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Performance evaluation of a wear test rig for positive displacement pumps

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Abstract.

The operation with abrasive particles is not recommended for most types of rotating displacement pumps. For these pumps, the scientific knowledge of the wear behaviour and the influence of the many parameters on the wear behaviour is sparse. This is especially true for multi-screw pumps. Therefore, the chair of fluid systems has developed a test rig for scientific research of the wear in rotating displacement pumps with a focus on repeatability of the test parameters. The practical challenges in achieving such a setup and the results of the commissioning of the test rig are shared in this paper in order to aid likeminded researchers in their development of a suitable test setup.

Keywords. wear, abrasion, test rig, displacement pumps, screw pumps.

1. INTRODUCTION

In order to cater to the industrial markets and remain relevant within globally competitive markets, component and system manufacturers need to meet all three dimensions of quality to their customers satisfaction, namely effort, availability and acceptability [1]. If the manufacturers fail to do so, they lose the ability to develop new markets and even have to face being pushed out of existing markets. Many types of positive displacement pump have historically only been used for non-abrasive applications. With the expansion of markets however, the pump manufacturers increasingly face applications with abrasive particles suspended in the pumped fluids. These applications pose a significant challenge for the manufacturers and operators of the pumps. From a manufacturer's perspective, only strict adherence to the cleanliness requirements allows for optimal life expectancy, while from the operator's perspective, these levels of cleanliness are difficult or impossible to achieve in many applications. Especially for pumps in continuous production processes with particle-laden products e.g., in the chemical or food industries, the abrasiveness poses a constant challenge due to high wear rates in the pumps, thus limiting service life.

For such applications, pumps based on soft sealing partners, such as membrane pumps or lobe pumps are often chosen. These soft sealing mechanisms however limit the maximum efficiency that can be achieved per pumping stage even in optimal operation. Furthermore, the pressure levels that can be achieved with soft sealing mechanisms are limited [2]. For diaphragm pumps, pump handbooks give a pressure limit of 17 bar for standard applications [3]. Hard sealing mechanisms as present in gear, vane, screw and lobe pumps allow for higher pressure levels, are however more susceptible to wear, when critical abrasive particles are present. The particles most critical are abrasive particles in a size close to the respective gap height, since these particles are likely to be entrained into the sealing gap by the relative motion of the sealing partners [4]. The sealing gaps are widened by wear, thus increasing internal leakage and reducing volumetric efficiency [5].

Wear to the sealing gaps can be described as a superposition of abrasive and erosive wear [4]. Abrasive wear, especially by means of three-body abrasion results from particles slightly larger than the gap height being drawn and rolled through the gaps when relative motion of the sealing partners is present. Erosive wear is caused by the flow through the sealing gaps, driven by the pressure difference. Abrasive particles smaller than the gap height are carried along by the leakage flow across the sealing gaps and cause erosion to the sealing partners. This mechanism does not require relative motion of the sealing partners [6].

The scientific literature does not offer adequate insight into the wear behaviour for many of the aforementioned pump types with hard sealing mechanisms when operated with abrasive particles. Wear in general cannot be characterised as a component's property, but is always dependent on the composition of the system that the components operate in. Schmidt [7] showed in her work on the wear behaviour in two-spindle screw pumps, that a correlation between the wear behaviour observed in standardised tribometer tests cannot be drawn to predict the wear behaviour in the field tests of the pumps. She performed a small series of experiments in an effort to analyse the wear behaviour. The tests were performed with water and 2 %-mass quartz-sand with a particle size of 40 – 150 µm (mean: 86 µm) at a pressure difference of 14 bar. The pressure was developed along the 3.3 chambers. With her work she showed the importance of performing wear experiments as close to the real application as possible, in order to not loose relevance to the real-world application.

Even when testing whole pumps, but removed from the real-world application, the pumps may show different wear behaviour when compared to real world applications, as was shown by the preliminary work for ISO/DIS 9632 [8] shows. Here pumps with similar real world wear behaviour showed different wear behaviour in the controlled test environment. This highlights the importance of well documented test rig setups for the repeatable experimental investigation of rotating displacement pumps.

The research paper that is presented here, covers the commissioning of a test rig, that has been developed in order to perform experimental research on the wear in pumps with hard sealing mechanism, as discussed above. The development of the test rig setup has been discussed in the scientific community at the screw machines conference in 2024 [9]. The presenting authors of this research paper aim at making their path to a newly developed test rig setup transparent. The test rig needs to offer a repeatable test environment. Due to logistical limitations and a lack in practical experience regarding the behaviour of such a test rig, strict control of all parameters for every experiment cannot be achieved. The repeatability with regards to the test results therefore relies on a combination of controlled parameters and monitoring of other parameters in a well-documented test environment, as will be elaborated on within this paper.

2. DESIGN AND COMMISSIONING OF THE TEST RIG

In order to achieve a test environment that allows for repeatable test parameters and offers the wide variability of adjustable parameters, the test rig has been designed with special focus on the conditioning of the suspension and on minimising dead-volumes in the pipelines. The test rig is comprised of two circuits, which are fed by a common suspension tank. The main circuit includes the measurement environment for the test pumps. The filtering circuit aids in the conditioning of the suspension. The conceptual design of the test rig is shown in figure 2.1. and explained below. Many of the design decisions could be evaluated during the commissioning phase.

2.1. Conceptional Design of the Test Rig

For the main circuit, the pipelines are kept short, while also considering the critical bend radius for the hoses and minimising the transitions in cross-sectional area. The suction side of the pump is connected to the tank, which is used for the preparation of the suspension and the temperature control. The mass flow as well as the density of the suspension is measured by a Coriolis-type flow meter located in the suction line. The difference in fluid temperature and in pressure are measured across the pump. Pump speed and torque are measured by a torque measuring shaft, which is coupled to a safety clutch that disconnects the pump from the motor in the event of a pump jamming. By means of these measurements, the operating point of the pumps can continually be monitored and changes to the pump behaviour caused by accumulative wear can be detected.

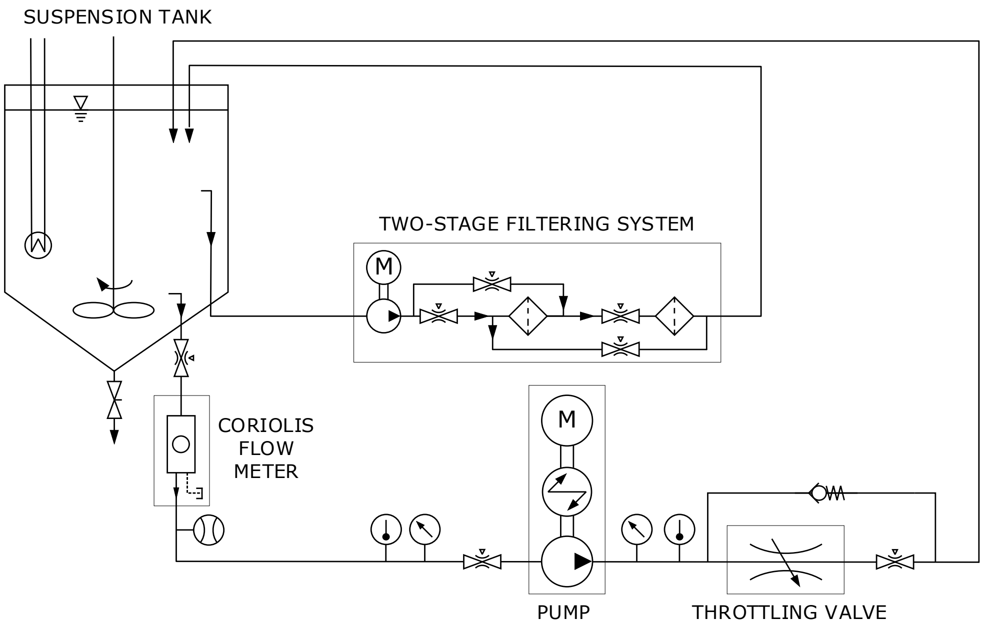

Figure 2.1. Hydraulic schematic of the test rig setup for wear analysis on pumps. [9]

In order to adjust the operating point of the pump, an adjustable pinch valve is used as a throttle. The valve, as shown in figure 2.2, is mechanically actuated and restricts the flow by pinching a flexible sleeve. After passing the throttle, the suspension can flow back to the suspension tank. The outlet of the return line into the tank is oriented against the direction of flow in the tank caused by the mixer, in order to aid the mixing by disturbing the flow. The suction inlet is oriented in a way that the pump draws in the suspension against the direction of flow caused by the mixer.

Figure 2.2. Mechanically actuated pinch valve. [10]

The filtering section needs to allow for ease of assembly and maintenance. Therefore, a routing was chosen that allows for the sections that need to be drained, to remain small and with a low point at the filters. The filtering unit is comprised of a pump and two filters that are operated in series. The suspension is first pumped through a coarse filter in order to separate the large particles, that are still sharp and most relevant for the wear in the sealing gaps. For the fine filter, a 5 µm filter was chosen, instead of the 10 µm filter that was discussed in the previous paper in order to aid the oil cleanliness.

The experimental tests focus on the wear to the spindles and liner, thus for each test a new set of spindles and liner will be used. This pump assembly will then be operated at one operating point for each respective test. The operating point is defined by rotational speed, pressure, oil viscosity, particle concentration, particle size distribution and particle type. Each of these parameters can be set independently. The requirements and limitations that had to be faced in the design of the test rig, as well as the components that were chosen for the construction of the test rig are covered in depth by the previous research paper [9]. Based on the conceptual design, the test rig has been built up and first commissioning tests were able to be performed, offering first insights into the behaviour of the test rig and additional challenges that have to be faced.

2.2. Test Procedure

The test procedure consists of a fluid pre-conditioning cycle, the wear test, and a detailed cleaning cycle to provide a reproducible and uncontaminated environment for the next tests. Within the previous publication, this test procedure has not been shared yet and is therefore discussed below.

The pre-conditioning cycle of the fluid is split up in two phases. First the fluid is brought up to temperature, while the particles remain in a sedimented state. In order to aid the homogenous temperature distribution throughout the test rig, the pump is operated at slow speed to allow heating not only the fluid in the suspension tank but also in the pipeline assembly. Additionally, the mixer is operated at slow speed in order to avoid hot zones near the heating element. Care must be taken, to not bring the particles into suspension, that have settled at the bottom of the tank since the previous test. When the desired test temperature of 40 °C is reached, the temperature is held at a constant level for the subsequent wear test. After the temperature pre-conditioning phase, the pump speed as well as the operating pressure are increased up to the operating point of the pump. Once the operating point has been reached, the mixer speed is increased in order to bring the particles into suspension, the wear test of the pump has started. The particle concentration in the suction line of the pump can continuously be monitored by means of the suspension density.

After the predefined test time the test pump is to be stopped, marking the end of the wear test. Now, the mixer and temperature control are turned off. Therefore, the pipelines are filled with particle-laden suspension. The particles remain in the pipelines and have a chance to settle at any given place in the test rig. This sediment needs to be removed from the pipelines in order to avoid introducing unsteady particle concentrations into the pumps during subsequent tests. Since disassembly of the test rig is not feasible in between all tests, the particles need to be flushed out of the pipeline, while in place. In-situ flushing of pipelines is common practice, especially in food industries or pharma applications, often called Cleaning-in-Place (CiP) [11]. By means of often turbulent flow of a cleaning aid, the pipes are flushed and sediments removed from the system [11]. Flushing the measuring section of the wear test rig in a similar way prohibits itself for two reasons. Firstly, the pipeline diameters of the test rig have specifically been chosen large in order to reduce erosive wear to the pipeline components by reduction of the flow velocity. Thus, turbulent flow can only be achieved with very high volume flows, which cannot be reasonably provided by the size of pump that would fit the available space or budget. Secondly, the particles shall remain in the suspension tank during the flushing cycle, in order to reduce effort in the test preparation and aftercare. Solutions with a suction side filter in the tank were not considered, since the size required to provide sufficient filter capacity would not fit the available space. Instead, the suspension is given time for sedimentation. Clean fluid for flushing is thus made available by allowing the particles to settle at the bottom of the tank. In order to not agitate the particles that have already settled at the bottom of the tank, the flushing cycle can only operate with low volume flow.

Instead of turbulent flushing, a concept based on mechanical agitation of the particles in the pipelines was chosen. A pipe cleaning spiral, fitted with a nylon brush, allows to agitate the particles, bringing them back into suspension. The suspended particles are then carried back to the tank by a low volume flow. In order to provide the necessary volume flow, a secondary flushing pump is used, that can be mounted in place of the test pump. With the flushing pump in operation, the cleaning spiral is inserted into the suction port in the tank and fed into the pipeline until the brush reaches the suction port of the pump. Thereby the sediments from the pipeline assembly can be flushed back to the tank while minimising disturbance to the sedimented particles in the tank.

This flushing concept is only possible thanks to the specific design of the pipeline assembly, which is based on the guidelines for food industries. Namely by avoiding dead spaces as well as sharp bends and aiming for smooth transition of diameters, it is possible for the brush and cleaning spiral to move freely through the pipes. Thanks to the design of the suction port of the secondary flushing pump, there is no risk of catching parts of the cleaning spiral or the brush in the moving parts of the pump. For changing the particle type, the return lines can be flushed accordingly by inserting the brush into the return line.

3. Performance Evaluation

The measures described above all focus on producing a repeatable test environment. The following paragraphs will show the performance of the systems and allow for an evaluation with regards to the repeatability of the test parameters.

3.1. Temperature Pre-Conditioning

The operating temperature for the test rig is 40 °C. The temperature is controlled to within ± 2 °C by a 9 kW heating element and two tube coil heat exchangers in the suspension tank. The temperature control allows for the test fluid to be preheated to 40 °C before starting the tests. For the preheating of the measuring section, the test pump is operated at slow speed, in order to not agitate the settled particles in the tank. The wear test is initiated by increasing pump speed and pressure to set the operating point and ramping up the mixer speed in order to bring the particles into suspension. Dependent on the environmental conditions at the time of the test and the operating point, the hydraulic losses may be great enough to keep the test rig at 40 °C or even heat up the test fluid. The temperature controller therefore adjusts the volume flow of coolant through the tube coil heat exchanger, thus allowing for continuous control of the temperature. Figure 3.1 shows the temperature in the tank and at the pump inlet during the pre-conditioning, confirming, that the temperature pre-conditioning cycle ensures repeatable test parameters, allowing for a consistent oil viscosity and density to be considered for the wear tests.

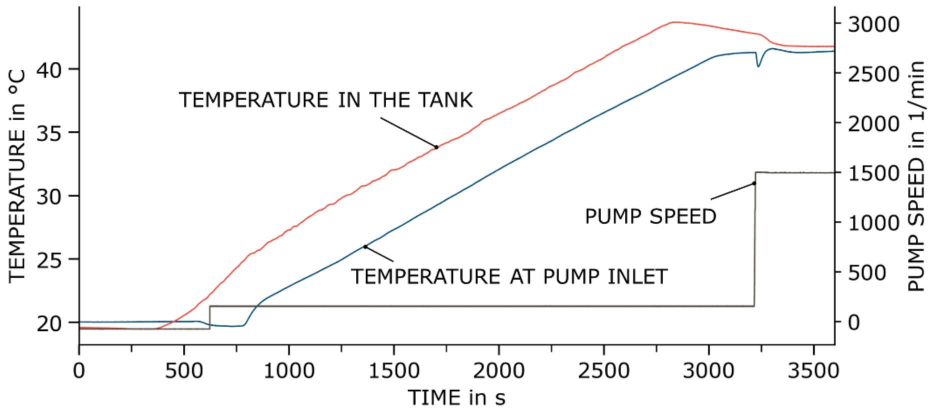

Figure 3.1. Fluid temperature pre-conditioning cycle and run-up of the pump.

3.2. Particle Concentration

The temperature pre-conditioning cycle discussed above must not introduce a critical amount of abrasive particles into the measuring pump. Additionally, the particle concentration introduced into the pump during the run-up of the pump and the mixer needs to be evaluated. The introductory paragraphs mention, that not all parameters can be controlled within the test rig. The particle concentration that is introduced into the pump is the most important parameter that can only indirectly be influenced by changes to the mass of particles in the tank and the run-up phase. Therefore, it is very important to monitor and document the particle concentration during all states and consider the findings when drawing conclusions from the measurement results.

Preliminary tests have shown, that with respect to the cleanliness achievable by the flushing cycles and the accuracy achievable in the measurement of the particle concentration, the temperature pre-conditioning cycle can be considered to not contribute to introducing particles into the measuring section. Fluid samples taken near the pump inlet in the tank after the pre-conditioning phase show, that no critical amount of particles was brought into suspension.

Figure 3.2 shows a pre-conditioning cycle after the oil has been heated to 40 °C with the pump and the mixer operated at slow speed, in order to provide uniform heating throughout the measuring section and the tank. Then, the pump is run-up to 1500 1/min in order to set the operating point, before the mixer speed is increased, in order to bring the particles into suspension. The density drops slightly below the expected reference value of 0.852 ± 0.002 kg/l during the temperature pre-conditioning cycle. The reference value was obtained using a Lauda TD3 tensiometer at a temperature of 40 °C. Once the pump has reached its operating speed of 1500 1/min, the density approaches the reference density, indicating that the pump does not stir up a critical amount of abrasive particles in the suspension tank.

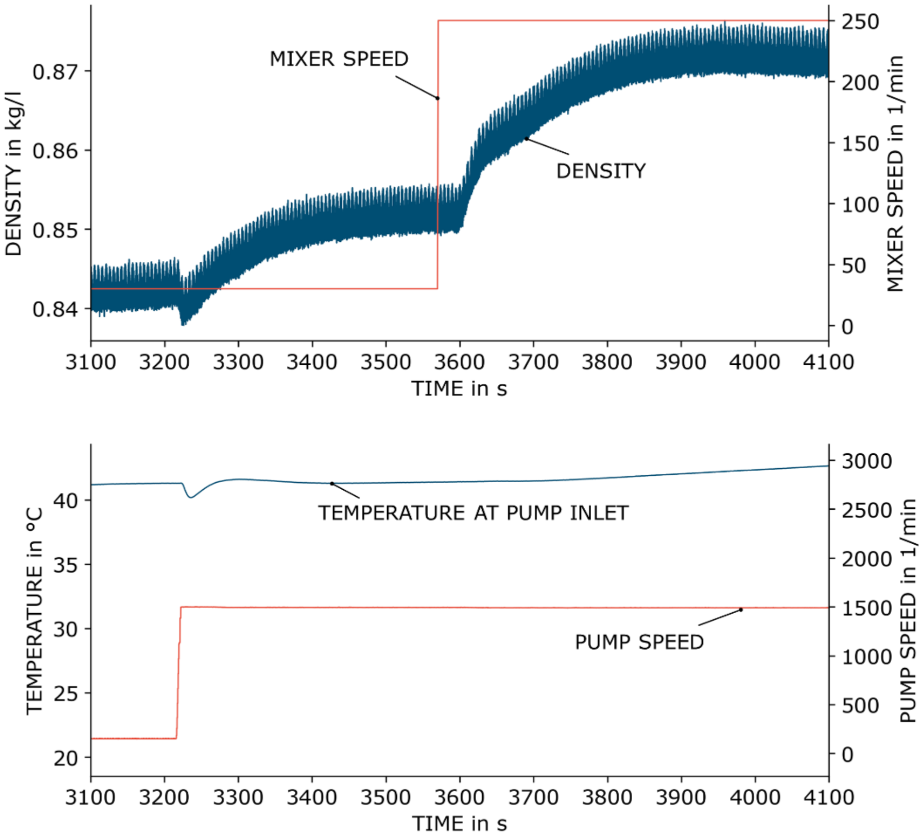

Figure 3.2. Suspension density and temperature at the pump inlet during pre-conditioning.

The density of clean oil at the same pump speed is shown in figure 3.3. Checking against the measurement in clean oil confirms, that for the run-up of the pump to 1500 1/min is safe to assume, that no critical amount of particles are stirred up from the bottom of the tank.

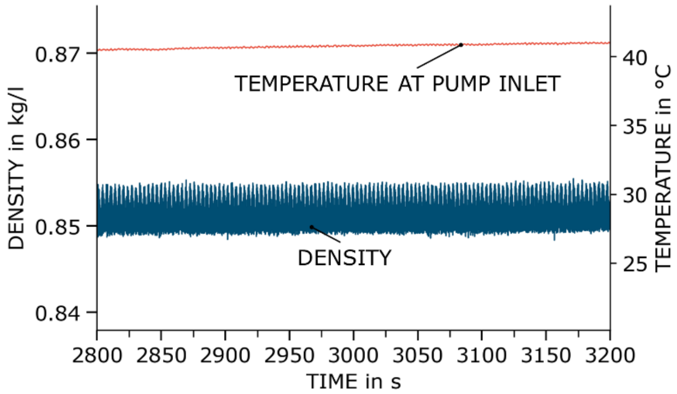

Figure 3.3. Clean oil density and temperature at the pump inlet.

Additionally, a fluid sample was taken from the tank, after the pump was run-up to 1500 1/min. After sufficient time for sedimentation of the sample, it could be confirmed, that no significant amount of particles was present in the oil. Thereby, both the temperature conditioning as well as the run-up cycle of the pump fulfil the requirements necessary for a repeatable test environment. This can also be confirmed by means of a sight glass in the suction line before the pump. Additionally, the fact that test pumps operated within these conditions did not show any signs of wear and upon disassembly did not show any signs of binding. Binding of the spindles within the liner due to particles within the small clearances has been observed with all pumps that were operated at test concentrations. The pre-conditioning phase can thus be considered to allow for sufficiently clean oil at the start of the tests, ensuring the repeatability of the tests.

After setting the operating point, the mixer speed is increased, in order to bring the particles into suspension. Figure 3.2 shows that the density increases. From the density, the particle concentration can be calculated. The supplier of the glass granule particles used for the commissioning tests, gives a range of 2.0 … 2.6 kg/l for the particle density. [12] Assuming a particle density of 2.2 ± 0.2 kg/l and an oil density of reference value of 0.852 ± 0.002 kg/l, a particle concentration of 1.53 % by mass can be calculated with a spread of +0.42 %, -0.31 %, matching the nominal particle concentration of 1.5 % by mass.

3.3. Flushing Cycle

Without clean pipelines at the start of a test, all other efforts to ensure a repeatable test environment are in vain. Unknown particle agglomerations, especially on the suction side may detach undetected and enter the pump. Thereby, the wear in the pump would no longer be able to be traced to known parameters. Since the density measurement only gives information about the density of the flow through the sensor, a manual inspection of the achievable cleanliness in the pipes has to be performed. The design of the test rig is such that critical dead volumes are minimised. Therefore, the remaining critical sections are the sharp transitions in diameter at the hose fittings and the step down in diameter at the pump inlet. These critical sections were checked by disassembly and showed, that no particle agglomerations were to be found.

Additionally, the density measurements of clean oil in the test rig at an ambient temperature of 21 ± 1 °C were compared to the density after flushing at the same temperature. The density in clean oil was 0.868 ± 0.004 kg/l, while the density after flushing was 0.870 ± 0.004 kg/l. Thus, the flushing cycle offers sufficient cleanliness for the tests.

3.4. Cavitation

The commissioning test showed, that at high volume flows and high pressure drops ($\Delta p > 8\,\mathrm{bar}$), cavitation could be noticed. The cavitation presented as vibrations within the hydraulic hoses, that were transferred back to the test pump. The origin could be traced to the pinch valve. The high pressure drop at the pinch valve that is used to set the operating pressure of the pump, leads to cavitation within the pinch valve, which transmits the vibrations to the hose assembly of the test rig. These high system vibrations highlighted an issue in the mounting solution for the Coriolis-type flow meter, since vibrations from the return hose were able to be transmitted into the mount of the flow meter. The flow meter, which operates in a frequency range of $400 \ldots 600$ Hz thus gave inconsistent measurements for the density of the suspension. Therefore, the flow meter was mounted more rigidly and isolated from transmission of vibrations. Thereby the negative effect on the measurements was omitted. Further, in order to reduce vibrations within the test rig and reduce cavitation erosion to the pinch valve, concepts for further throttling were developed and will be added to the test section.

4. CONCLUSIONS AND OUTLOOK

Based on the results of the preliminary and commissioning tests, the test rig can be set up for the parameter studies to analyse the wear behaviour in screw pumps. Final adjustments to the throttling of the measuring section and to the filtering section can be performed. The performance of the test rig will continuously be monitored, and future changes documented in order to avoid the propagation of systemic changes to the experimental findings. The tests that will be performed, aim at the starting phase of wear in screw pumps in order to enhance the knowledge of critical parameters and better understand safe vs. critical operating points.

The experiences in the design and commissioning process of the test rig are further discussed below in order to aid future researchers by providing a condensed lessons learned. Future experiences in the operation and upkeep of the test-rig are intended to be shared as well.

Some practical findings to keep in mind during the design of a similar wear test rig, that became important during the commissioning tests are summarized below.

In order to reduce particle agglomerations within the pipeline system, smooth transitions are to be chosen, when variations to the inner diameter of pipes and connectors cannot be avoided. Adhering to that principle made the flushing concept described above possible. However, it can be noted that the step at the transition from the hydraulic hose to the barbed hose fitting leads to increased settling of particles at that transition. Therefore, for applications with particle suspensions it is recommendable to design the leading edge with sufficient taper.

Wear will not only affect the measuring section, but the filtering unit as well. Cumulative wear will lead to a decrease in volume flow, thus reducing the filtering rate. This reduction in the filtering rate can currently not be characterised since the filtering section is not equipped with a flow sensor. For ensuring consistent filtering, it is recommendable to add a flow sensor to the filtering section.

The suspension tank has been chosen with a focus on adaptability and dead volume free design. Therefore, a cylindrical tank from the food industries has been chosen that is equipped with a dished bottom and total drain. The tank has been equipped with two tube coil heat exchangers that are nested. These are oriented concentric to the central mixer and mounted to the wall of the tank. The mounting hardware serves double duty. They affix the coils in the tank and at the same time act as baffles preventing the formation of a vortex as a result of the centrally mounted mixer. Some of the mounts break through the fluid-air interface, thus allowing air entrapment into the flow around the mounts at high flow rates of the pump. The influence on the experimental results is expected to be minor, since the air bubbles remain close to the surface and are few in number. Nevertheless, it is advisable to avoid disturbing the fluid air interface to mitigate air entrapment.

Further focus needs to be put on the wear to the test rig itself. While it is designed with low wear rates to the components in mind, the test rig needs to be checked for wear periodically. Especially the throttling components, that are subject both to cavitation and highly erosive conditions need to be checked frequently. A standardised, sacrificial wear body may be added to the outlet of the pipeline assembly in order to pose as an indicator for cumulating wear in the test rig components.

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Biographies

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