The results of a detailed measurement campaign on the effect of modifications to the pump compartment on spatial velocity profiles in vertically submersible pumps

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Abstract. A detailed measurement campaign is performed in which the effect is determined of modifications to the pump compartment on the velocity profile in the suction pipe of a vertically submersible pump. These measurements are performed in a scale model of a simple pumping station of which the dimensions are equal to the ANSI/HI 9.8-2012 guidelines (HIS standard). A set of generally accepted modifications like splitters, fillings, curtain walls and baffles has been tested. The investigation showed that the acceptability of a velocity profile is not significantly influenced by these modifications (if well-designed). Some modifications have a local effect on the velocity profile. However, the locations with the largest spatial deviation, which determine the acceptability of the velocity profile, are not affected. Therefore, the statement in the HIS standard that small modifications to the pump compartment improve the velocity profile seems to be not generically valid.

1. Introduction
In order to have a safe, reliable and sustainable water intake system for a plant, the flow patterns in such an intake system should be verified. This is normally done using a hydraulic scale model of an intake structure. In such a model test, all hydraulic phenomena that are present in a pumping station can be investigated in detail. The main goal is to obtain a proper pump feeding and consequently sustainable and efficient pump performances.

The ANSI/HI 9.8-2012 standard (HIS standard) for Pump Intake Design is world-wide accepted as the standard for these scale model tests. This standard is based on present literature and provides acceptance criteria for the occurrence of vortices, the swirl-angle and the velocity profile in the suction pipes of the pumps. The spatial and temporal velocity fluctuations are judged at the level of the bell mouth throat. Both the temporal and spatial velocity variations should not be more than 10%. The spatial velocity variation is determined by comparing the measured velocity with the cross-sectional average. In addition to these criteria, the HIS standard states that by improving the approach flow, the spatial velocity profile can be changed: “Therefore, all of the above-described flow control devices, …. may be needed to achieve the desired uniformity of velocities”. However, the authors observed during their physical model tests (>30 designs tested) in the last years that the spatial variation of the velocity profiles is to a large extent not sensitive to the approach flow.

To obtain a better understanding of the influence of the approach flows on the velocity profiles, a set-up is built to accurately measure velocity profiles as function of different modifications to the pump compartment, such as splitters, fillings, curtain walls and baffles. In this paper the results of the
investigation are presented. First, the set-up and test program will be described. This will be followed by a description of the test results. The paper ends with conclusion and a discussion on the relevance of the test results.

In literature, background information cannot be found on the HIS standard statement that the velocity profile can be improved by improving the approach flow. Most literature on physical scale model tests of pumps handles on vortices. Only a small part is about velocity profiles. As summarized in Knauss et al., the literature only discusses acceptance criteria for velocity profiles and not how to improve them. In a previous research of Verhaart et al. (2014) the development of the velocity profile in the suction pipe was investigated. This research showed that the velocity profile is very sensitive for the distance to the bell mouth entrance. A few millimeter increase in measurement height (model dimensions), decreases the spatial deviation with a few percent.

2. Experimental set-up

2.1. Description of the basic set-up

A standardized set-up, based on the HIS standard, is built in the Deltares pump sump facility (see Figure 1). A bell mouth (diameter 200 mm) with a smooth curvature is connected to a suction pipe with an internal diameter of 110 mm. The throat is located at a distance of 55 mm from the bell mouth entrance. A cone is placed below the suction pipe to avoid a submerged vortex from the bottom entering the pump. The discharge is 25 l/s and the water level is 0.8 m. The water level is selected such that both the HIS (2012) criterion for submergence and the stricter criterion of Knauss et al. (1987) are fulfilled. It is therefore not likely that free-surface vortices, which can influence the measurements, occur. A more extensive description of the set-up is given in Verhaart et al (2014). More information on submergence acceptance criteria can be found in Fockert et al. (2014).

![Figure 1 Sketch of the set-up. Left: top view, right: side view.](image)

3.2 Measurement equipment

Velocity profiles and velocity fluctuations are measured by means of a method based on the pitot tube principle. The total head is measured in a confined compartment located at the outside of the suction pipe (see Figure 2), where the flow velocity is zero. The static head is measured at the locations indicated in Figure 2. Two high-accuracy (95% accuracy interval: +/- 0.075% of the span) pressure difference cells (dp-cell) are used to measure the heads. One dp-cell measures the pressure difference (H-h_{s,m}) between the total head and the static head at the position in the middle of the suction pipe. The other dp-cell measures the difference between the static head at the middle position and the static head at one of the other positions (h_{s,m} – h_{s,x}). Velocities at different locations are measured after each other.
The applied tubes have a diameter of 6 mm. By use of the following equations (Bernoulli) the velocity at the different points is determined (a description of the symbols is given at the end of this paper):

\[ V_m^* = \sqrt{2g \left( H - h_{s,m} \right)} \]  
\[ V_m = C_g C_A C_p \sqrt{2g \left( H - h_{s,m} \right)} \]  
\[ V_x = C_g C_A C_p \left( V_m^* \right)^2 + 2g \left( h_{s,m} - h_{s,x} \right) \]

Nine tubes (6 mm diameter) are attached to a frame, which is installed in the suction pipe, to measure the static head. This frame can move along the suction pipe to measure at different distances from the bell mouth entrance. Two different frames are used to measure respectively the blue and red locations as indicated in Figure 2. To be able to measure both section A&B and section C&D, the pump is rotated (-45°) after measuring section A&B to measure section C&D.

![Figure 2 Points at which the velocities are measured. Left the standard set-up. Right the set-up which is used to determine the correction factor C_p.](image)

### 3. Measurement program

The measurement program consists of three steps. First detailed velocity profiles (33 points) are measured at 110 mm, 115 mm and 120 mm from the bell mouth entrance to determine accurately the correction factor $C_p$. Reference is made to Verhaart et al. (2014) for more background information regarding $C_p$. Thereafter, the repeatability of the measurements is determined by measuring 6 times a velocity profile for the standard layout (Figure 1, cone installed). Finally, the influence of (~25) modifications to the pump compartment is determined. The tested modifications are (for dimensions see Figure 3 and Table 1):
- Bottom splitter
- Backwall splitter
- Corner and backwall fillings
- Curtain wall
- Energy dissipating structures (EDS)
- Strainer below the pump (open area of respectively 44% and 69%)

All velocity profiles are measured in the bell mouth throat (55 mm distance from the bell mouth entrance), except for the $C_p$ measurements.
Table 1 Dimensions of the different modifications in mm (as indicated Figure 3).

| Curtain wall | Bottom splitter | Backwall splitter | Corner filling | Backwall filling | EDS |
|--------------|-----------------|-------------------|---------------|------------------|-----|
| A            | B 100-220       | C 70              | D 300         | E 140            | F   |
|              | -               | -                 | -             | -                | -   |
| B            | - 100-220       | - 70              | - 300         | - 140            | -   |
|              | -               | -                 | -             | -                | -   |
| C            | 100-220         | 70                | 300           | 140              | -   |
|              | 100-220         | 70                | 300           | 140              | -   |
| D            | 100-220         | 70                | 300           | 140              | -   |
|              | 100-220         | 70                | 300           | 140              | -   |
| E            | 100-220         | 70                | 300           | 140              | -   |
|              | 100-220         | 70                | 300           | 140              | -   |
| F            | - 100-220       | - 70              | - 300         | - 140            | -   |
|              | - 100-220       | - 70              | - 300         | - 140            | -   |
| G            | - 40            | - 350             | -             | -                | -   |
|              | - 40            | - 350             | -             | -                | -   |
| H            | - 80            | - 80              | - 300         | - 140            | 50  |
|              | - 80            | - 80              | - 300         | - 140            | 50  |
| I            | - 300           | - 300             | - 140         | -                | -   |
|              | - 300           | - 300             | - 140         | -                | -   |
| J            | - 140           | - 140             | -             | -                | -   |
|              | - 140           | - 140             | -             | -                | -   |
| K            | - 50            | - 50              | -             | -                | -   |
|              | - 50            | - 50              | -             | -                | -   |
| L            | - 80            | - 80              | -             | -                | -   |
|              | - 80            | - 80              | -             | -                | -   |
| M            | - 33.4          | - 40              | -             | -                | -   |
|              | - 33.4          | - 40              | -             | -                | -   |
| N            | - 400           | - 400             | -             | -                | -   |
|              | - 400           | - 400             | -             | -                | -   |
| O            | - 400           | - 400             | -             | -                | -   |
|              | - 400           | - 400             | -             | -                | -   |
| P            | - 400           | - 400             | -             | -                | -   |
|              | - 400           | - 400             | -             | -                | -   |
| Q            | - 400           | - 400             | -             | -                | -   |
|              | - 400           | - 400             | -             | -                | -   |
| R            | - 400           | - 400             | -             | -                | -   |
|              | - 400           | - 400             | -             | -                | -   |

Figure 3 Dimensions of the different modifications.

4. Results

4.1. \( C_p \) value

By using pitot tubes for velocity measurements, a correction for the shape of the pitot tubes is required (Zhiqiang et al. (2009), Klopfenstein (1998)). It followed from Verhaart et al. (2014) that the correction factor \( C_p \) gives the largest contribution to the uncertainty of the measured velocity. Therefore, it is of importance to determine the \( C_p \) accurately. By measuring detailed velocity profiles (33 points) at three different heights, it was determined that \( C_p \) is 0.9740 with a 95% confidence interval of +/- 0.0005.

4.2. Repeatability of measurements

If the velocity at a certain position is measured several times, the difference between measurements is larger than expected based on the measurement accuracy. For the basic set-up as described in section 2, the velocity profile is measured 6 times. Between those measurements, the pump is removed from the set-up and the pitot tubes are re-installed. The measured velocities at position D1 are shown in Figure 4. This figure illustrates that there are systematic deviations in the measurements, which are mainly caused by the turbulent behaviour of the flow in the intake structure. In addition, slightly different placement of the pump and the pitot tubes can cause these deviations. However, to overcome these systematic deviations, they are taken into account during the analysis of the measurement data.

The systematic deviations differ between the measurement positions. A standard deviation varying between 0.011 m/s to 0.026 m/s (see Table 2) is found. There is no relation observed between
locations with a high repeatability and locations with a low repeatability. As a conservative approach, the 95% accuracy interval of the point with the least repeatability is used in the remaining of this paper. So, the error lines indicated in the remaining of this paper corresponds to a 95% confidence interval of +/- 0.052 m/s.

### Table 2 Repeatability of the measurements at all positions.

| Location | Section A       | Section B       | Section C       | Section D       |
|----------|-----------------|-----------------|-----------------|-----------------|
| 1        | 0.010 m/s (0.4%)| 0.021 m/s (0.7%)| 0.012 m/s (0.4%)| 0.026 m/s (0.9%)|
| 2        | 0.020 m/s (0.8%)| 0.016 m/s (0.7%)| 0.024 m/s (1.0%)| 0.015 m/s (0.6%)|
| 3        | 0.013 m/s (0.6%)| 0.013 m/s (0.6%)| 0.013 m/s (0.6%)| 0.013 m/s (0.6%)|
| 4        | 0.013 m/s (0.5%)| 0.012 m/s (0.5%)| 0.013 m/s (0.5%)| 0.013 m/s (0.5%)|
| 5        | 0.011 m/s (0.4%)| 0.021 m/s (0.7%)| 0.012 m/s (0.4%)| 0.019 m/s (0.7%)|

4.3. Influence of modifications

The velocity profile for the basic set-up, including the 95% confidence interval, is shown in Figure 5. The lowest velocities are measured in the middle of the suction pipe and the highest velocities close to the wall of the suction pipe. Such a velocity profile, that is the inverse of a normal pipe profile, is typical for the bell mouth throat of vertically submersible pumps. In addition, the velocity profile is slightly asymmetric (velocity differences of ~3% along a concentric circle (Nakato (2000))). The acceptability of the velocity profile according to the HIS criteria, is determined by the locations B5 & D5 (maximum positive spatial deviation) and location 3 (maximum negative spatial deviation).

Figure 5 Velocity profile for the basic set-up. Straight line is the cross-sectional averaged velocity and the dotted lines indicated the maximum allowable spatial deviation of 10%.

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Figure 4 Repeatability of the measurement at position D1.

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Figure 4 Repeatability of the measurement at position D1.
Figures 6 show the influence of the different modifications on the velocity profile. In these figures the velocity differences relative to the basic set-up are shown. The dotted lines show the 95% confidence interval of the basic measurements with no modifications installed. The installation of a curtain wall significantly influences the measured velocity at the positions B1 and D5. At these positions the velocity profile is improved because the spatial deviation decreases significantly (decrease in measured velocity). However, the location B5 is not improved. Therefore, the entire velocity profile has not been improved by installation of a curtain wall. The spatial deviation is still larger than 10%. It has to be concluded that the installation of a curtain wall results only in local improvements and does not improve the entire velocity profile.

![Figure 6 Influence of the installation of a curtain wall and different combinations splitters and fillings. For dimensions see Figure 3.](image-url)
The installation of a bottom splitter has no significant effect on the velocity profile, as shown in Figure 6. The installation of a backwall splitter and the installation of the combination of a bottom and backwall splitter has a limited effect on the velocity profile (see Figure 6). The velocity at position C1 is influenced significantly. C1 is the measurement location which is located closest to the backwall splitter. The backwall splitter minimizes the flow between the pump and the backwall and therefore decreases the velocity at position C1. As the locations at which the largest spatial deviations are measured are not affected, it can be concluded that the overall velocity profile is not influenced by the installation of a backwall splitter.

The installation of a complete set of splitters (bottom & backwall splitter and corner & backwall fillings), which is normally required to fulfill the HIS acceptance criteria with respect to vortices and pre-rotation, has no significant effect on the velocity profile. This is illustrated in Figure 6.

Two different Energy Dissipating Structures (EDS) have been tested. Both EDS consist of a row of parallel columns. The open space between the columns is respectively 20 and 33 mm, while the size of the columns is equal. The EDS with an open space of 33 mm did not influence the velocity profile significantly. The other EDS provided some remarkable results. This EDS is the only modification that influences the shape of the velocity profile (see Figure 7). The velocities in the middle of the suction pipe are significantly higher. In addition, the temporal velocity variations were significantly larger than for all other velocity profiles (Figure 7). It has to be noted that the head loss over this EDS was 2 cm (in model scale) and that the small flow through areas caused vortex shedding from the columns, resulting in very unstable flow patterns. It is therefore concluded that a poorly designed EDS influences the velocity profile in a negative way because of the increased temporal velocity fluctuations compared to the basic set-up.

The installation of a strainer below the pump introduces an additional head loss. The results presented in Figure 8 are corrected for this additional head loss. This correction should be made because the measurement principle applied is based on a zero head loss over the bell mouth. It is concluded from Figure 8 that the strainer does not have a significant effect on acceptability of the velocity profile. The velocity profile is only affected locally (A4, B2 and D5) and the position (B5) with the highest spatial deviation is not influenced.
5. Conclusions
The measurement campaign showed that well-designed modifications to the pump compartment, like splitters, fillings and curtain walls do not influence the acceptability of the velocity profiles. Some modifications (curtain wall, backwall splitter) can influence the velocity profile locally. However, at the locations at which the highest spatial deviations are measured, the velocity did not change significantly. Both for the basic set-up and the set-up with modifications installed, the maximum spatial variation varied between approximately 9% and 11%. Therefore, it can be concluded that well-designed modifications to the pump compartment will not change the acceptability of a velocity profile (according to the HIS standard). However, poorly designed modifications have a negative influence on the velocity profile. The most important influence is that the temporal velocity variations become much larger. For example, a poorly designed EDS can increase the temporal velocity fluctuations from 1% to 5%.

In addition to the modifications presented in this paper, the influence of changes to the main dimensions, like bottom clearance, backwall clearance, angle of the approach flow and bell mouth geometry were already investigated by Verhaart et al. (2014). These modifications also did not influence the velocity profile significantly. Therefore, it has to be concluded that the velocity profile is inherent to the pump design. The statement in the HIS standard that the velocity profile can be significantly improved by making (small) modifications to the pump sump seems to be not generically valid.

6. Discussion
Different interpretations of the measurement location as indicated in the HIS standard are possible, as the bell mouth throat is often not a single point, but extended over a certain length. In combination with the fact that modifications to the intake structure do not have an influence, the same approach flow can be judged different. However, the impeller of the pump receives exactly the same velocity profile. Therefore, as also discussed in Verhaart et al. (2014), a more specific criterion for the velocity profile should be developed. By developing this criterion, it is of utmost importance that the relation between scale models and the exact effect on a prototype pump is determined.

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Nomenclature
\( C_A \) correction factor for area occupied by pitot tubes (-)
\( C_p \) correction factor for layout of pitot tubes (-)
\( C_Q \) correction factor for varying discharge between measurements (-)
\( g \) gravitational acceleration (m/s\(^2\))
H  total head (m)
h_s  static head (m)
m  measurement point in the middle of the suction pipe (-)
V^*  uncorrected velocity (m/s)
V  velocity (m/s)
x  measurement location

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