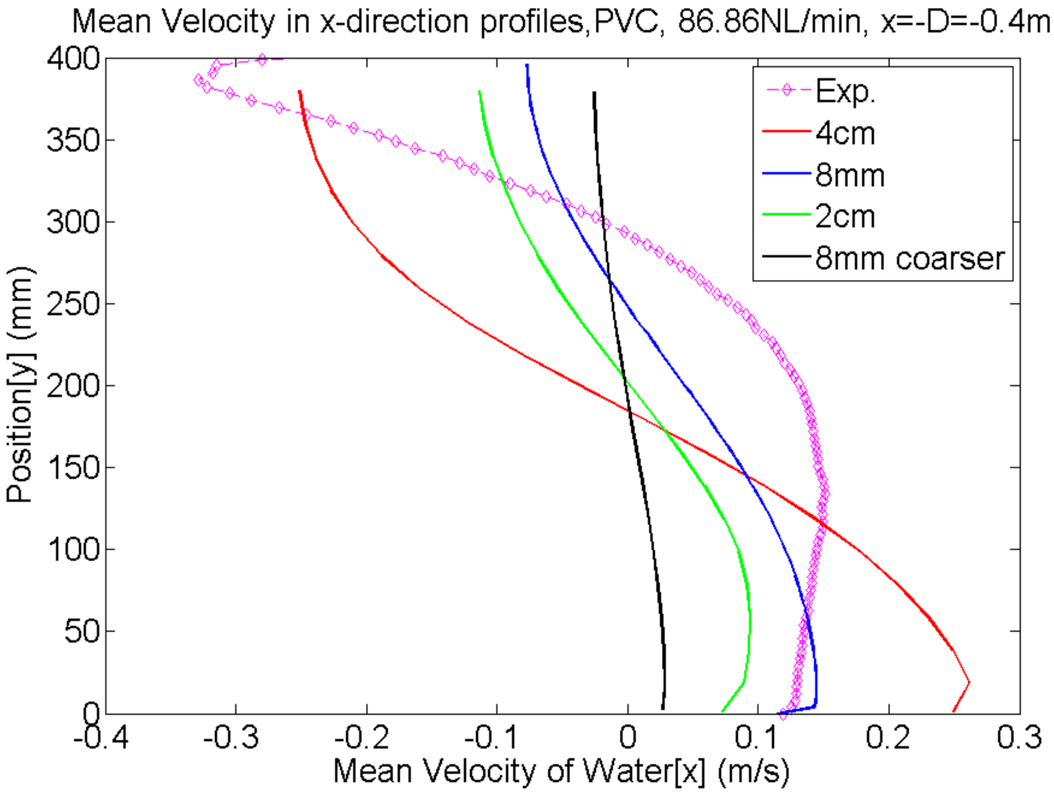
Lina concluded that a narrow inlet was needed whereby the inlet velocity of the bubbles was close to or above the terminal velocities of the bubbles (for a given bubble size). However, owing to the short duration of her internship it was not clear that her final simulation was converged. In her report she claimed that 30 s of simulation time was needed to reach a steady state (see figure below).



Time history plot of water velocity for coarse simulations performed by Lina Nikolaidou

However, the final results presented in her report for the final solution on a very fine mesh had only run 11 s by the end of her internship. This simulation was subsequently simulated (by Tom O'Mahoney) for a longer time. The time history plot from Star-CCM+ for a point velocity monitor is shown in the next figure and clearly indicated that the result extracted at 11 s is not representative of the steady state solution. Subsequently the steady state profile is given in the final figure and the agreement shown by Lina is not present. It can therefore only be concluded that Lina was unable to reproduce the conclusion of Mike van Meerkerk that an Euler-Euler model can achieve good velocity profile of a lab experiment of a bubble screen without density differences.





## Conclusions

The main conclusions that can thus far be drawn from the validation work of CFD for bubbles screens at Deltares are as follows:

- Bulson, Wen and Torrest and the new experiments of Deltares by Pepijn van der Ven are the best source of validation material for CFD of bubble screens. Only the Deltares experiments include measurements with density differences.
- The experiments of Dick Mastbergen and the simulations of Geert Keetels do not give enough confidence that their CFD model has been validated as only a cursory comparison with experiments was made.
- An agreement with the Bulson empirical relation of the surface velocities does not imply that the rest of the profile is well captured (specifically the total amount of entrained water in the bubble screen).
- The experiments of Wen and Torrest are still a good source of data for a wide range of flow rates.
- The validation work of Mike van Meerkerk is still the best result achieved thus far but a detailed mesh sensitivity study is not included in his report.
- The validation wort of Lina Nikolaidou was not able to reproduce the conclusions of Mike van Meerkerk for the new Deltares' experiments but the analysis was not complete. However, the sensible application of the model of Mike van Meerkerk to this case did not result in good agreement which does not give confidence in the general applicability of the model.
- Attempts to extend the use of the model to situations with density differences in order to predict a reduction factor are thus far inconclusive and show large variations in results as a function of mesh size. Again this does not give confidence in the general applicability of this model.
- Finally, Deltares' research to validate an Euler-Euler model of a bubble screen have not lead to a consistent conclusion about its general applicability despite seemingly promising qualitative results.

## References

[1] R. E. Uittenbogaard and G. H. Keetels, "Ontwerpstudie en Praktijkproef Zoutlekbeperking Volkeraksluizen," Deltares2010.
[2] P. S. Bulson, "Currents produced by an air curtain in deep water," vol. 42, p. 8, 1961.
[3] J. Wen and R. S. Torrest, "Aeration-induced circulation from line sources. I: Channel flows," *Journal of Environmental Engineering,* vol. 113, p. 17, 1987.
[4] I. R. Riess and T. K. Fannelop, "Recirculating flow generated by line-source bubble plumes," *Journal Hydraulic Engineering,* vol. 124, no. 9, pp. 932-940, 1998.
[5] G. H. Keetels, R. E. Uittenbogaard, J. M. Cornelisse, N. Villars, and v. Pagee, H., "Field study and supporting analysis of air curtains and other measures to reduce salinity transport through shipping locks," *Irrigation and Drainage,* vol. 60, pp. 42-50, 2011.
[6] P. P. D. v. d. Ven and V. A. Wieleman, "The use of small scale experiments for a hipping lock's bubble screen," in *4th International Symposium of Shallow Flows*, Eindhoven University of Technology, The Netherlands, 2017.
[7] v. Meerkerk, M., T. O'Mahoney, and A. Twerda, "Development of a CFD Model of an air curtain for saltwater intrusion prevention," in *36th IAHR World Congress*, The Hague, The Netherlands, 2015.