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Rim Driven Thruster as Innovative Propulsion Element for Dual Phase Flows in Plug Flow Reactors

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Abstract: The purpose of this work was to test a new setup to pump water with entrained air for application in gas fermentation. A mixed flow, where gas is contained in a liquid to be pumped, rapidly reduces the efficiency of a conventional pump, due to the compressibility of the gas. It is not always possible to degas the fluid, for instance in gas fermentation, which is preferably carried out in tubular reactors (loop fermenters) to achieve a high conversion rate of the gaseous feedstocks. Method: In this work, a rim-driven thruster (RDT) was tested in a lab-scale, cold flow model of a loop reactor with 5–30% (by volume) of gas fraction (air) in the liquid (water) as alternative propulsion element (6 m total pipe length, ambient temperature and pressure). As a result, it was found that the RDT, in connection with a guiding vane providing swirling motion to the two-phase fluid, could pump a mixed flow with up to 25.7% of gas content (by volume) at atmospheric pressure and 25 °C and 0.5 to 2 m/s flow speed. In conclusion, an RDT is advantageous over a classic propulsion element like a centrifugal pump or axial flow pump for transporting liquids with entrained gases. This article describes the potential of rim-driven thrusters, as known from marine propulsion, in biotechnology, the chemical industry, and beyond, to handle multiphase flows.

Keywords: gas fermentation; loop reactor; mixed flow; entrained gas; pumping

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1. Introduction

Pumps are used in virtually all industries, to transport various liquids. The types and sizes are as diverse as the media, pressures, and flow rates that are required. A classic pump type, for instance, is a centrifugal pump. For high(er) pressure, piston pumps can be used, and for high(er) flow rates, axial flow pumps lend themselves to be deployed. The concept of a rim-driven thruster (RDT) [1] was proposed by Ludwig Kort (Germany) around 1940 but only became commercially practical in the early 21st century due to advances in direct current (DC) motor controller technology. As of 2017, commercial models of between 500 kW and 3 MW have become available from manufacturers such as Rolls-Royce, Schottel, Brunvoll, and Voith [2,3], for application in marine propulsion, but they have not been tested as pumping devices yet. Pumping is required, as an example, in plug flow reactors like loop reactors. Such loop reactors are commonly employed to produce polyolefins. Also, they find use in gas fermentation [4]. Gas fermentation is a process by which single cell protein (SCP) for feed and food, as well as biopolymers, amongst them polyhydroxyalkanoates (PHA), can be obtained from gaseous feedstocks such as CH_4, synthesis gas (CO/H_2) or CO_2 plus H_2. Further products of interest are ethanol [5] and biobased building blocks [6]. A high mass transfer [7–9] is desired to achieve good productivity. Airlift reactors [10,11] of different embodiments [12] have been tested, with and without an external pump, to scale up gas fermentation processes to make cost-effective commodities such as fuels, biopolymers, and proteins. Large-scale gas fermentation vessels utilize axial flow pumps [13]

1.1. Gas Fermentation

Fermentation is one of mankind's oldest technologies. Common processes deploy sugar as raw material, to obtain, e.g., ethanol as first-generation biofuel. Primary agricultural products are no scalable feedstocks for large-volume products such as polymers, because of competition over arable land with feed and food production, and resource consumption e.g., fertilizers, as experience with biofuels has shown, where sustainability concerns have led to research on second and third generation materials. The concept of gas fermentation, as the name implies, utilizes gaseous raw materials. For instance, aerobic methanotrophic bacteria can use methane (CH_4) as their sole carbon and energy source. Anaerobic acetogenic bacteria feed on synthesis gas (CO, and H_2 + CO_2). These C1-substrates [14] can be obtained from a wide range of raw materials, which makes large-volume products accessible. Production can be decoupled from agricultural raw materials, requiring low amounts of land, water, and energy. The feed gases can be derived from waste streams, e.g., CO from blast furnaces, CO_2 from industrial point sources, synthesis gas from biomass gasification, or methane from biogas. An integration with excess renewable energy, under a power-to-X concept, is also feasible, by providing green hydrogen from electrolysis and/or obtaining CH_4 from H_2/CO_2 methanation. Several companies are scaling up gas fermentation technology for various products. For recent reviews, see e.g., [15,16].

1.2. Pump Technologies for Multi-Phase Flows

While gases are moved using blowers and compressors, for liquids, different types of pumps have been developed, depending on the required flow rate and pressure (head). Solid particles in a pumped liquid can cause abrasion, which is counteracted by material selection. Gas bubbles in pumped liquids are a reason for concern, too, as they limit the pumps' efficiency, compare Figure 1.

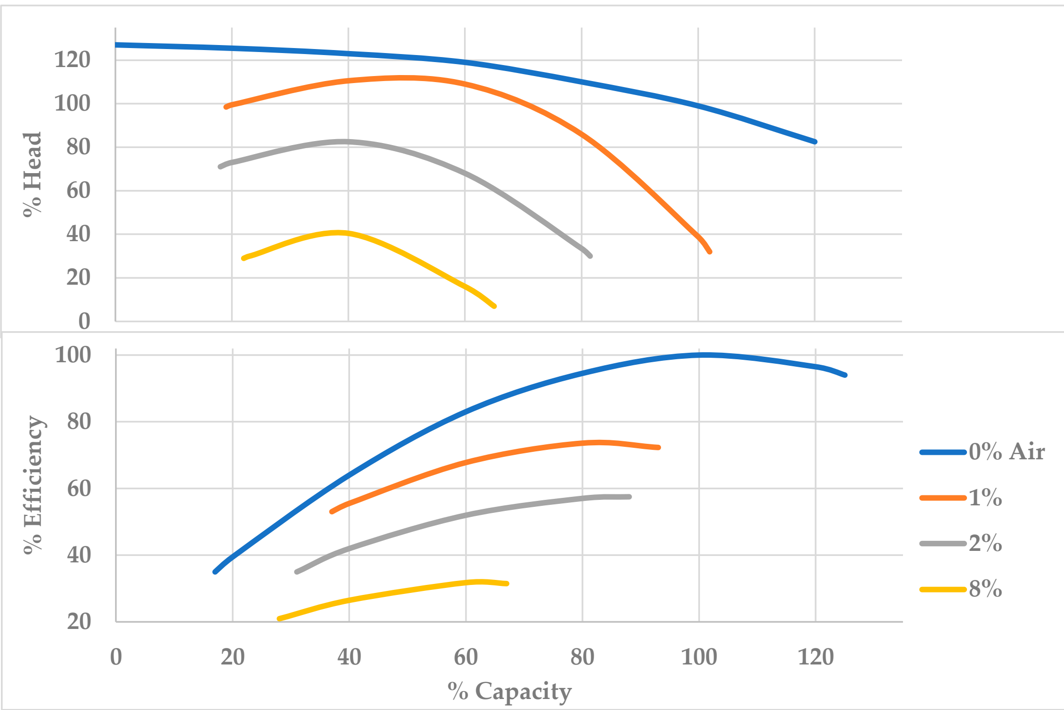


Figure 1. Schematic example for a set of pump curves as a function of gas fraction. Redrawn from [17].

As Figure 1 shows, already small fractions of gases in liquids to be pumped strongly reduce the flow rate. A treatment of all pump types would lead too far here, so the reader is kindly referred to a textbook on pumps, see e.g., [18].

A common approach to deal with gases in pumped liquids is to separate them, which, however, is not feasible in gas fermentation, where a gassed liquid has to be pumped since the gas needs to be present throughout the reaction volume and flow (turbulence) is required for a high mass transfer rate. Because of the large, desired flow rates, typically axial flow pumps are utilized in loop reactors, and efficiency losses due to the contained gas bubbles are accepted. Figure 2 shows different setups of bioreactors.

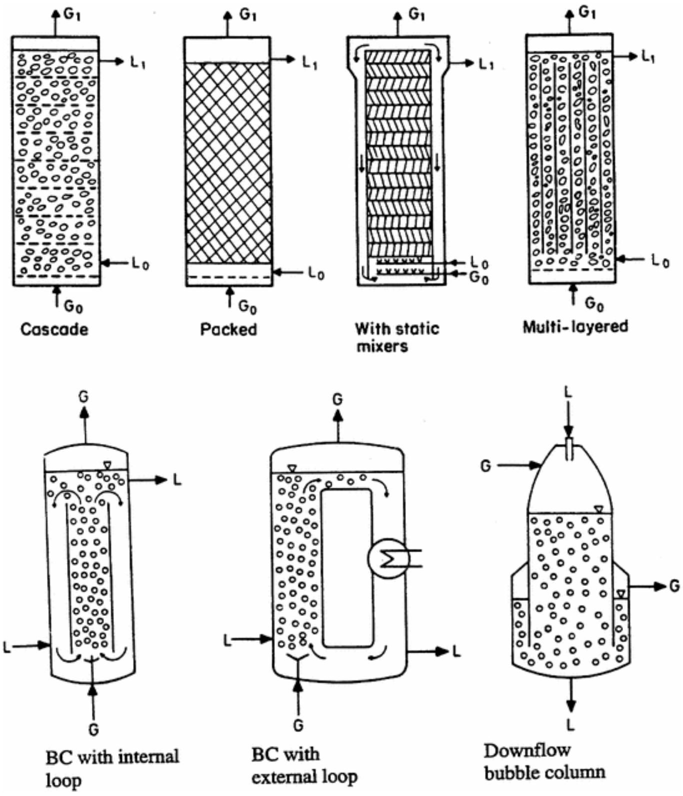


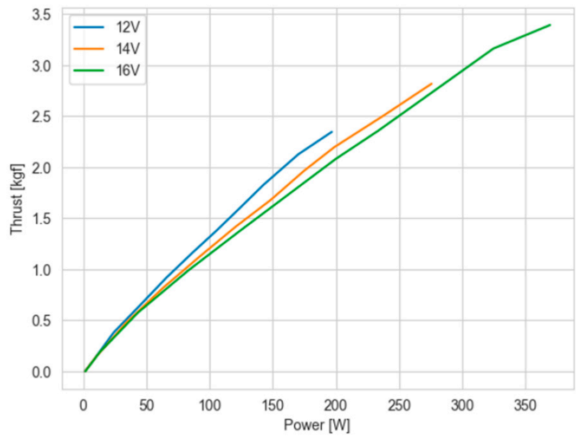
Figure 2. Different embodiments of bubble column reactors (BC). The BC with an external loop gives a homogeneous residence time distribution. Mass transfer is enhanced when an additional pump is deployed, which is how the loop reactor was developed. Source: [19] (reproduced with permission).

A classic stirred tank reactor is not ideally suited for gas fermentation because a significant portion of the feed gas will be lost. By contrast, a plug flow reactor (loop reactor) allows for high conversion rates of the feed gas, which is consumed as the fluid makes its round trip. It was found that a bubble column (BC) with an external loop can give a narrow residence time distribution, and the mass transfer is enhanced by increasing the flow speed, which is how the loop reactor was developed out of the bubble column and airlift reactor concepts. The difficulty which is thereby encountered is the gas bubbles in the liquid. This work aims at improving the pumping process in gas fermentation so that energy can be saved and the reliability of the process is improved. For a review of 2-phase emulsion flows, see [20], which is out of the scope of the current work.

2. Experimental

In this work, a small-scale laboratory installation was realized to experimentally test a rim-driven thruster (RDT) for pumping a mix of air in water at ambient temperature and pressure. A DiskDrive™ 50, made by a Swiss underwater robotics company called Hydromea that focuses on the miniaturization of underwater technology, was used in the experiments. DiskDrive™ is a patented innovation in the form of ultra-slim, rim-driven brushless thrusters. The device was developed as a thrust element for marine applications, e.g., drones, ships, and submarines. Their thin size and hubless design make them ideal for in-line pump applications, especially where waste or foreign objects are present in water. The hubless design eliminates the risk of propeller entanglements. The design contains no seals; it is pressure-proof, hydro-lubricated and oil-free. The simple design allows the user to swap propellers quickly and without any special tools. A picture of the RDT is given in Figure 3 together with its characteristic curves.

(**a**)



(**b**)

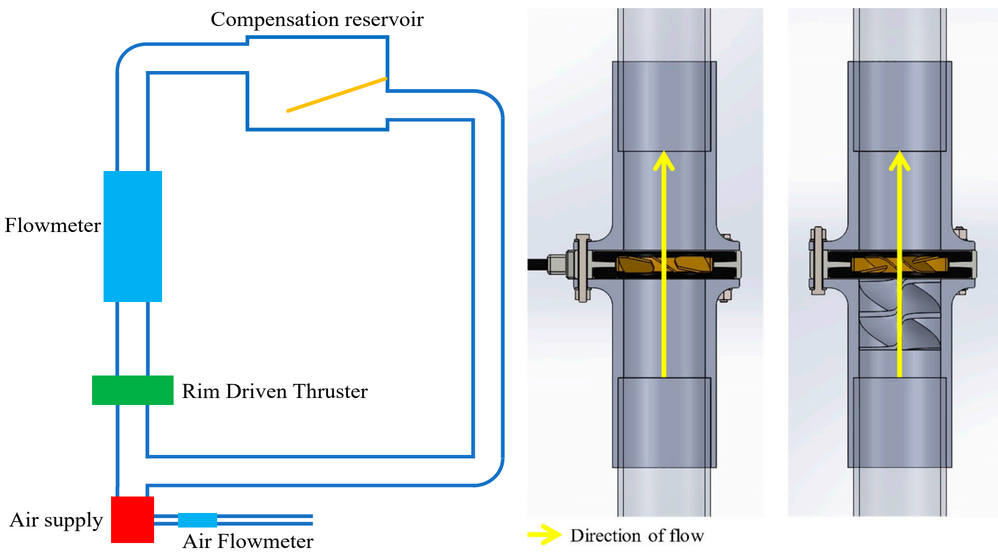
Figure 3. (**a**) Picture of the RDT. (**b**) Characteristics of thrust as a function of power and voltage.

In order to simulate a loop reactor for gas fermentation, a cold flow model with transparent tubes (inner diameter 50 mm, PMMA) was built and operated with water (liquid phase) and air (gaseous phase) without any bacteria at ambient temperature (25 °C) and ambient pressure (1 bar). The installation was rectangular with 2 horizontal legs (approx. 1.5 m in length) and 2 vertical ones (also 1.5 m in length) and was connected with 4 bends, so that the water/air mixture could be pumped in a loop, giving 6 m in total pipe length and at 0.5–2 m/s design flow speed, a "round trip" time of 3–12 s. The RDT was installed in the rising vertical leg, below the flow meter (rotameter, 1–10 m^3/h measurement range). "Rising" in this context means upward flow. Below the RDT, the optional guiding vanes (guide vanes, made from polyamide by additive manufacturing) were installed, and below them, the air was introduced, also metered. The top horizontal leg was equipped with a degassing vessel, to separate air from water. The water was recirculated through the second vertical leg "downcomer" and bottom horizontal leg, before being sent through the gas sparging section, guide vanes, RDT, and flow meter again. At the design flow speeds of >0.5 m/s, all gas bubbles were dragged downwards in the gas downcomer section together in the water phase. Figure 4 shows the setup.

The RDT was operated at a constant power of 300 W with 15 V (approx. 3000 rpm). It was equipped with either a hubless or hub-type impeller of simple geometry, see Figure 5 below.

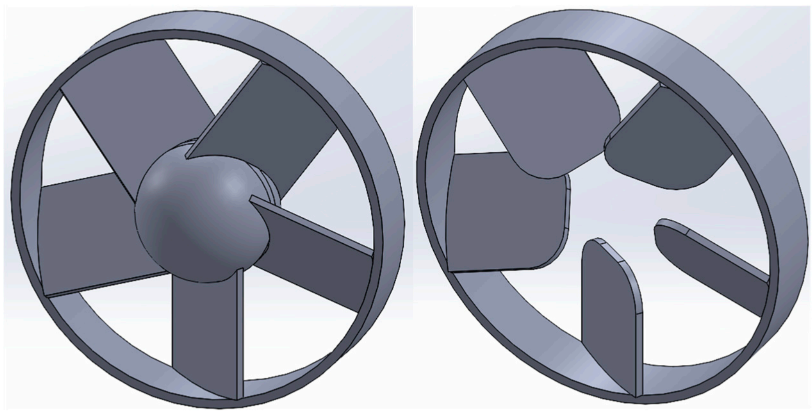
The 2 impellers (rotors) could be exchanged easily. A simple design was chosen for best comparability. The 2 parts, as well as the guiding vane and adaptors, were additively manufactured by SLA (selective laser sintering). The components were made from polyamide PA11 (Tensile modulus: 1600 MPa; Tensile strength: 48 MPa; Strain at break: 45%) on an EOS Formiga P110 (EOS, Krailling, Germany).

The experiments were carried out in the laboratory without microorganisms. The 2 vertical and the 2 horizontal sections were 1.5 m in length, given a square setup when viewed from the front as illustrated in Figure 4a. The uncertainty in our experimental setup was estimated to be within ±5% for all measured variables, including flow rate and gas content. Repeatability tests were performed, confirming the reliability and precision of the measurements under the specified conditions.



(a) (b)

Figure 4. Experimental setup with details on static guide vanes. (**a**) Schematic illustration of the experimental setup. Total pipe length 6 m, flow rate clockwise. (**b**) The adapter without guide vanes is on the left and with guide vanes is on the right. Guide vanes provide a swirl, pushing the gas phase to the center of the RDT, increasing its performance.



(a) (b)

Figure 5. (**a**) Impeller with hub. (**b**) Hubless impeller. 5 simple (plain) blades were used. The device is driven from the side, hence the name "rim-driven thruster" (RDT). Diameter = 50 mm.

3. Results and Discussion

The following Figures 6–8 show the results of the tests. In Figure 6, the air content in the fluid (water at ambient temperature) was varied between 0% and 13% (by volume) for the setups with hubless and hub-type impellers from Figure 5. The system was operated at ambient pressure (atmospheric, with hydrostatic pressure of approx. 0.15 bar in the lower horizontal leg.

At the beginning of the experiment, the flow rate was 0.7 m/s (100%). An air content of 7.5% could be pumped with the hub-type impeller, and an air content of 13.5% (by volume) was feasible with the other, hubless impeller in an otherwise constant setup. As Figure 6 shows, the hubless setup allows for a 5% higher gas fraction to be pumped. The loss in flow rate was approx. 40% between 5 and 10% of air content (0.4 m/s flow speed in absolute number). Figure 6 shows a setup without guiding vanes.

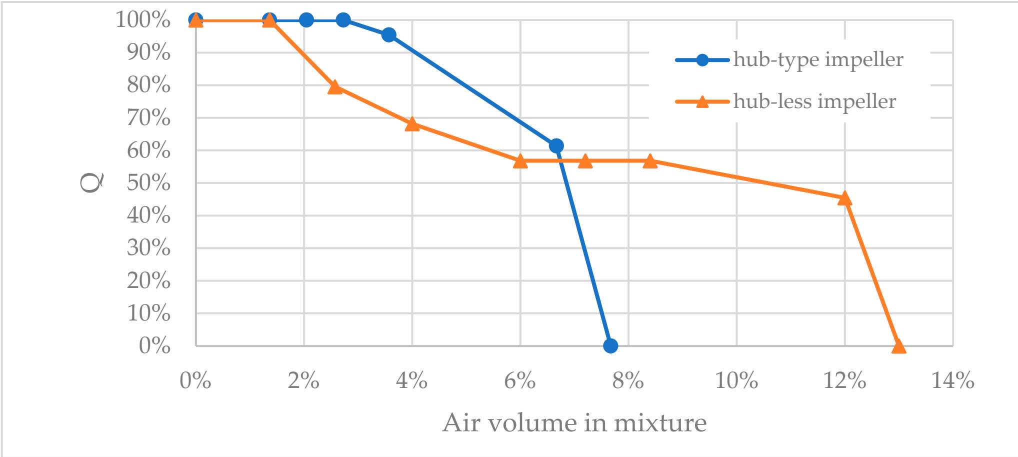


Figure 6. Total flow rate as function of air content in the fluid without guiding vanes. Impeller with hub (blue, circle) and hubless (orange, triangle). Configuration without guide vanes. The hubless setup can pump 5% more air fraction than the other one. Q = flow rate.

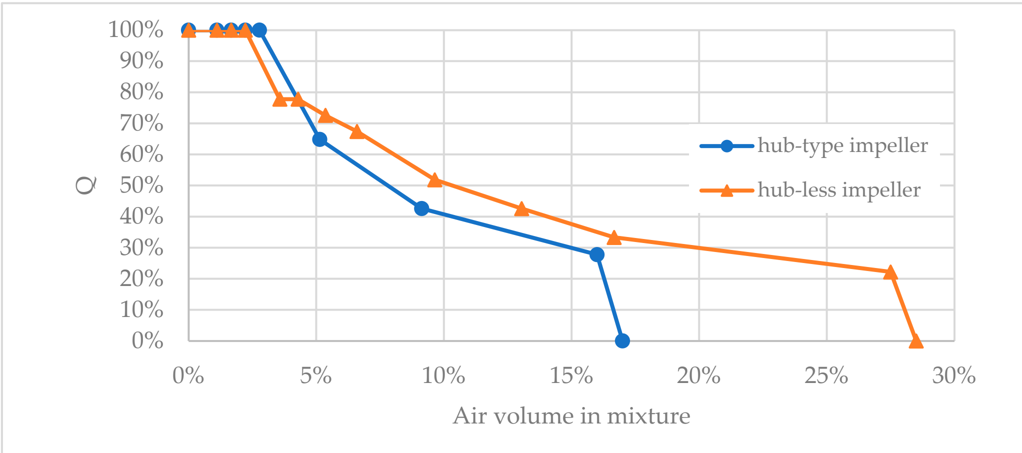


Figure 7. Total flow rate as function of air content in the fluid with guiding vanes. Impeller with hub (blue, circle) and hubless (orange, triangle). Configuration with guide vanes below the upwards-pumping RDT.

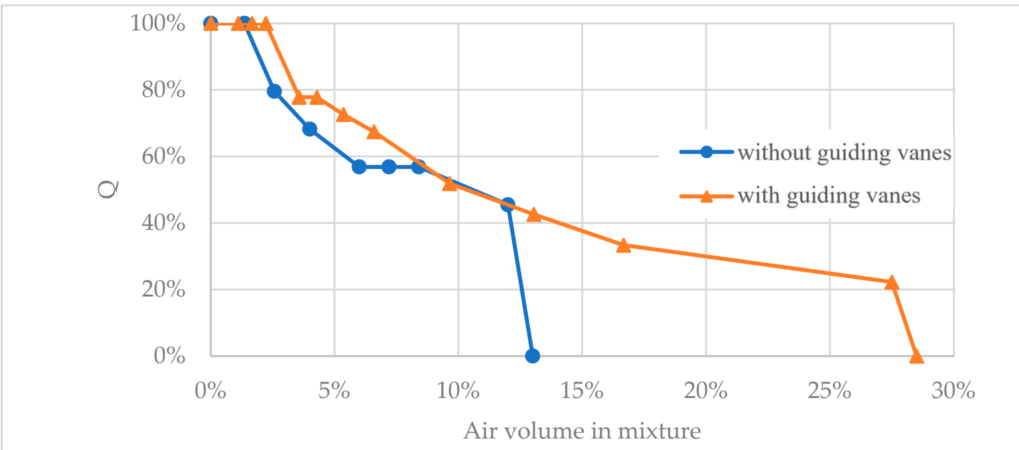


Figure 8. Total flow rate as function of air content in the fluid with hub-type impeller and direct comparison of the setups with guide vanes (orange line with triangles) and without guide vanes (blue with circles).

The two curves in Figure 7 were taken with the same setup as in Figure 6, but, in addition, a guiding vane had been positioned upstream of the RDT. That guiding vane was intended to provide swirling motion to the fluid and separate (at least partially) the gas and liquid fractions. The working hypothesis was that the rotation of the liquid would move the liquid toward the outer cross-section and the gas fraction toward the inside.

As Figure 7 shows, both impellers were able to transport approx. Double the gas content in the fluid, and the hubless setup was again able to transport more fluid. The beneficial effect of the guide vanes can be seen by direct comparison, see Figure 8.

In Figure 8, the results from the setup of a "hub-type impeller" with and without guide vanes are shown, and almost 15% more gas fraction could be pumped in combination with guide vanes. By depleting the outer section of the fluid from gases, a less compressible fluid was sent to the vanes, thereby allowing more efficient transport.

The highest flow rates were observed at 0% air admixing to the water, as would also have been the case with a conventional pump. For the configuration without and with guiding vanes, the maximum flow rates were 4.4 and 5.4 m^3/h, respectively. Both impeller types initially (at 0% air content) had the same mass flows. The flow was turbulent (starting at a Reynolds number of 31,000–38,000, which was still >3500 at a flow rate of 0.5 m^3/h. A mass flow of 3.5 m^3/h corresponds to a flow speed of 0.5 m/s (Re = 25,000), which is a typical value for gas fermentation in a loop reactor setup [21]

With pumps, it is known that guide vanes can enhance the angle of attack of the impeller, leading to increased pump efficiency. In this work, that effect was not studied deeply, as the guide vanes were used here only to inflict a swirling motion to the fluid flow, thereby pushing the air bubbles with lower density than the liquid to the center of the pipe. This work hypothesized that when the blades of the RDT can interact in the outer section of the pipe with a fluid depleted in gas bubbles and therefore being less compressible, the mass flow (and hence efficiency) should increase. As Figure 8 shows, the experiment confirmed the hypothesis.

In this work, a small-scale rim-driven thruster (RDT) was tested as an alternative propulsion element in a lab-scale cold flow model of a loop reactor, to pump a mixed flow of water and air. The hypothesis that the mass flow in the transparent loop reactor model can be further increased for a given gas fraction by using a guiding vane (swirl element) upstream of the rim-driven thruster could be confirmed. Also, it could be shown that the RDT is capable of handling large gas fractions of 20 and even 30% (by volume), particularly in the configuration with the swirl element. As expected, the hubless impeller proved to be advantageous by providing a higher flow rate and allowing the highest possible gas fraction to be pumped.

As mentioned, both impellers initially had the same total flow rate at an airflow of 0 (yet a 22% higher flow rate was observed with the guide vanes installed). The hub-type impeller maintains the same flow rate up to an airflow rate of 2.0 L per minute before dropping rapidly (its geometry mimics a conventional axial flow pump). The pump flow rate reaches 0 at an airflow rate of 3.5 L per minute with that hub-type impeller. The authors estimate the measurement uncertainty at better than $\pm 5\%$.

By contrast, the hubless impeller behaves differently from the hub-type impeller, with the total flow rate already dropping at a rate of 1.5 L per minute. Unlike the hub-type impeller, the flow rate remains constant for an airflow rate of 2.5 to 3.5 L per minute but drops again at an airflow rate of 4.0 L per minute until it reaches 0 at an airflow rate of 4.5 L per minute, which is almost 30% more.

When no guiding vanes are used, it is observed that the hubless impeller can operate with a gas content in the mixture of up to 12%, while the hub-type impeller is no longer able to pump the mixture with a gas content exceeding 6.67% (by volume). This shows that the hubless impeller can operate with almost twice the gas content in the mixture compared to the hub-type impeller.

In the setup with guiding vanes before (upstream of) the RDT, the possible air fraction is significantly higher. When using the hubless impeller, an air content of up to 27.5% in the fluid mixture could be achieved before the fluid was no longer pumpable. This amount is nearly twice that of the hub-type impeller. In the series of tests with guide vanes, the hubless impeller was always more efficient than the hub impeller, except for small air fractions of less than 5%.

Rim-driven thrusters are available commercially e.g., with 2.1 MW power (inner and outer diameter 2300 and 2850 mm, respectively) [3]. This is comparable to the power and radial dimensions of large axial flow pumps [22] for loop reactors for fermentation of several 100 m^3 volumes. From the current work, it can be inferred that RDT is an attractive pumping system for lab-scale to commercial-scale loop reactors and other pipe flow systems. Compared to standard axial flow pumps, the maintenance requirements should be reduced, since there are fewer moving parts. Fittings and bearings that connect an impeller to the drive via a shaft are avoided, making the system less complex to build and operate. The system can be scaled up to be used with aerobic fermentation processes (based on CH_4) and anaerobic ones (based on syngas, H_2, CO, CO_2). In aerobic systems, oxygen or air can be deployed. Also, it can be used in a wide temperature and pressure range. Thermophilic strains have their growth optimum at up to 65–70 °C [23], and elevated pressures are advantageous for gas fermentation, too [24].

Future research could study a cascade of several RDTs to compare their performance to axial flow pumps in series. A sequence of RDT can also be interesting to increase back mixing in a pipeline by operating an inner RDT in a reverse flow direction, possibly with shorter blades. For instance, the petrochemical industry uses inline blending, where the required pipe lengths could be reduced. In the marine industry, RDTs are appreciated for their robustness against debris (e.g., fishing gear), which can pass through easily. An RDT can be an advantageous pump in a loop reactor for polymerization, where insensitivity against agglomerates can be better than with conventional pumps. Another field of further study can be the cavitation behavior of RDT, as well as blade geometry optimization. A loop reactor is a plug flow reactor that allows for high conversion rates of the feedstock. The dual-phase flow—air in water—can be handled advantageously with the new setup in comparison to standard centrifugal or axial flow pumps.

The novel setup seems suitable for use with different microorganisms in bioreactors, from yeasts (fungi) to bacteria and algae. Algae can be grown in photobioreactors, where bubbling with CO_2 is required.

Entrained gases are known to reduce the efficiency of conventional pumps and, above a volume fraction of typically around 10–15%, can lead to a complete loss of flow, which is undesired and can lead to dangerous situations, for instance when a fuel flow is interrupted by vapor bubbles forming at low pressures. That situation is known as air lock in e.g., aviation. While degassing a fluid that needs to be pumped is not always feasible, existing solutions like grooved rotors [25] or inducers of centrifugal and axial flow pumps have shown limited results. In this work, an innovative setup consisting of a rim-driven thruster and guide vanes was tested in a lab-scale, cold-flow model of a loop reactor with 15–30% gas fraction (air) in water. It was found that the configuration allowed for higher flow rates and higher permissible gas contents, which is an advantage for mixed flows. In gas fermentation, a gas fraction in the tested range of around 10–20% (vol./vol.) is needed in a loop reactor to ensure high feedstock conversion rates and high productivities, since the feedstock gases CH_4, H_2, and CO show low solubility in water. Fine bubbles and high turbulence increase the k_La value [26]. It is expected that rim-driven thrusters can replace conventional axial flow pumps in loop reactors, as they are used in polyolefin polymerization as well as bioreactors in gas fermentation. Gas fermentation can convert gaseous feedstocks (methane, synthesis gas, and industrial off-gases) into value-added products such as biofuels, bioplastics, protein, and biobased building blocks such as mono- and divalent acids and alcohols. Biogas can be obtained from virtually any wet biomass, and synthesis gas is accessible through waste biomass (dry wood, municipal solid waste, etc.). There is a huge feedstock base, and by converting the carbon into a gaseous intermediate, contamination issues of the raw materials are circumvented. It is expected that gas fermentation will become a key technology in scaling up the circular bioeconomy, because of the flexibility, availability, and low costs of the underlying feedstocks—waste and side streams of biomass—and the RDT can make the required fermenters (loop reactors) more efficient.

4. Conclusions

By gas fermentation, commodities such as single-cell protein (SCP) and bioplastics can be made from gaseous feedstocks, amongst them CH_4 (e.g., from biogas) and synthesis gas (e.g., for biomass gasification). A major advantage is that non-agricultural feedstocks can be used. Also, the process is scalable, which is of particular importance e.g., for bioplastics, as they need to be produced in significantly larger quantities in the near future to replace fossil plastics [27]. For instance, polyhydroxyalkanoates (PHA), which are produced on the order of less than 100 kt/a, have the potential to replace a large fraction of commodity plastics such as PE, PP, and PVC. PHA are both biobased and biodegradable, also in the marine environment. It is becoming increasingly known as a concern that plastic articles produce large amounts of micro- and nanoplastics throughout their life cycle, and the majority of these particles cannot be retained. Significant sources of primary microplastics are car tire attrition plastics pellets (nurdles) from the plastics industry, and fibers from clothes (which often contain PPT and PET polyester fibers), while secondary microplastics stem from littering, and, as a matter of fact, the largest fraction of plastics waste today is mismanaged and littering an uncontrolled problem. PHA, with their versatility, can technically replace non-degradable plastics. Today, their production costs are high and driven by the feedstock (sugars, but also waste streams such as glycerol or waste cooking oil) [27]. By making PHA through gas fermentation, a broad feedstock base is made accessible, thereby allowing scale-up of PHA for low-cost mass applications such as packaging, where the setup with an RDT can offer significant advantages. Gas fermentation [28,29] holds great promise to be the platform technology for the circular economy.

The new setup in this work, which used a rim-driven thruster with an optional guiding vane to drive a mixed fluid in a bioreactor, was presented for the first time in this paper. This setup was shown to make gas fermentation more efficient. The authors trust that their setup can be deployed in a multitude of settings, saving energy and increasing flow rates where liquids contain gases.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: M.L. is employed by the company CIRCE Biotechnologie GmbH (Austria); A.L. is employed by the company Habibi Bikes (Germany). F.S. and M.V.E. are employed by the company Hydromea SA (Switzerland). The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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