

**Centrifugal Pumps as Extractors**

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The generation of dispersions with defined droplet size distributions is important for liquid-liquid extraction. In this respect, the capability of a centrifugal pump to generate dispersions was investigated for different operating points. For the analysis of the mixing process, a centrifugal pump was designed translucent. High-speed images reveal the mechanism of particle breakup. Optical measurement technology and image processing with neural networks were used to determine droplet size distributions. The influence of flow rate, rotational frequency and holdup are discussed for a paraffin oil-water system.

**Keywords:** Centrifugal pump, Horizontal pipe flow, Liquid-liquid dispersion, Process engineering

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1 Introduction

In the process industry, pumping, dispersing and coalescing of fluid mixtures are essential tasks, e.g., in liquid-liquid extraction processes. For this purpose, three main types of apparatus are generally used: pumps for transporting fluids, a mixer generating a dispersion and a settler for separating the phases. The idea is to realize all three tasks in the pump and piping system.

Liquid-liquid two-phase flows in centrifugal pumps are rarely investigated. In contrast, there exists already knowledge in gas-liquid systems. Gas entrainment can occur due to strong vortex formation in the storage tank [1]. Especially with nuclear power plants, chemical and oil industry, it is of great importance to use reliable centrifugal pumps, where one sometimes must cope with a large amount of gas, leading to a malfunction.

The motion of bubbles in the impeller region depends on the bubble size. It was found that small dispersed bubbles follow the fluid flow from the inlet to the outlet. Large bubbles, on the other hand, tend to be laterally deflected and remain close to the inlet region of the pump [2]. For this reason, efforts are being made to homogenize the two-phase flow with static mixers and axial inducers as well as geometrical adaptation of the centrifugal pump in order to be able to pump higher gas phase fractions until failure occurs [3].

Increasing the tip clearance gap reduces single phase performance in semi-open impeller centrifugal pumps by increasing secondary flow across the blades. In two-phase operation, however, this leads to higher particle breakup within the pump impeller. This shifts the abrupt performance drop of the centrifugal pump towards higher gas holdup and provides more robust two-phase pumping [4].

The gas-liquid flow inside the pumps can be categorized into four flow patterns: isolated bubbles flow, bubbly flow, gas pocket flow and gas-liquid separation flow. For isolated bubbles flow and bubbly flow, the bubbles in the impeller region follow the impeller movement. The bubbles in the volute flow follow the volute passage. Some bubbles, however, flow back into the impeller region in the area of the tongue. At higher gas volume fractions, even bubbles from the discharge pipe flow back into the volute [5]. It was found that bubble size distributions are normally distributed and that there is a shift towards smaller bubble diameters with increasing rotational frequency [6].

In the oil industry, liquid-liquid two phase flows (oil and water) are observed. For example, the influence of droplets on the centrifugal pump performance was investigated [4] and it could be found that almost no drop breakup takes place in the impeller channels on electric submersible pumps. The entrained droplets break before they enter the impeller channel, mainly in areas where they are faced to a sudden change in direction and momentum. The acceleration of the oil droplets reached hundreds of m·s⁻². Most of the oil droplets in the impeller channels had spherical and elliptical shape. The droplet movement in the impeller blade channels is dependent on the droplet size. For the low oil concentration considered in the experiments no coalescence could be observed [7].

Despite the negative effects of a two-phase flow, the dispersing effect of centrifugal pumps is already exploited for the continuous production of oil-water emulsions. Two bulk phases pass through a centrifugal pump in a bypass circuit. The result is a reliable reproducible emulsion with defined droplet size distributions (DSD) [8]. Research in the wastewater treatment for handling of multiphase flows have shown the influence of centrifugal pumps on the transport

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of oil-water emulsions. Morozova and Eskin [9] investigated the influence of centrifugal pumps on predefined emulsions and found that the number of small droplets increases over time when pumping in a loop.

A dispersion generated in the centrifugal pump must then be transported via horizontal and vertical pipes in order to make it usable for subsequent processes. Simmons and Azzopardi [10] investigated DSD in liquid-liquid flow for different flow regimes in vertical upflow and horizontal pipes. In horizontal pipes one can find different flow patterns, including stratified flow, stratified flow with interface mixing, double dispersion and water-in-oil dispersions. In vertical upflow, a generated homogeneous dispersion remains stable and no stratification can be observed.

The dispersion generated in a pump can be used for mass transfer at a certain residence time in vertical upflow or turbulent flow in horizontal pipes. Stratification in horizontal pipes with low mixture velocities can be used for separation. This alternative method of liquid-liquid extraction would save additional mixers and large separators.

2 Experimental Work

2.1 Centrifugal Pump Test Rig

For dispersion tests, a centrifugal pump test rig (see Fig. 1) was constructed that consists of two storage tanks, a booster pump, a gear pump, a static mixer, a radial centrifugal test pump and a gravity settler. Reversed osmosis water (0.01 μS cm⁻¹) from storage tank 1 is pumped by the booster pump at constant flow rate towards the measuring section. Paraffin oil as organic phase from storage tank 2 is injected by the gear pump into the pipe system upstream the static mixer with nominal diameter of 25 mm (DN 25) before entering the measuring section with DN 15. In order to evaluate dispersion characteristics, two optical multimode online probes (OMOP) [11] were integrated into the measuring section up- and downstream of the test pump. It is equipped with telecentric lenses and collimated transmitted light in order to detect shadowgraphic images of droplet swarms. The test pump is a transparent reproduction of the Schmitt MPN 101⁰ radial centrifugal pump made from acryl glass in order to allow high-speed photography of the two-phase flow within the pump. The pump has a specific speed of 22 min⁻¹, which categorizes the radial impeller as high head impeller. The half-open impeller with six blades has a diameter of 75 mm and a constant tip clearance of 2.4 mm. The pump volute is annular shaped and has a tangential discharge nozzle. Suction and discharge nozzles are both connected to a DN 15 pipe. Rotational frequency is regulated via a speed-controlled 0.18-kW three-phase motor from JS Technik. The two-phase flow leaves the measuring section for separation into two coherent liquid phases in a gravity settler, before re-entering into the storage tanks.

Figure 1. Centrifugal pump test rig.
2.2 Experiments

For evaluation of dispersion characteristics, different operating points of the centrifugal pump are investigated at flow rates \( Q \) from 500 to 900 L h\(^{-1}\) (see Tab. 1). Holdup was varied in the range of 1 to 5 vol % and the rotational frequency was varied from 0 to 2030 rpm. For each experiment, OMOP measurements were taken up- and downstream of the test pump. For dispersion tests, paraffin oil FC 2006 and deionized water were used. Properties are listed in Tab. 2. The experiments were conducted at a temperature of 22 °C.

Table 1. Experiments for different operating points.

| Flow rate [L h\(^{-1}\)] | Holdup [vol %] | Rotational frequency [rpm] |
|--------------------------|----------------|----------------------------|
| 500                      | 1 / 5          | 0 / 290 / 870 / 1450 / 2030 |
| 700                      | 1 / 5          | 0 / 290 / 870 / 1450 / 2030 |
| 900                      | 1 / 5          | 0 / 290 / 870 / 1450 / 2030 |

Table 2. Material properties.

|                       | FC 2006 | Deionized water |
|-----------------------|---------|-----------------|
| Density [kg m\(^{-3}\)] | 823     | 997             |
| Viscosity [mm\(^{2}\)s\(^{-1}\)] | 9.50    | 1.004           |
| Interfacial tension [mN m\(^{-1}\)] | 37      | –               |

Image processing was done using a convolutional neural network (CNN), like U-Net introduced by Ronneberger et al. [12]. It was trained by computer-generated images and not by experimental data as described by Schäfer et al. [13]. For a determination of DSD in the transparent centrifugal pump, the images were analyzed manually by setting marker points at the droplet edges.

3 Results and Discussion

The development of different characteristic diameters, such as \( d_{10}, d_{20}, d_{30} \) and \( d_{32} \), were examined, assuming that the particles are axisymmetric. Fig.2 shows exemplarily the development of the characteristic diameters as function of the number of droplets for a flow rate at 700 L h\(^{-1}\) at a holdup of 1 % and a rotational frequency of 870 rpm. In Fig.2 (right), the average deviation to the previous 250 particles is plotted. As one can see, the characteristic diameters at the beginning of the measurements vary strongly. This fluctuation decreases in the subsequent development and almost constant values are obtained for each diameter. This is also reflected in the representation of the percentage deviations. A maximum deviation of 0.5 % is observed at an analyzed droplet number of 3000.

The DSD for the variation of the rotational frequency for a constant flow rate of 900 L h\(^{-1}\) and a holdup of 1 % is shown in Fig. 3. Log-normal distributions represent the volume-based distribution functions with high determination coefficient of around 99 % for each measurement. This is in good agreement with literature for entrained air bubbles in centrifugal pumps [14]. Exemplarily, discrete measurement of the volume-based DSD is shown for 0 rpm. For a better clarity, the discrete measurement points have been omitted for the other rotational frequencies. It can be observed that with increasing rotational frequency the larger droplets break up and the amount of small droplets increases. As the speed increases, the DSD becomes narrower. In Fig.3 (right), exemplary images obtained by the OMOP are depicted.

Fig.4 shows the Sauter mean diameter (SMD) dependence of the investigated system on the total flow rate and rotational frequency for a holdup of 1 %. The curves have a different starting diameter at 0 rpm since the same static mixer was used for all experiments. The SMD up- and downstream the test pump at 0 rpm show similar results. As to this, for simplification only the SMD at 0 rpm are given in the diagrams. For rotational frequencies of 0 and 290 rpm the SMD for 900 and 700 L h\(^{-1}\) are the same. The SMD at 500 L h\(^{-1}\) becomes smaller in this frequency range. At higher rotational frequencies the SMD decreases for all the experiments and the different measured drop sizes from the different operating conditions converge at a frequency of 1450 rpm. It can be concluded that at frequencies higher than 1450 rpm, the influence of the volumetric flow rate diminishes for the investigated setup.

A similar trend exists for the higher holdup of 5 % (Fig. 5), despite the fact that the droplet size remains nearly

![Figure 2. Evolution of characteristic diameters at 700 L h\(^{-1}\), 870 rpm and 1 % holdup.](image-url)
unchanged for the first two investigated frequencies. At frequencies of 1450 rpm and higher a similar drop size can be observed for the investigated cases.

Fig. 6 shows a section of an impeller blade during pumping operation. The direction of rotation of the impeller is counterclockwise. There is little to no breakup in the impeller channels. A strong drop deformation takes place due to high shear forces primarily at the leading edge of the impeller. As a result, the droplets break up at the leading edge of the impeller before they reach a stable droplet size.

Previous work about gas entrainment in centrifugal pumps also shows that bubbles with a specific size become stable at a radius equal to the pump intake [14, 15]. For quantitative analysis of the change in SMD 1500 droplets have been evaluated in the impeller channels manually. Tab. 3 shows...
Since the droplets downstream the pump are small to very small droplet sizes at the pump outlet for 700 and pump inlet to medium droplet sizes in the impeller channel at 870 rpm show a successive transition from large SMD at the inlet breakage occurs inside the centrifugal pump. The SMD from high-speed analysis inside the pump has negligible deviation from OMOP measurements at the inlet and outlet. Measurements with higher rotational frequency of 870 rpm show a successive transition from large SMD at the inlet to medium droplet sizes in the impeller channels to small droplet sizes at the pump outlet for 700 and 900 L h\(^{-1}\). Since the droplets downstream the pump are smaller than inside the pump it can be concluded that droplet breakage in the pump has not yet terminated in the impeller region. Droplet breakup must also occur in the non-optically accessible discharge nozzle.

### Table 3. Sauter mean diameter analysis at pump inlet, in pump and at pump outlet

| Flow rate [L h\(^{-1}\)] | Holdup [vol %] | Rotational frequency [rpm] | \(d_{32,\text{in}}\) [mm] | \(d_{32,\text{pump}}\) [mm] | \(d_{32,\text{out}}\) [mm] |
|--------------------------|----------------|--------------------------|---------------------|-------------------|-------------------|
| 700                      | 1              | 290                      | 0.455               | 0.461             | 0.456             |
| 700                      | 1              | 870                      | 0.455               | 0.378             | 0.330             |
| 900                      | 1              | 870                      | 0.334               | 0.290             | 0.234             |

The SMD from OMOP measurements and high-speed analysis. At 700 L h\(^{-1}\) and a pump frequency of 290 rpm no breakage occurs inside the centrifugal pump. The SMD from high-speed analysis inside the pump has negligible deviation from OMOP measurements at the inlet and outlet. This is expected for this low energy input and, thus, validates the high-speed analysis with the OMOP measurements. Measurements with higher rotational frequency of 870 rpm show a successive transition from large SMD at the pump inlet to medium droplet sizes in the impeller channels to small droplet sizes at the pump outlet for 700 and 900 L h\(^{-1}\). Since the droplets downstream the pump are smaller than inside the pump it can be concluded that droplet breakage in the pump has not yet terminated in the impeller region. Droplet breakup must also occur in the non-optically accessible discharge nozzle.

4 Conclusions and Outlook

In this study, a transparent model of a regular radial centrifugal pump was investigated for two-phase flow, as a pump mixer in liquid-liquid extraction. The aim was to investigate the dispersive effect of centrifugal pumps and to determine the internal particle breakage process. Investigations were carried out by variation of rotational frequency, flow rate and holdup. The following conclusions can be drawn:

1) The SMD decreases with increasing speed and with decreasing flow rate.
2) Above a certain impeller speed, the influence of speed on breakage is more dominant than the influence of flow rate in the considered volumetric flow range. At rotational frequencies of 1450 rpm and above almost the same SMD was measured for all flow rates (500 to 900 L h\(^{-1}\)).
3) Breakage mainly takes place at the blade leading edge and in the housing close to the discharge nozzle.
4) Breakup almost does not occur in the impeller channel.
5) The breakage of the droplets does not end in the pump housing but continues in the discharge nozzle.
6) The log-normal distribution is an appropriate representative distribution function for dispersions generated in centrifugal pumps.

Experiments have shown that centrifugal pumps can do more than just transport fluids. They have a great potential to be used as dispersion units for liquid-liquid extraction processes. DSD can be adapted for different process requirements by varying the rotational frequency or the flow rate. The pipe system has to be included in the overall concept, especially when residence time and mass transfer is considered. It can be expected that extractive processes can be designed with higher energy efficiency by a reduction of additional mixers and of the separator dimensions.

Since coalescence can be expected, further studies concerning the operation of the pump at higher holdup are planned. Computational fluid dynamics will be used in addition to study the influence of pump geometry and pump discharge nozzle. Zones of increased energy dissipation will be localized to enable comparisons with experimentally determined breakup and coalescence. The variation of droplet size will be accounted by population balance modeling.

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Symbols used

- \(d_{10}\) [mm] arithmetic mean diameter
- \(d_{20}\) [mm] surface mean diameter
- \(d_{30}\) [mm] volume mean diameter
- \(d_{32}\) [mm] Sauter mean diameter

Abbreviations

- CNN convolutional neural network
- DN nominal diameter
- DSD droplet size distribution
- OMOP optical multimode online probe
- SMD Sauter mean diameter

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Centrifugal Pumps as Extractors
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Communication: Centrifugal pumps can be used as mixing device in liquid extractors. Besides pumping, dispersions with defined droplet size distributions can be generated in liquid-liquid two-phase flows. According to a change of operating parameters the influence on drop size distributions is given.