THE OPTIMAL VORTEX PUMP IMPELLER - AN EXPERIMENTAL STUDY ON CLOGGING BEHAVIOUR

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ABSTRACT
This paper analyses the clogging behavior of vortex pumps by comparing the characteristics of two impeller designs. The impellers have dissimilar heads and efficiencies; the water was either clear or it contained non-woven textiles. An acrylic casing allowed observing the operation behaviour of the vortex pump while, at the same time, monitoring the data. Principle differences in the clogging behavior of the two impellers could be observed: One impeller outperformed the other in clear water transportation and indeed pumped more of the textiles. However it also lost more of its efficiency and accumulated more textiles declining it as the harder clogging. These results speak against the common approach of designing vortex pumps impellers under clean water operation condition, assuming that the same conditions apply for solid-containing fluids.

KEYWORDS
VORTEX PUMP, IMPELLER, CLOGGING, EXPERIMENT

NOMENCLATURE
Q flow rate
H head
\( \eta \) efficiency
\( \Delta Q \) ratio of the flow rate under clogging to clear water operation
\( \Delta H \) ratio of the head under clogging to clear water operation
\( \Delta \eta \) ratio of the efficiency under clogging to clear water operation
\( \Delta \text{textiles} \) proportion of not-pumped textiles to total amount of textiles

INTRODUCTION
Vortex pumps have a semi-open impeller, which is set back in the casing. As a result, an enlarged gap between casing wall and impeller occurs. This gap makes vortex pumps highly suitable for transporting solid-containing fluids. Despite their wide applicability, the hydraulic efficiency of vortex pumps often does not exceed 50%. Compared to conventional centrifugal pumps vortex pumps are thus relatively inefficient. Ever raising energy prices and the urgent demand of meeting energy goals (to slow a further climate change) make reaching higher efficiencies not only a desirable but an imperative goal for mechanical engineering. Consequently, many attempts have been made to improve the efficiency of vortex pumps. Paradoxically, all attempts so far aimed at improving the hydraulic characteristics under clear water operation, thus ignoring the challenges, which result from pumping solid-containing water - the primary area of
operation for vortex pumps. For example, when solid-containing water is transported clogging is an ever-present threat. Thus, in order to find an optimal design for vortex pumps impellers, clogging behavior must be rigorously addressed in the first place. In order to build better vortex pumps their design must fit the area of operation and not a stylized, clean environment.

An additional challenge for designing better vortex pumps is the fact that the optimal design parameters (in terms of best performance) are not known. This is because the working principle of a vortex pump is not yet sufficiently understood. There are two principally different views on the working principle: The first view compares the operation of vortex pump to that of a side channel pump where the impeller induces a vortex in the enlarged side chamber and thereby transports the fluid (e.g. Lubieniecki (1972)). The second view sees the vortex pump as a poorly designed conventional centrifugal pump where the missing front shroud and the enlarged gap causes high exchange losses and result in the low efficiency (e.g. Ruetschi (1968)). Against the background of these opposing views, best practice approaches do not exist. Advices on the selection of parameters for reaching higher heads and better efficiencies are piecemeal. For example, it is known that more blades and high outlet angles improve vortex pumps (see Ruetschi (1968) and Guan et al. (1989) for the number of blades; see Ruetschi (1968), Sha et al. (2004), Guan et al. (1989) and Sha et al. (2005) for the outlet angle). However, all these studies were conducted with clear water and none addressed the specific challenges of pumping solid-containing fluids, such as clogging. It thus seems that all advices have been based on the assumption that a vortex pump, which performs well under clear water conditions also performs well under condition of clogging - but this assumption was never tested so far. The state of the art knowledge is thus a combination of piecemeal design advice for vortex pumps that are optimized to stylized environments. To systematize the applied knowledge, this paper analyzed the clogging behaviors of two vortex pump impellers. These impellers were chosen due to their geometrical adjustments, which led to different heads and efficiencies in a prior investigation with clear water (Gerlach et al. (2016)).

Water contained non-woven textiles to simulate the operation under clogging. The operation was monitored during the clogging tests. The clogging behavior was observed via an acrylic casing. The tested impellers behaved very differently during the clogging tests than during clear water operation. The impeller with the smaller head and the lower efficiency for clear water operation outperformed the other impeller during the clogging test in terms of its operation data. However, it was less capable of pumping textiles compared to the impeller that was designed according to literature recommendations.

**EXPERIMENTAL SETUP**

**Tested Impeller**

One impeller had 4 curved blades and a diameter of 240 mm (see the left of Figure 1). The design of the first impeller is based on the recommendations of Ou et al. (2012) who suggested it already constitutes an optimal design. Ou et al. (2012) evaluated the influence of geometric modifications in an orthogonal study via numerically simulating various impeller configurations. They then experimentally compared the most promising impeller designs and selected the “winner” in terms of efficiency. The geometric factors of this existing impeller design were modified in a prior study (compare Gerlach et al. (2016)) and ended with the second impeller. The second impeller had 8 straight blades and a diameter of 205 mm (see the right of Figure 1). The design of the second impeller is in accordance to recommendations of literature which says a high number of blades and an outlet angle of 90° led to the highest heads
and efficiencies. The 8-Straight-Blades impeller was superior in term of head and efficiency under clear water operation, as shown in Figure 2.

**Test Pump**

The test pump had a ring casing with a ball passage of 80 mm, which was the same for the suction pipe and the pressure pipe (see Figure 3 and Figure 4). The casing was made of acryl glass to guarantee optical access during the entire operation. The motor was relatively large (22kW) to guarantee operation even under severe clogging. The drive train of pump including motor was mounted on rails to fast change the impeller and to access to clogged textiles in the casing. The pump was equipped with an incremental encoder to measure the rotational speed. It was attached to a frequency converter, which measured the consumed power.

**Test Rig and Measurements**

The clear water test and all clogging tests were performed on the test rig depicted in Figure 5. The test rig consisted of two tanks, which could be separately connected to the pump. It was equipped with a magnetic inductive flow meter to assess the flow rate. Pressure was measured according to the regulations of ISO 9906. A detailed description of the test rig design can be found in Pöhler et al. (2015). The same test rig served to measure the throttle curve and performance characteristics under clear water operation. Textiles of non-woven material simulated the
operation condition under different degrees of clogging (see Figure 6). To this end, pre-defined amounts of textiles were added to clear water, which was subsequently pumped. The textiles were thus 12 hours soaked in clear water to avoid floating. All textiles were rectangular (30.5 cm x 21.5 cm) and weighted 3.8g - 4.1g. Two different clogging tests were performed: A ”short test” and a ”long test”.

In the ”short test” one tank was filled with either 50, 100 or 200 textiles and 2 \( m^3 \) of clear water. The vortex pump transported the textile-containing fluid via a filter to the second tank, which was empty. The ”short test” was finished when all of the 2 \( m^3 \) of water and textiles were pumped from the first tank to the second tank. Immediately after the ”short test”, it was evaluated how many textiles remained in the pump. This amount of not-pumped textiles was estimated via dividing the dry weight of the clogged textiles by the dry weight of all textiles. This procedure was repeated two times. In the ”long test”, either 50, 100 or 200 textiles were mixed with 2 \( m^3 \) of clear water in the first tank. The textile-containing fluid was then pumped from the first tank in circle for one hour to the first tank. Similar to the short test, the clogged textiles after one hour of testing were compared to the total amount of textiles via their dry weight. The ”long test” was done one times for tests with either 50, 100 or 200 textiles. For all tests, the flow rate, head, rotation speed and power consumption were monitored. Additionally, the casing and parts of the pressure pipe were videotaped to document the clogging behavior and the flow in the casing. The operation point for the clogging tests was the Best Efficiency Point under clear water operation. This means, only the clogging behavior for the Best Efficiency point of clear water operation was evaluated.

These tests are in accordance to the test procedure of Pöbler et al. (2015). The authors evaluated the composition of wastewater and specified the named amounts of non-woven textiles to test clogging behaviour.

**Presentation of Data**

The two tested impellers differ in their characteristics for clear water operation. Therefore, the results for the two clogging tests are presented by comparing the characteristics val-
ues during the clogging tests to the characteristics values during clear water operation. Non-dimensional values are calculated as the ratio of the values for the clogging tests to the values for clear water operation. Average characteristics values for the clogging tests are averages over all two repetitions of the "short tests". Average characteristics values over the time of one hour testing are used for the "long test".

In particular, the ratio of the flow rate \( \Delta Q \) is defined as:

\[
\Delta Q = \frac{Q_{\text{clogging test}}}{Q_{\text{clear water}}} \tag{1}
\]

In line with this definition, changes in head \( \Delta H \), power consumption \( \Delta P \), and efficiency \( \Delta \eta \) are defined as:

\[
\Delta H = \frac{H_{\text{clogging test}}}{H_{\text{clear water}}} \tag{2}
\]

\[
\Delta P = \frac{P_{\text{clogging test}}}{P_{\text{clear water}}} \tag{3}
\]

\[
\Delta \eta = \frac{\eta_{\text{clogging test}}}{\eta_{\text{clear water}}} \tag{4}
\]

To evaluate how many textiles were pumped the proportion of clogged textiles to the total amount of textiles \( \Delta \text{textiles} \) is:

\[
\Delta \text{textiles} = \frac{\text{textiles not pumped}}{\text{textiles total amount}} \tag{5}
\]

RESULTS

Performance Comparison

This section presents only the results of the performance data for the "short test". Displayed are always the averaged results for each impeller over all two repetitions of the "short test". The findings on the ratios defined by the formulas 1 to 5 of the "long test" were essentially similar to those of the "short test" and therefore not separately discussed.

Figure 7 shows the ratio of the flow rate \( \Delta Q \) over the number of textiles from clean water to 50 over 100 to 200 textiles. Overall, the number of textiles had little effect on the flow rates of the two impellers. Yet the two impellers differed in their clogging characteristics compared to the clean water operation. The 4-Curved-Blades impeller reached somewhat higher flow rates under clogging. In contrast, the 8-Straight-Blades impeller lost flow rates under clogging operation compared to the clear water operation.

Figure 8 displays the respective values for the ratio of head \( \Delta H \). Again, the 4-Curved-Blades impeller reached overall higher heads during the clogging test as compared to the 8-Straight-Blades impeller and the clean water operation. The 8-Straight-Blades impeller lost head under clogging conditions. However, for both impellers was the change of head moderate.

Figure 9 shows the ratio of power consumptions under clogging and clear water operation \( \Delta P \) over the degrees of clogging. Power consumption increased for both impellers with increasing amounts of textiles. It is noteworthy that the power consumption was 1.6 to 1.7 times higher under 200 textiles whereas the flow rate and the head under different degrees of clogging were nearly constant.

Figure 10 depicts the ratio of efficiencies \( \Delta \eta \) under clogging operation. Both impellers steeply lost efficiency when textiles were added. However, the drop of the 4-Curved-Blades
was not as steep as the drop of the 8-Straight-Blades impeller. As a result the 4-Curved-Blades impeller reached better ratios of efficiencies under operation of clogging, but, the Straight-8-Blades impeller was better for clear water operation in the first place (cf. Figure 2). Thus, Figure 11 provides the not-normalized values of efficiency. Whereas the 4-Curved-Blades impeller was
inferior to the 8-Straight-Blades impeller for clear water operation, the two impellers reached similar values of efficiency for different degrees of clogging.

Figure 12 shows the ratio of the not-pumped textiles to the total amount of textiles. The closer the ratio moved to zero the more textiles were pumped. Overall, the 4-Curved-Blades pumped less textiles than the 8-Straight-Blades impeller did. The pumped textiles of both impellers decreased the more textiles were added to the water. This is because the same volume of 2m$^3$ clear water was used for all tests. As a consequence the concentrations of textiles increased with the more textiles were added.

**Performance Comparison over Time**

Figure 13, Figure 14 and Figure 15 illustrate for a "long test” the ratio of the flow rate $\Delta Q$, the ratio of the head $\Delta H$ and the ratio of the power consumption $\Delta P$, respectively. All plots show one hour of testing with 100 textiles. The findings of the "long tests” with 50 and 200 textiles were similar to the “long tests” with 100 textiles. Therefore, they are not separately discussed.

The results suggest that the 4-Curved-Blades impeller operated without drastic changes in
any of the three ratios. Over time, the behavior under clogging moved closer to the behavior under clear water operation. This convergence may be due to the shredding of textiles. In strong contrast, the 8-Straight-Blades impeller showed drastic shifts in the flow rate, the head and power consumption and little convergence of the values for clogging to the values under clear water operation occurred. All three ratios rose around 1100 seconds (ca. 18 minutes) peaking in high rates of flow, head and especially power consumption, which was 2.5 times the power consumption under clear water condition. After this peak, ratios rapidly fell back to the values of clear water transport. A comparable event occurred around 2600 seconds (43 minutes) again although the peak was less intense. This pattern suggests major clogging events from which the pump could free itself and then continued pumping normally.

**Qualitative Comparison of the Clogging Tests**

The acrylic casing allowed optical access during testing and it provided additional insights into the quality of the clogging. Table 1 exemplifies some observations during the clogging tests and it depicts the not-pumped textiles. The observations suggest that the distribution of textiles in the casing were different for the two impellers. The 4-Curved-Blades impeller had a homogeneous and cloudy distribution of textiles and the suction mouth remained visible. Not-pumped textiles were shredded. In contrast, the 8-Straight-Blades impeller had a more heterogeneous distribution of textiles and the suction mouth was invisible. Not-pumped textiles were closely attached to the impeller and they were knotted. This might be the reason why 8-Straight-Blades impeller came off badly in its performance data during the clogging tests. However, for both impellers the pumped textiles are shredded.

**CONCLUSIONS AND DISCUSSIONS**

This study analyzed the operation behavior of a vortex pump with two different impeller designs under several degrees of clogging and clean water condition. The two tested impellers were chosen because of their different characteristic values for head and efficiency under clear water operation. The first impeller, the 4-Curved-Blades impeller, is based on a design tested in literature and was geometrical modified in a prior study to gain higher heads and efficiencies. This prior study led to the second impeller, the 8-Straight-Blades impeller. It was designed according to the recommendations of the literature, with a high number of straight blades. All
Table 1: Qualitative Comparison of Clogging Tests

<table>
<thead>
<tr>
<th>Impeller</th>
<th>The pump during the &quot;long test&quot; with 200 textiles</th>
<th>Not-pumped textiles after the &quot;long test&quot; with 100 textiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-Curved-Blades</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>8-Straight-Blades</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

clogging tests were conducted with different amounts of textiles to simulate different degrees of clogging. In sum, the vortex pump nearly kept its flow rate regardless of the used impeller and the degree of clogging; the head was largely similar to the head under clear water operation; however, power consumption dramatically rose under clogging conditions.

"Short tests" revealed remarkable differences in the behaviors of the two impellers under clogging conditions. Whereas the 4-Curved-Blades impeller had some little increase of flow rate and head under clogging conditions these characteristics were declining for the 8-Straight-Blades impeller. For both impellers increased the power consumption during the clogging tests. Although the 8-Straight-Blades impeller was able to pump more of the textiles its efficiency was lowered to the level of the 4-Curved-Blades impeller. A comparison of the ratio of efficiency for the clogging tests to the efficiency for clear water operation suggests that 4-Curved-Blades impeller was superior to 8-Straight-Blades impeller under clogging although 4-Curved-Blades impeller was more inefficient under clear water operation.

The "long tests" further showed different behavioral patterns over time. Whereas the characteristic of the 4-Curved-Blades impeller remained relatively stable the 8-Straight-Blades impeller peaked in terms of its head, flow rate and power, indicating some severe clogging events. Such events would be in line with the structure of the textiles, which were found in the pump after the testing. Textiles in the 8-Straight-Blades impeller were knotted and accumulated. In contrast, textiles found in the 4-Curved-Blades impeller were shredded. Especially, the high power consumption under clogging conditions suggests that the Straight-8-Blades impeller is unsuitable for transporting solid-containing fluids because the motor could break down. This is especially noteworthy because the 8-Straight-Blades impeller was designed according to the recommendations for vortex pump impellers. The oversized motor allowed an operation that might differ from operation at a real application. In reality the clogging events leading to significant overload would stop the pump. Depending on motor power reserve, relay trip-class and settings the stop could happen after a few second with 10-20% overload (related to nameplate amps). For an application where automatic restart is not allowed this would require human interaction to restart and maybe even clean the pump. But for other applications the pump could...
restart automatically after a short stopping time which might clean the pump.

However, it has to be considered that the clogging behaviour was simulated by using non-woven textiles. Other solids might trouble different and leading to another style of clogging. Yet, these are the first attempts to evaluate the clogging behaviour of a vortex pump.

The ring casing design seems to have influenced the transport of textiles, suggesting that textiles were caught on the tongue and therefore could not leave the pressure pipe. Zheng et al. (2000), who analyzed casing designs for vortex pumps, showed that a ring casing is preferable in terms of head and efficiency for clear water transport. These tests were done with a ring casing too. The optimal casing design for solid-containing fluids thus seems an open question.

All in all, these findings strongly speak against the so far common practice of designing vortex pump impellers for the transportation of solid-containing fluids through optimizing their clear water behaviour. Clogging matters and new approaches for better-adapted vortex pump impellers are needed.

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REFERENCES


