Developments to minimize the occurrence of surface and subsurface vortices at pump intakes

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Abstract

Surface vortices have been classified [1] and are widely used as parametric criteria to evaluate the acceptability of the hydraulic inlet conditions at pumps. The geometry of the pump sump, pump inlet and the flow characteristics (fluid structure interaction) normally depict the tendency for the formation of surface vortices. The presence of surface vortices will invariably lead to un-uniform loading on the pump inlet, leading to vibration and possible structural failure. Current literature [2,3] reflects the submergence requirements at pump intakes to prevent the occurrence of surface vortices. The accepted hypothesis is that by increasing the submergence the formation of vortices will be reduced. This hypothesis is challenged on the basis that surface vortices can only occur when the vertical flow component is significant and that this can be limited by the accentuation of the horizontal flow velocity that will dissipate the vertical flow component and thus reduce the submergence requirement significantly. Physical and computational modelling was conducted to verify the relationship of flow velocities on the required submergence to prevent surface and subsurface vortices.

Keywords: pump intakes, vortices, deflector beam, vane turning box, submergence, swirl angle, pre-rotation, horizontal flow.

1 Introduction

The criteria suggested for effective pump operation entail, the limitation of surface vortices, ensuring a balanced velocity distribution and limiting the pre-rotation at the pump inlet [4].
It is generally accepted that unsymmetrical conditions in the sump, breakaways from discontinuities, circulation zones and stagnation locations in a sump may contribute to the violation of one or more of the suggested criteria.

It is accepted that in all pump station sumps, there needs to be a horizontal flow (hydrostatic driven mass movement to replaced the discharged volume) and that the creation of instability that is related to flow velocity can be minimised by minimizing the velocities. The decrease in the flow velocity requires a higher flow depth that in turn results in the definition of submergence requirements. Cases have been documented that unfavourable pump inlet conditions even occurred under high submergence [5]. Alternative solutions for reducing submergence requirements are discussed in this paper.

Results from two model studies are discussed that reflect that submergence could be reduced if full cognisance is taken of the local velocity energy at the pump intakes. Two separate model studies for vertical inlet pumps and horizontal intake pumps were investigated and are discussed in this paper.

2 Model studies to improve the pump inlet condition

2.1 Pump inlet conditions for vertically installed pumps

2.1.1 System description and model scales
The prototype system of the Sheik Zayed Water Supply consisted of multiple vertical pump sets, with a capacity of 8.5 m$^3$/s. The physical model of a single pump was constructed as an undistorted model to a scale of 1:10 and Froude uniformity (Figure 1). The maximum model flow rate of 26,879 l/s was evaluated at the lowest operating water level in the pump sump (LOL = 190.89 m).

In the test runs, the pre-rotation and velocity distribution profiles in the pump intake were recorded.

2.1.2 Physical and computational model investigation for vertical installed pumps
In the model study it was found that the potential formation of vortices was more significant at the maximum operation level (MOL = 192.82 m) and that the pre-rotation was marginally less than the criteria of 5° for the swirl angle. The swirl angle, \( \theta \), is measured with a vortimeter and is calculated as indicated below:

\[
\theta = \arctan \frac{V_b}{V_a} \text{ [degrees]}
\]

Where:

\[
V_b = \pi d_v n/60 \quad \text{and} \quad V_a = \frac{Q_E}{A_C}
\]

\[d_v = \text{diameter of the propeller in m} \]
\[n = \text{revolutions per minute (min}^{-1}) \]
\[Q_E = \text{discharge in the suction pipe in m}^3/\text{s} \]
\[A_C = \text{cross sectional area of the pump column in m}^2\]
Based on the original results two alterations were incorporated to improve the velocity profiles and reduce vortex formation associated with MOL. A vane-turning box (Figure 2(a)) was installed at the pump intake to improve the velocity profile while a baffle wall (Figure 2(b)) was installed in the approach channel to reduce the surface vorticities. These alterations proved to provide significant improvements.

Figure 1: Section through the pump sump – design flow rate = 8.5 m$^3$/s.

Figure 2: Alterations that were implemented, Vane Turning Box (a) and Baffle Wall (b).
The velocity distribution that is reported here was measured along the center line, while the pre-rotation was measured just downstream from the bell mouth. The results for the improved system with the turning vanes and the baffle wall incorporated, are indicated in Figures 3 and 4 respectively which reflects a balanced loading on the impeller and a balanced flow distribution.

![Influence of vanes on the velocity distribution at the pump inlet](image1)

**Figure 3:** Velocity distribution along the centreline for the original design and the improved layout.

![Swirl angle, MOL - Q\text{design}](image2)

**Figure 4:** Graphical presentation of the pre-rotation for the original design and the improved layout.

Numerical modelling (Computational Fluid Dynamics, CFD) was undertaken to verify the free surface flow conditions and the effectiveness of the baffle wall to reduce the surface vortices. The modelling was conducted using the VOF module of FLUENT. The results confirmed the effectiveness of the baffle wall and illustrates that the horizontal velocity can be used to limit formation of
surface vortices. Figure 5 reflects the flow paths resulting from the installation of the baffle wall, which accentuated the horizontal flow velocity and eliminated surface vortex formation.

![Flow paths resulting from the introduction of the baffle wall.](image)

**Figure 5:** Flow paths resulting from the introduction of the baffle wall.

### 2.1.3 Final impressions of the alternatives to improve the inlet conditions for vertical pumps

The investigation indicated the advantage of the inlet turning vanes to improve the flow velocity profile and to reduce the pre-rotation at the pump intakes for vertical installed pumps. The inclusion of the vertical baffle wall limits the tendency of surface vortices and reduces the required submergence to 1.0 D (D = the bellmouth diameter).

### 2.2 Pump inlet conditions for horizontal pump intakes

#### 2.2.1 System description and model scales

The Grootfontein pumping system was constructed in the early seventies to deliver water to SASOL II from Grootdraai dam. The pump station consists of four pumps each with an operating capacity of 2.1 m$^3$/s. Figure 6 reflects a front view of a portion of the pump station and the forebay.
Water flows from the forebay through screens and then down a vertical shaft to the horizontal inlets of the pumps (Figure 7(a) and 7(b)). Theoretically the pumps operate under a positive suction head of about 12 m. High wear on the pumps were experienced since the commissioning of the pump station and a number of alterations to the inlets were made, but none eliminated the problem.
A model was constructed to a scale of 1/6,536 (Froude uniformity) and the sides of the wet shafts were constructed in Perspex to provide unrestricted observation of the flow conditions. The layout and dimensions were in accordance to the details that were obtained from the as-build drawings. Two of the vertical wet shafts were constructed to provide a direct comparison of the changes that might be incorporated to improve the flow conditions at the pump intakes. The model flow rate was 19.23 l/s per pump.

2.2.2 Physical model investigation for horizontal inlet pumps

In the model, vertical wet shaft A was used to include the layout variations, while vertical wet shaft B was used to reflect the conditions that can be associated to the current layout.

During the experimentation it was found that no surface vortices were dominant enough to create air entry into the pump. However, the flow tended to be down the back wall, resulting in some re-circulation of the water in the vertical shaft, which probably resulted in vertical upward flow that was previously reported by others [5]. This flow down the back wall was deflected away from the back wall by the step just above the bell mouth intake creating subsurface vortices. This worsens the flow conditions at the bell mouth intake and invariably led to pressure fluctuations at the inlet to the pumps. Figure 8(a) and 8(b) give a schematic representation of the flow lines, indicating the recirculation and the break away at the pump inlet for the original layout (a) as well as the influence of the deflector beam (b). During the tests PVC beads and dye were introduced to the flow to provide a means of visualizing the flow lines.

Although no sub atmospheric subsurface vortices were identified, the change in the pre-rotation direction, reflected by the vortimeter, pointed to the fact that

![Schematic presentation of the flow lines for the original layout (a) and the influence of the deflector beam (b).](image-url)
excessive unstable turbulent flow occurred at the bell mouth near the intake of the pumps. The pre-rotation in the pump reflected that the flow conditions were unstable and that the pre-rotation angle varied excessively over time. This phenomenon was only marginally affected by the operating water level.

Based on the initial observations, it was decided that a uniform vertical flow velocity should be established in the wet shaft. The options that were considered were the inclusion of a vane turning box upstream from the pump intake and the addition of a deflector beam on the back wall that will eliminate the sheet flow down the back wall. The scenarios that were considered were numbered numerically and can be summarized as follows: 1 – Original layout, 2 – Turning vanes, 3 – Turning vanes and deflector beam and 4 – Turning vanes with a reduced area and deflector beam. Details of the deflector beam (Figure 9(a)) and the vane turning box (Figure 9(b)) are reflected below.

Figure 10 reflects the pre-rotation in shaft A and B for the different scenarios that were considered.

![Flow direction](image)

(a) (b)

Figure 9: Alterations that were incorporated: Deflector beam (a) and Vane turning box (b).

![Measured swirl angles in the shafts for the different scenarios](image)

Figure 10: Graphical presentation of the measured pre-rotation in the two shafts for the different scenarios that were evaluated.
2.2.3 Final impressions of the alternatives to improve the inlet conditions for horizontal pumps

The investigation reflected that the criteria of submergence are not sufficient to ensure effective operation of pumps. Furthermore the use of the deflector beam and the vane turning box resulted in almost ideal conditions at the pump intake.

3 Conclusion

The results from these investigations indicated that:

- Submergence can be reduced by incorporating of turning vanes that will prevent pre-rotation and ensure an acceptable velocity distribution for vertical and horizontal pump inlets
- Accentuating the horizontal flow velocity can reduce the tendency for the creation of surface vortices.

These findings have been incorporated in the designs of the systems, which now operate successfully.

It is however appreciated and understood that the flow dynamics are unique for any system under review and that further research in this regard should be supported to provide new design guidelines with regard to the required submergence.

References