Conference on Modelling Fluid Flow (CMFF'22)
The 18th International Conference on Fluid Flow Technologies
Budapest, Hungary, August 30 -September 2, 2022

OPTIMIZATION OF THE PRESSURE INCREASE OF AN ADAPTED PITOT PUMP FOR THE SEPARATION OF OIL-WATER MIXTURES

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ABSTRACT

A Pitot-tube jet-pump for separating and transporting liquids of different densities is in use in our group for cleaning oil-contaminated water. Previous simulations and experimental validation tests showed that a separation efficiency over 99% can be achieved. The separation efficiency has been experimentally confirmed for various oils, such as sunflower oil, rapeseed oil, diesel fuel, heating oil, and motor oil.

This high separation efficiency is essential; however, a sufficient pressure increase is also necessary to transport the purified water afterwards. But measures providing additional head should not induce back-mixing and decrease of the separation efficiency. A new version of the impeller with cut-off blades has been developed. The position and geometry of the blades must be optimized to increase pressure while keeping excellent separation efficiency. Experiments have been carried out for various impellers; their effect on separation efficiency and pressure head are investigated.

First success has already been obtained with a very simple design. Adapting further the blade shape, even better results are expected.

experiments, liquid-liquid separation, Pitot-tube jet-pump, radial pump

NOMENCLATURE

Latin letters

FS	[-]	flow-split
g	[m s^{-2}]	gravitational acceleration
H_{HPO}	[m]	pressure head
$\dot{m}_{inlet}$	[kg s^{-1}]	inlet mass flow rate
n	[s^{-1}]	rotational speed
p	[Pa]	static pressure

Greek letters

α	[-]	oil concentration
ρ	[kg m^{-3}]	mixture density
η	[-]	separation efficiency

Subscripts and Superscripts

CF	Coriolis mass flowmeter
HPO	high-pressure outlet
inlet	flow properties at inlet
LPO	low-pressure outlet
Sep	separation
OiW	oil in water
ppm	parts per million
rpm	revolutions per minute
PTJ	Pitot-tube jet-pump

1. MOTIVATION/BACKGROUND

Environmental efforts due to water pollution are becoming increasingly relevant for society. Disasters are becoming more frequent and oil is a growing threat to oceans and rivers [1].
In 2010 more than 800 million litres of crude oil spilled into the Gulf of Mexico caused by the *'Deepwater Horizon'* disaster. There have also been plenty of examples of oil spills in past years. E.g., the accident off Mauritius in 2020, when a tanker sank off the coast and 1,000 tons of crude oil spilled. In Norilsk (Siberia) an industrial accident occurred in which 21,000 tons of diesel oil spilled into the surrounding rivers. It was attempted to build barriers around the contaminated areas, but this takes too much time and oil was also detected behind those barriers. Alternatives, like the use of chemicals and controlled burning might have worst effects on the ecosystem than the oil itself [2,3].

Even in Germany there is a need for an innovative technical solution, to remediate water after illegal oil disposal in lakes, truck accidents polluting the surrounding rivers with their fuels, or most recently the disastrous floods in parts of Germany; oil tanks from basements that leaked, and spilled fuel from vehicles contaminated surface water and groundwater.

No existing solution is fast, scalable, and robust enough to meet all these challenges. Our approach relies on a novel Pitot-tube Jet-Pump (PTJ) to separate multiphase mixtures based on the prevailing centrifugal forces, and transport afterward the separated, pure phases. Thanks to the simultaneous separation and pumping, high separation rates can be achieved and the purified water can be returned to the sea/watershed in the shortest possible time.

2. ADAPTED PITOT-TUBE JET-PUMP

The modified PTJ pump is an innovative solution for integrating oil-water separation and transport of the two separated phases. It has been developed at the *Laboratory of Fluid Dynamics and Technical Flows* in Magdeburg within the last years, in cooperation with an industrial partner [4–7].

The standard PTJ pump is an unconventional, single-stage radial pump. It is generally used for strongly increasing the pressure head and consists of three main elements: The rotor, the impeller and the stationary Pitot tube. Figure 1 shows a PTJ pump. Rotating components are marked in yellow, while the stationary components are red or grey. The fluid enters the casing through an impeller. It rotates in the rotor with almost the same speed as the rotor walls. The Pitot tube (red in Fig. 1) extends in radial direction from the rotation axis almost up to the inner wall of the rotor (used as a centrifuge). At this point, the liquid reaches its highest velocity and enters the Pitot tube [4].

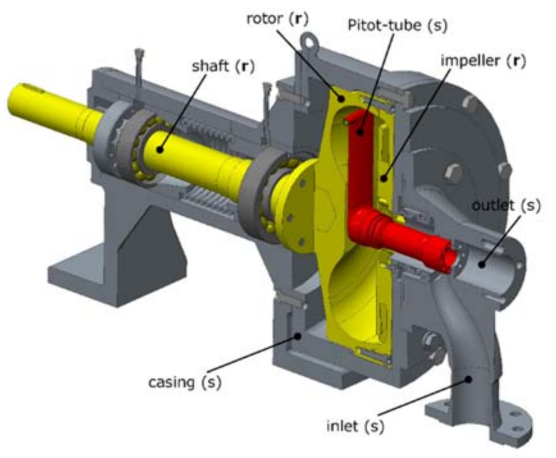

Figure 1. Standard Pitot-tube jet-pump [5].

Both, the name and principle of the whole system are based on the concept of Henri Pitot. Typically, a Pitot tube consists of a spindle-shaped metal body which is aligned in the flow direction and has a drilling on top of the Pitot tube. The drilling is connected to the surroundings. Ideally, the fluid flows parallel into the drilling. If the Pitot tube would be closed at the other end, the fluid in the tube would come to a complete standstill, allowing the measurement of total pressure. However, in a PTJ pump, the Pitot tube is not a (closed) measuring probe but an open diffuser. It is therefore connected to the high-pressure outlet and is typically constructed with a constant cross-sectional extension, though better designs are possible. Within the Pitot tube, the high kinetic energy of the fluid inside the rotor is converted into useable pressure energy. In that sense, the Pitot tube takes the same role as a volute casing in a classical centrifugal pump. The PTJ pump is widely used, in particular as a cleaning system in the food industry, for paper production and petrochemicals, but also for high-pressure water injection in gas turbines [6]. The main advantages of the PTJ pump are on one hand its simple and robust design and on the other hand the operating point, which is at low specific speeds. This means that very high pressures can be achieved at low mass flows.

Figure 2 shows a PTJ pump modified for separating fluid-fluid mixtures. As in the standard PTJ pump also the modified Pitot tube is stationary while the rotor rotates around the pitot tube. There is now an inlet and two separate outlets. The entering liquid, for instance an oil-in-water (OiW) emulsion, again experiences centrifugal forces within the rotor, working as a centrifuge. The heavier phase (water) is pressed toward the rotor walls, while the lighter phase (oil) gathers in the core close to the rotation axis. Hence, the water exits through the Pitot tube and experiences there a pressure increase before exiting through the high-pressure outlet (HPO), while the oil leaves the rotor through the low-pressure outlet (LPO).

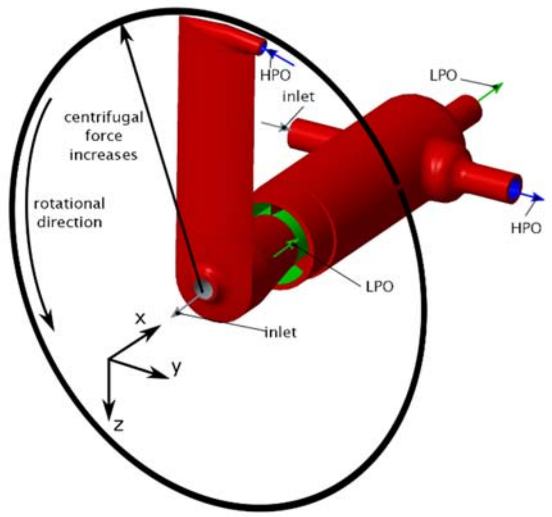

Figure 2. Modified Pitot-tube for separating liquids of different densities [5].

The central objective of the separation system is to obtain water with a high purity at the HPO. Four parameters define the operating conditions:

- rotational speed n
- inlet mass flow rate $\dot{m}_{inlet}$
- oil concentration α_{inlet}
- flow-split FS.

The rotational speed n and the inlet mass flow rate $\dot{m}_{inlet}$ are standard quantities for any turbomachine. The flow-split FS is specific to the PTJ pump and describes the ratio between the mass flow-rate at the outlets and at the inlet

$$FS = \frac{\dot{m}_{LPO}}{\dot{m}_{inlet}} = 1 - \frac{\dot{m}_{HPO}}{\dot{m}_{inlet}} \tag{1}$$

This non-dimensional quantity varies between 0 (all of the entering fluid leaves through the HPO) and 1 or 100% (all of the entering fluid leaves through the LPO). The value of FS is controlled during operation by a throttle valve.

Two parameters measure the resulting efficiency of the PTJ pump. The first parameter is the separation efficiency:

$$\eta_{Sep} = 1 - \frac{\alpha_{HPO}}{\alpha_{inlet}} \tag{2}$$

The separation efficiency is the ratio between the oil concentration at the HPO α_{HPO} and the oil concentration at the inlet α_{inlet}. If $\eta_{Sep} = 1$, pure water is found at the HPO. If $\eta_{Sep} = 0$, the oil content at the HPO is equal to the initial oil content at the inlet, and no separation occurs.

The second parameter is the pressure head at HPO, a standard quantity for turbomachines:

$$H_{HPO} = \frac{p_{HPO} - p_{inlet}}{\rho_{HPO} \cdot g} + \frac{v_{HPO}^2 - v_{inlet}^2}{2g} \tag{3}$$

It is possible to achieve a high separation efficiency η_{Sep} of the pumped water at HPO using the PTJ pump, as demonstrated by preliminary experiments. The corresponding experimental procedure is explained in the next section.

3. EXPERIMENTAL SETUP

The schematic setup is shown in Figure 3. The central component of the setup is the separation pump, shown with concentric yellow/blue circles. The water and oil for the experiments are stored in separate tanks. A pipe system connects the tanks to the rest of the system. The fine-adjustment valves are used to control the appropriate mass flows so that the oil content of the mixture can be set. The mass flows, as well as the temperatures and densities of oil and water, are measured at the Coriolis mass flowmeters (CF). The measured values are displayed directly on the CF, but also displayed and stored in the connected *Diadem* software. Check valves between the CF and the T-piece prevent communicating tubes which, amplified by the buoyancy of the oil, cause undesired mixing of the liquids during standstill. Before the mixture flows into the centrifuge, the reference pressure is measured.

Inside the centrifuge, the mixture is separated and due to the PTJ structure, the separated fluids flow from two separate outlets. The water is forced to the outer edge of the centrifuge due to centrifugal forces, where it is then removed at the head of the Pitot tube and pumped out of the centrifuge. A pressure gauge and a Coriolis gauge are attached to the HPO; thus, the pressure difference and the achieved pressure build-up can be determined. Mass flow, density and temperature are measured again via the CF. Based on the mass balance of density at the oil inlet, water inlet and at the high-pressure outlet, the residual oil concentration at the HPO can be determined. The oil flows out of the low-pressure outlet; the pressure is also measured there and the pressure build-up is calculated. However, no significant pressure build-up is expected at the low-pressure outlet, close to the rotation axis. Valves for fine adjustment of the mass flow can be found at both the HPO and the LPO. This allows to control the ratio of the mass flow rate between the two outlets, FS. These valves and adjustment possibilities are very important in order to adjust the operating parameters and to determine its influence on the objectives.

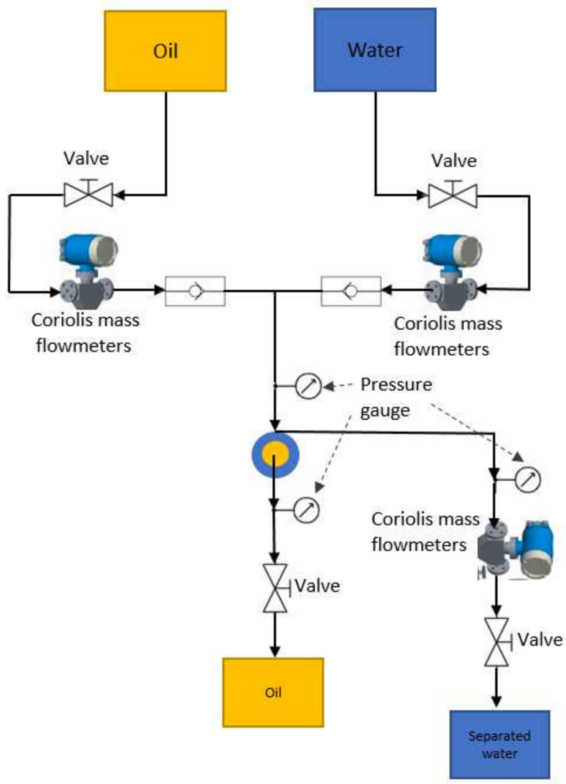

Figure 3. Schematic setup of the pilot plant

Figure 4 shows a section of the Pitot-Tube Jet-pump test rig during operation at the laboratory. The transparent rotor rotates while the pitot tube is stationary. It can be clearly seen here that an interface is formed during operation; the two immiscible fluids are reliably separated in the rotor. The operating point in the figure was set so that a separation efficiency above 99% at the high-pressure outlet (HPO) was achieved.

The *Diadem* software is used for data storage and evaluation of the recorded measurement data from the pressure and CF gauges. Not only could a separation efficiency of over 0.99 be detected here, but the collection tanks also show a clear separation of the water from the oil. Figure 5 shows the two collection tanks during operation. The left tank collects the purified water (high-pressure outlet), while the right tank collects the oil from the low-pressure outlet (LPO).

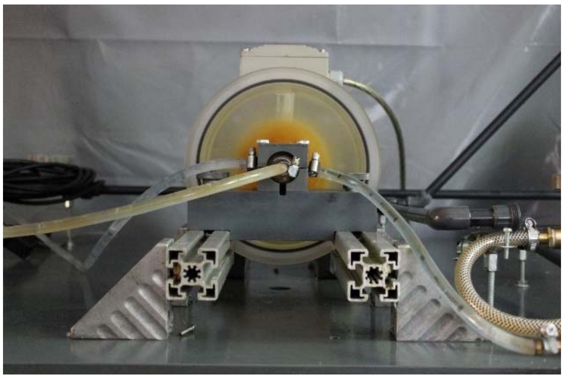

Figure 4. Centrifuge during operation

Figure 5. Containers after separating oil and water

4. EXPERIMENTAL RESULTS

For an efficient operation the separation efficiency and the pressure head need to be maximized simultaneously. These two parameters quantify the main objectives of the PTJ pump, as explained in Section 2. The next experiments investigate the influence of various operating parameters on the objectives. The purpose of these tests is to increase the pressure head while keeping the separation efficiency at a high level. This pressure build-up is necessary to allow the separation pump to function as a pump and not only as a simple separator – like a centrifuge.

The first correlation to be analyzed is the effect of the mass flow on the pressure head and the separation quality (Figs. 6 and 7). With an increasing mass flow at the inlet a decrease in pressure head and separation quality can be seen. The drop in head H_{HPO} with increasing mass flow $\dot{m}_{inlet}$ corresponds to a typical pump characteristic. The decreasing separation efficiency η_{Sep} with increasing mass flow $\dot{m}_{inlet}$ is easily explained by the decreased residence time within the rotor. A lower residence time means less time for the separation processes and thus a higher residual oil concentration at the HPO.

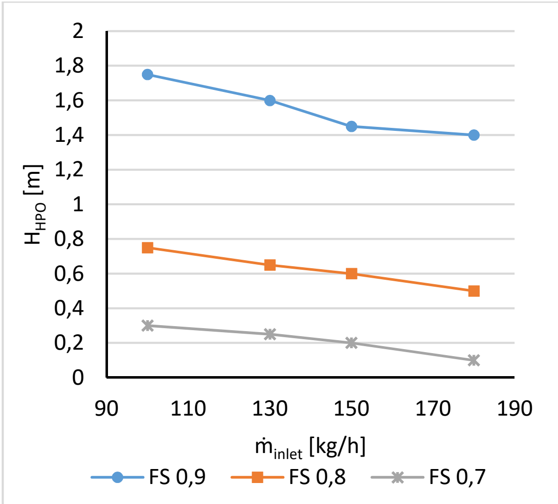

Figure 6. Pressure head H_{HPO} as a function of the mass flow $\dot{m}_{inlet}$

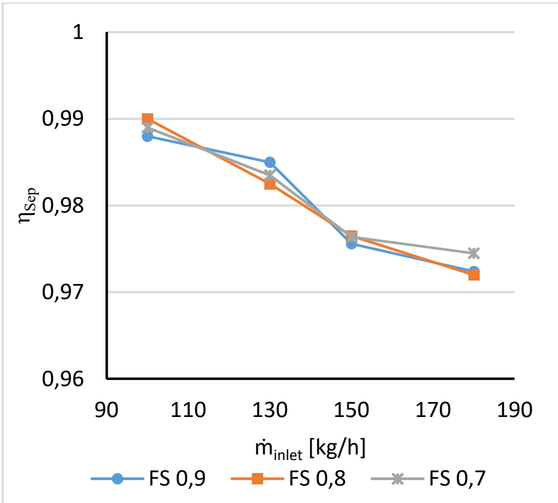

Figure 7. Separation efficiency η_{Sep} as a function of the entering mass flow $\dot{m}_{inlet}$

As already implied in the previous diagram it can be seen that the head H_{HPO} increases with an increasing speed *n*. This happens due to the higher kinetic energy of the fluid at higher tangential speeds and it corresponds to the typical behavior of centrifugal pumps according to the affinity laws (Fig. 8).

However, as the rotation speed n increases, the separation efficiency η_{Sep} decreases (Fig. 9). This behavior is explained due to the higher shear forces and the resulting smaller droplet size, leading to lower sedimentation velocities and hindering separation.

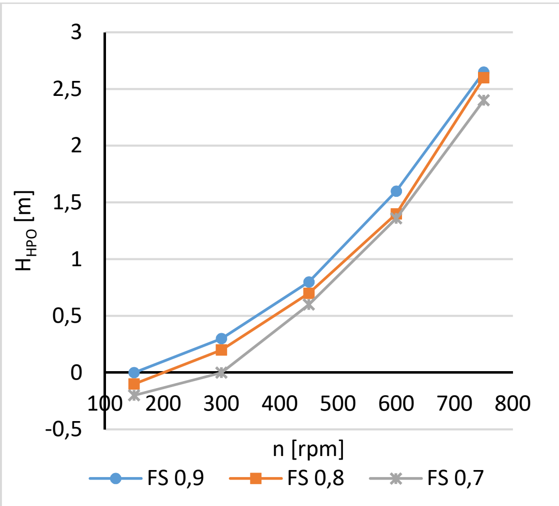

Figure 8. Pressure head H_{HPO} as a function of the rotational speed *n*

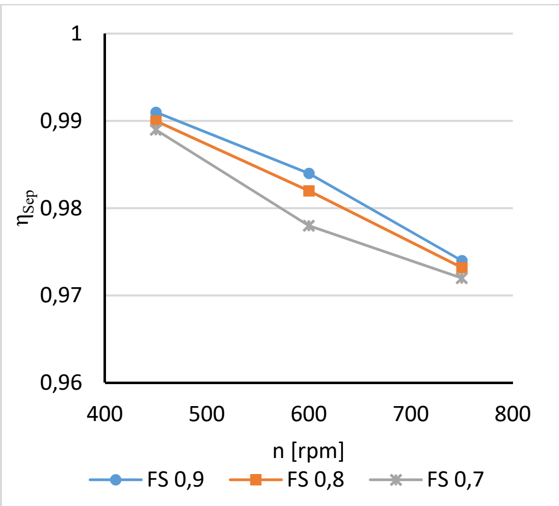

Figure 9. Separation efficiency η_{Sep} as a function of the rotational speed *n*

The operating parameter *oil concentration at inlet* α_{inlet} does not directly affect the objectives. The head H_{HPO} is not influenced by an increasing oil fraction as long as the mass flow $\dot{m}_{inlet}$ remains constant. The separation quality η_{Sep} is only affected if the oil concentration at the inlet α_{inlet} exceeds a certain value. If the oil core in the centrifuge becomes too large, the oil is discharged at the high-pressure outlet, which leads to an increasing oil concentration at the outlet, and to a decreasing separation quality η_{Sep}. However, if the oil content remains below a certain threshold, then there is no influence on the separation quality.

Previous studies have shown that a positive correlation exists between the flow-split *FS* and the separation efficiency η_{Sep}. As can be seen in Figure 10, separation efficiencies over 0.9 can only be achieved for a flow-split above 0.6. This correlation is relevant, since the negative effects of mass flow, oil concentration, or rotational speed can often be compensated by a higher flow split. This allows the separation efficiency to remain above 0.99 while the rotational speed is increased in order to achieve an increase in pressure head.

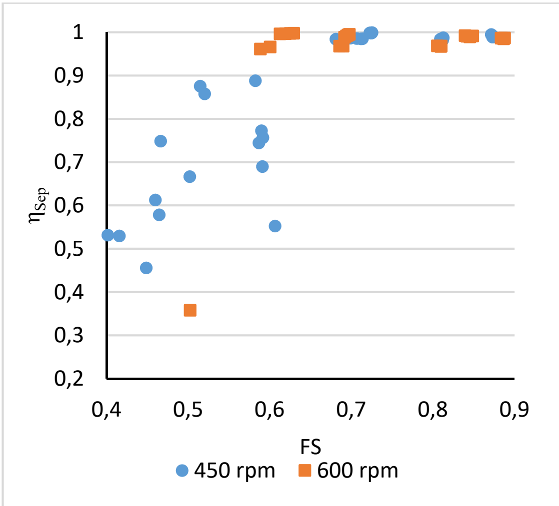

Figure 10. Separation efficiency η_{Sep} as a function of the flow-split *FS*

5. GEOMETRY OPTIMIZATION

In order to be able to use and operate the pump effectively, it is important to optimize the pressure head as well as the separation quality. In the tests performed so far, the influence of the boundary conditions on the separation pump have been determined and adjusted so that the separation quality is maximized.

Although an increase in pressure can be achieved by varying the operating parameters, this also has a significant effect on the separation efficiency. Furthermore, the pressure head alone is not sufficient to guarantee an efficient operation. Therefore, the geometry of the cover plate will be modified in the next steps. The blade geometry must be optimized to increase the pressure head without affecting the separation efficiency.

Figure 11 shows the reference model of the cover plate, without any blades. The preliminary tests were performed with this geometry.

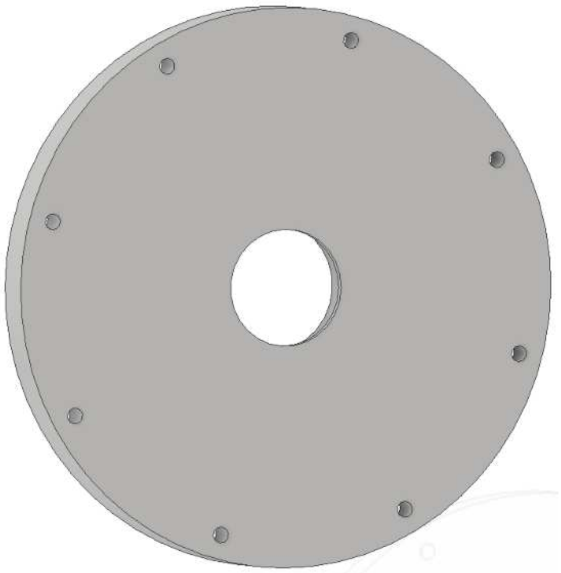

Figure 11: V0 Reference geometry

By using this geometry, a maximum pressure head of 2.5 m was achieved. The separation efficiency is constant at 0.99 (the measurement uncertainty of our system). This represents the initial situation. The pressure head is now to be maximized while maintaining the separation efficiency.

As a first variant, a cover plate was constructed in which four blades were attached. During operation, the blades rotate both in the oil and in the water phase. Figure 12 shows this blade geometry.

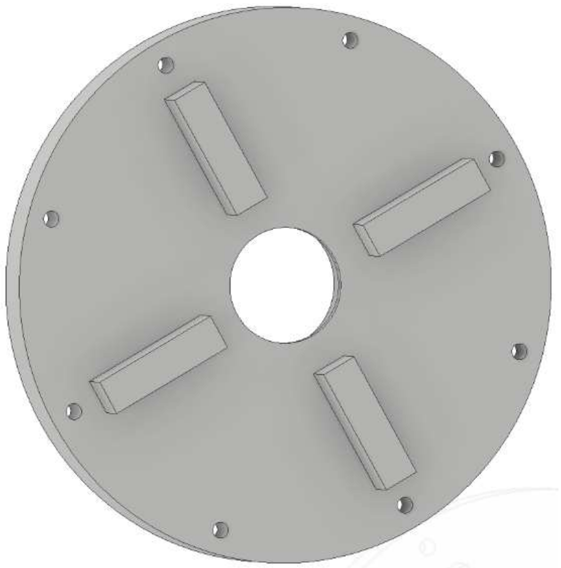

Figure 12: V01 Geometry

Although an increase of the pressure head to 4.2 m was achieved with V01, the separation efficiency decreased to 0.93. Hence, this geometry is not suitable. Due to the blades rotating in both phases, a strong back-mixing of the two phases is observed.

The next geometry variation is shown in Fig. 13.

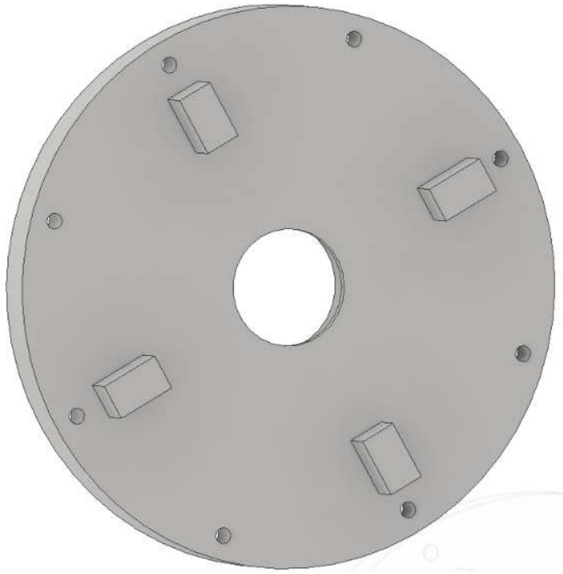

Figure 13: V02 Geometry

For the second variant, a blade cover was designed in which the blades have been shortened and rotate only in the water phase, so that back-mixing can be minimized.

With V02, the pressure head increases to 11.2 m while the separation efficiency stayed stable over 0.99 (the limit of our measurement system).

6. CONCLUSION

In this paper, optimal operating conditions of the Pitot-tube Jet-Pump have been discussed. The influence of these operating points on the objectives was determined. By varying the operating conditions, a separation efficiency above 0.99 could be achieved (this value being limited by the accuracy of the measurement system). The intention is to increase the pressure at HPO while maintaining optimal separation efficiency.

The increase in pressure is to be achieved by changes in the operating parameters and by constructive modifications.

It has been shown that these measures are successful. With a simple geometry involving shortened blades, attached to the cover plate of the centrifuge, a head of 11.2 m could be achieved, compared to only 2.5 m without any blade. Together with this massive increase of almost 350% in pressure head, the separation efficiency still remains stable at over 0.99.

In the next steps, the blade geometry will be optimized again.

ACKNOWLEDGEMENT

This Project was funded by the German Federal Ministry for Research (BMBF) as ZIM project (ZF4063102KO8).

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