Research Article

Development of a method for reliable power input measurements in conventional and single-use stirred bioreactors at laboratory scale

Power input is an important engineering and scale-up/down criterion in stirred bioreactors. However, reliably measuring power input in laboratory-scale systems is still challenging. Even though torque measurements have proven to be suitable in pilot scale systems, sensor accuracy, resolution, and errors from relatively high levels of friction inside bearings can become limiting factors at smaller scales. An experimental setup for power input measurements was developed in this study by focusing on stainless steel and single-use bioreactors in the single-digit volume range. The friction losses inside the air bearings were effectively reduced to less than 0.5% of the measurement range of the torque meter. A comparison of dimensionless power numbers determined for a reference Rushton turbine stirrer \( N_{P} = 4.17 \pm 0.14 \) for fully turbulent conditions) revealed good agreement with literature data. Hence, the power numbers of several reusable and single-use bioreactors could be determined over a wide range of Reynolds numbers between 100 and \( >10^4 \). Power numbers of between 0.3 and 4.5 (for \( Re = 10^4 \)) were determined for the different systems. The rigid plastic vessels showed similar power characteristics to their reusable counterparts. Thus, it was demonstrated that the torque-based technique can be used to reliably measure power input in stirred reusable and single-use bioreactors at the laboratory scale.

Keywords: Measurement / Power input / Single-use bioreactors / Stirrers / Torque

1 Introduction

Power input (or volumetric power input) is one of the most important engineering and scale-up criteria for bioreactors, since it is related to most unit operations, such as mixing, gas dispersion, gas–liquid mass transfer, heat transfer, and solid suspension [1–3]. Furthermore, power input is associated with hydrodynamic stress, which may affect cell growth and/or productivity of shear-sensitive production organisms [4–6]. However, unlike pilot and production scale agitators, only limited data on power input in laboratory-scale bioreactors are available, in particular for single-use bioreactors. In contrast to their reusable counterparts, these systems are delivered by the manufacturers that are preassembled, sterilized, and ready to use [7,8]. Furthermore, most single-use bioreactors are agitated by specially designed impellers making it difficult to compare them with their reusable counterparts.

As described in the review by Ascanio et al. [9], temperature- and torque-based measurement techniques prevail over others, something which is also confirmed by Table 1 that summarizes some studies on power measurements described in the literature [10–37]. Even though this overview is far from complete, it is obvious that the majority of these studies focused on standard stirrers, such as Rushton turbines [10–24], pitched blade impellers [10, 15, 20, 23, 25–27], curved blade impellers [12, 21, 24], or more modern stirrers, such as SCABA [14, 28] and Lightnin [16, 19, 27, 29–31] impellers. These are commonly used for agitation in baffled, flat-bottomed tanks. In fact, only one experimental study on power input investigations in single-use bench-top bioreactors was found [32], where the Mobius CellReady 3L, the UniVessel 2L SU, and the BioBLU 5L (formerly known as CelliGen BLU) were investigated for a few operational conditions that only examined water-like viscosities with Reynolds numbers in excess of \( 3.5 \times 10^4 \) [32]. This means that most
Table 1. Examples of power input measurements described in the literature

| System/stirrer | Geometrical details | Flow regime (Re) | Ref. |
|---------------|---------------------|------------------|-----|
| Load cell     | Rushton turbine and curved blade impellers in baffled, flat-bottomed, cylindrical vessel | Turbulent (8.86 × 10^4–2.72 × 10^5) | [24] |
| Electrical power | Minibioreactor with triple Rushton turbine | Transition–turbulent (1 × 10^3–6 × 10^3) | [33] |
|              | Four-bladed 45° pitched-blade and flat-blade impellers in a flat-bottomed, baffled mixing tank | Turbulent (2.5 × 10^5–7 × 10^5) | [26] |
|              | Rushton turbine, Prochem Maxflo T, and Lightnin A-315 in fermentor tank | Transition–turbulent (300–10^6) | [19] |
| Strain gauge  | Rushton turbine, Smith turbine, pitched blade impellers in baffled vessel | Transition–turbulent (100–8 × 10^4) | [15] |
|              | Two-stage four flat-blade turbines in unbaffled, flat-bottomed cylindrical vessel | Transition–turbulent (300–9 × 10^4) | [34] |
|              | Lightnin A-315 impeller in flat-bottomed cylindrical vessel with baffles | Laminar–low turbulent (1–10^3) | [29] |
|              | Xanthan fermentation with Rushton turbines, Prochem Maxflo T or SCABA 6SRGT impellers | Turbulent\(\text{a) (1.63} \times 10^6–5.72 \times 10^6\) | [28] |
|              | Prochem Maxflo T and Lightnin A315 in baffled, cylindrical, flat-bottomed vessel | Turbulent\(\text{b) (10^3–6.4} \times 10^9\) | [30] |
|              | Rushton turbine, Smith turbine, pitched blade turbine, and propeller in baffled, cylindrical flat-bottomed vessel | Turbulent (3 × 10^4–2 × 10^5) | [20] |
|              | Rushton turbine, 45° pitched blade impellers in baffled vessel | Turbulent\(\text{b) (9.6} \times 10^4–3.15 \times 10^6\) | [25] |
|              | Four-blade and six-blade Scaba SRGT impellers and Rushton turbine in flat-bottomed, baffled, cylindrical vessel | Transition–turbulent (10^3–0^6) | [14] |
|              | Rushton turbine, Smith turbine, Lightnin A315 in flat-bottomed, baffled, cylindrical vessel | Turbulent (9.5 × 10^4–2.52 × 10^5) | [31] |
|              | One or two 6-bladed disc turbines in baffled, cylindrical vessel under aeration | Turbulent | [22] |
| Dynamometer   | Baffled minibioreactor with Rushton turbine | Transition–turbulent (2 × 10^3–1.3 × 10^4) | [35] |
|              | 6-blade disk turbines, 2-blade flat paddles, and 4-bladed 45° pitch turbines in baffled, flat-bottomed, cylindrical vessels | Low-to-medium turbulent (6 × 10^3–10^5) | [10] |
|              | Rushton turbine in flat-bottomed, cylindrical vessel with baffles | Transition–turbulent (2 × 10^3–10^5) | [17] |
|              | Rushton turbine, six-bladed pitched turbine, EKATO Intermig, Lightnin A-310, and Chemineer HE-3 in baffled cylindrical vessel | Laminar–turbulent (40–10^5) | [16] |

\(\text{Continued}\)
available data are for moderate or fully turbulent conditions, but there is still a lack of available data for lower Reynolds numbers, which are relevant for shear sensitive production organisms and highly viscous, non-Newtonian culture broths. The latter applies, for example, to fungi-based or plant cell based cultures [38–40].

Particularly at laboratory scales, most measurement techniques suffer from a low degree of measurement accuracy. In temperature-based measurements, this lack of accuracy is related to low heat generation and losses to the surroundings. However, in torque-based setups it may be caused by low resolution of the sensors being used and/or high losses from agitator bearings and mountings.

Hence, the objective of the present study was to develop a measurement setup that is suitable for power input measurements in reusable and single-use bioreactors with working volumes in the one-digit liter range and to determine power input over a wide range of turbulence conditions. The system was designed to be flexible, easy to use, and reproducible, and should offer the possibility for automation. The DECHEMA single-use technology working group recommends estimating power input in single-use bioreactors by determining the impeller torque with torque meters [41, 42], but there is a lack of experimental data to validate this approach. Hence, a further aim of the present study is to generate experimental data that provides additional evidence for the DECHEMA recommendation. In order to encourage standardization of future work, the experimental method is described here in detail.

2 Materials and methods

2.1 Tested stirrers and bioreactors

If not mentioned otherwise, the power input in all bioreactors was determined with 2 L working volumes. Initially, the power input of a standard Rushton turbine with a diameter d of 53 mm (geometrical details provided in Table 2) was measured...
Table 2. Summary of the geometrical details of the stirrers investigated

| Configuration          | Vessel diameter D (mm) | Impeller diameter d (mm) | Off-bottom clearance z_M/D (−) | Impeller distance z_R/d (−) | Baffle thickness s_d/D (−) | Blade angle α (°) | Blade height b_d/d (−) | Baffle width B_S/D (−) | Baffle thickness H_S/D (−) | Baffle thickness a_S/D (−) |
|------------------------|-----------------------|--------------------------|-------------------------------|-----------------------------|--------------------------|-------------------|----------------------|--------------------------|--------------------------|---------------------------|
| Glass vessel with Rushton turbine | 130                   | 0.41                     | 1.00                          | 0.43                        | 0.43                     | 0.47              | 0.47                 | 0.47                     | 0.47                     | 0.47                      |
| SmartGlass 3L          | 130                   | 0.43                     | 0.87                          | 0.87                        | 0.87                     | 0.87              | 0.87                 | 0.87                     | 0.87                     | 0.87                      |
| SmartVessel 3L         | 130                   | 0.43                     | 0.87                          | 0.87                        | 0.87                     | 0.87              | 0.87                 | 0.87                     | 0.87                     | 0.87                      |
| UniVessel 2L SU        | 128                   | 0.41                     | 1.02                          | 1.02                        | 1.02                     | 1.02              | 1.02                 | 1.02                     | 1.02                     | 1.02                      |
| Mobius CellReady 3L    | 130                   | 0.55                     | 0.44                          | 0.44                        | 0.44                     | 0.44              | 0.44                 | 0.44                     | 0.44                     | 0.44                      |

Values are given for the lower/upper impellers.

n.a. = not available.

2.2 Measurement setup

The experimental setup is schematically shown in Fig. 1. The bioreactor vessels of interest were placed into a vessel holder and covered by a specially designed stainless steel head plate, which required the removal of the original head plates from the single-use bioreactors. An air bearing with an inner diameter of 13 mm and length of 50 mm (IBS precision engineering, Netherlands) was integrated into the head plate, in order to minimize the load free torque. The porous media bushing, which was supported with 5.5 bar pressurized air, provided an almost frictionless radial bearing (see also discussion below).

The dynamic torques were measured using a T20WN torque meter with a nominal torque of 0.2 Nm (HBM Hottinger Baldwin Messtechnik GmbH, Germany). The torque meter was held axially and centrically by a plate that was perpendicularly fixed to the head plate. According to the manufacturer, the sensor provides a measurement accuracy and RSD of reproducibility of ±0.2% and <0.05% of the nominal torque, respectively [44].

Two metal bellow-type couplings (Uiker AG, Switzerland) were used to install the torque meter between the brushless AC servo motor (AKM2, Kollmorgen, Germany) and the impeller shaft with a diameter of 13 mm (tolerance: −0.0076 mm) and length of 325 mm that was provided by Bioengineering AG (Switzerland). The bellow-type couplings compensated for parallel and angular misalignments as well as imbalances of the impeller shafts.

A PC-based RPDPmini control unit (kindly provided by Finesse Solutions Inc.) was used to control agitation, gas flow, and vessel temperature using μTruBio PC control software (v. 3.1). For data acquisition with Catman easy software (HBM, Germany), the torque sensor was connected to a Spider-8 AD converter (HBM, Germany).
2.3 Measurement procedure

The power input in the liquid $P_L$ was calculated directly from the effective torque ($M_{\text{eff}}$) and the rotational impeller speed ($N$) using Eq. (1):

$$P_L = 2 \cdot \pi \cdot M_{\text{eff}} \cdot N = 2 \cdot \pi \cdot (M_L - M_D) \cdot N$$

where $M_{\text{eff}}$ was obtained from the difference between the torque measured in liquid $M_L$ and the dead torque $M_D$ (torque without liquid inside the vessel). The dimensionless power number $N_p$ (also known as Newton number) was calculated using Eq. (2), where $\rho_L$ is the liquid density:

$$N_p = \frac{P_L}{\rho_L \cdot N^3 \cdot d^4} = \frac{2 \cdot \pi \cdot M_{\text{eff}}}{\rho_L \cdot N^2 \cdot d^5}$$

Even though the dead torque is very low, due to the air bearing, it was determined for each bioreactor for rotational speeds of between 50 and 900 rpm. However, the effective measurement range was limited to 300 rpm for all unbaffled examples due to vortex formation, which was limited to vortex depths of approximately 20 mm based on visual inspection. For each experiment, the vessels were filled with 2 L pure water or sucrose solution (20–60% w/w). The density and viscosity of the solutions were calculated based on data from [45]. Some reference measurements were also conducted using a DCAT 11 tensiometer (Dataphysics, Germany) and a MCR 302 Modular Compact Rheometer (Anton Paar Switzerland AG). All samples showed good agreement (relative deviation ≤5%) with the literature data. The impeller Reynolds numbers ($\text{Re}$) were then calculated using Eq. (3):

$$\text{Re} = \frac{N \cdot d^2 \cdot \rho_L}{\eta}$$

Using the recipe tool integrated in the $\mu$TruBio PC software, up to 110 individual measurements could be conducted in a single experiment. A typical measurement profile is shown in Fig. 2, where the impeller speed of the Rushton turbine was increased stepwise over time. After each adjustment of the impeller speed, peak values in the torque signal were observed. The peak torque signal values are related to the PID-based impeller speed controller and the initial acceleration of the liquid. In order to obtain a stable torque signal for each measurement point, the impeller speed was kept constant for 3 min and the peak torque after each speed adjustment was ignored. The measured torques ($M_L$) represent the average value obtained from a minimum of 240 data points with a measurement frequency of 2 Hz, as shown in Fig. 2. For the majority of measurement points, the RSDs of these mean values were lower than 3%, which indicates stable measurement signals.

3 Results and discussion

3.1 Determination of dead torque

Based on our experience, reducing the dead torque (i.e. torque during agitation without liquid) is one of the most important
Figure 2. Example measurement in the 2 L baffled glass bioreactor with a Ruston turbine. The impeller speed was increased every 3 min from 150 to 450 rpm in steps of 30 rpm. The black lines indicate the averaged torque values of the individual measurement steps.

Figure 3. Dead torque as a function of the impeller tip speed in the CellReady 3L bioreactor. The dashed line indicates the expected effective torque based on experimental data [32] and CFD models [46].

Factors for accurate power input measurements, particularly in laboratory-scale bioreactors, whereas often it does not need to be taken into account in larger vessels, as proposed by [19, 26, 34]. As can be seen from Fig. 3, the dead torque in the CellReady 3L bioreactor with the built-in bearing was between 9.4 and 20 mNm depending on the rotational speed, i.e. tip speed defined as:

$$u_{\text{tip}} = \pi \cdot N \cdot d$$

(4)

This is up to two orders of magnitude higher than the expected effective torque based on experimental data [32] and computational fluid dynamics (CFD) models [46]. For the Univessel SU, dead torque values of approximately 3 mN-m at a rotational speed of 150 rpm have been reported [32]. Considering the measurement accuracy of the sensors used, it is difficult to resolve such small effective torque values, i.e. differences in torque in liquid versus air. This is particularly true for low impeller speeds.

Using the zero-friction air bearing, the dead torque was effectively reduced to values between 0.4 and 0.9 mN-m. Thus, the ratio $M_{\text{eff}}/M_{\text{eff,predicted}}$ (based on the predicted effective torque) was only between 0.2 and 1.5. It should be emphasized that the residual dead torque in the CellReady 3L bioreactor was still the highest of all the tested bioreactors, which can be explained by the built-in impeller shaft fixing on the vessel bottom. During rotation, the impeller shaft collided with this fixing, a fact that can also be observed during cultivation experiments.

For the other agitators that were tested, residual dead torque values in the order of 0.1–0.5 mN-m were observed, which may be caused by minor radial misalignments of the impeller shaft.
reliable results, only those measurements for which the RSD of the nominal torque equal to ±0.2% of the nominal torque was considered in further experiments.

Furthermore, none of the tested agitators had a bearing near the vessel bottom. Consequently, even very small bends in or imbalances of the impeller shaft could result in significant oscillations during rotation, particularly in the single-use bioreactors, due to the fact that their shafts are made out of plastics and are, as a result, more flexible.

3.2 Measurement reproducibility

Measurement reproducibility was evaluated using a Rushton turbine operated at impeller speeds of between 100 rpm and 900 rpm (corresponding to tip speeds of 0.27 and 2.45 m·s⁻¹). As can be seen in Fig. 4, the SDs of the four replicates decrease as tip speed increases (from 21–<1%). This agreed with expectations due to the lower relative importance of the dead torque and the higher absolute torque at elevated impeller speeds. Qualitatively similar scattering has also been reported after comparisons between nine different laboratories (Members of the German GVC-VDI working group on mixing) that have measured power inputs for Rushton turbines and pitched blade impellers in 0.4 m diameter vessels, i.e. 50 L scale [47]. Using different measurement systems, including strain gauges, shaft-mounted torque meters, and turntables, system intrinsic deviations have been reported for measured values equal to 10% or less of the nominal torque. In the present study, the effective torque values obtained with the air bearing were between 0.5 and 16 mN·m, which corresponded to 0.25 and 8% of the nominal torque of the sensor that was used. Thus, reliable measurements were obtained for very low torque values related to the nominal measurement range.

It should be emphasized that most measurement points were within the confidence interval around the mean values based on the sensor accuracy provided by the manufacturer (i.e. ±0.2% of the nominal torque equal to ±0.4 mN·m [44]), which is presented as a dashed line in Fig. 4. Nevertheless, in order to ensure reliable results, only those measurements for which the RSD of replicates was <5% and the effective torque was ≥2 mN·m, corresponding to 1% of the nominal torque, were considered in further experiments.

3.3 Power input of standard and single-use agitators under nonaerated conditions

3.3.1 Rushton turbine

In Fig. 5, the determined power input of the Rushton turbine in a 2 L working volume is shown for Reynolds numbers between 1·10² and 3·10⁴. Using impeller speeds between 150 and 450 rpm, the Reynolds numbers were also influenced by the liquid density (998.2–1286.5 kg·m⁻³) and viscosity (0.89–58.5 mPa·s) of water and the sucrose solutions, with mass fractions of up to 60% w/w. As expected, individual profiles were obtained for each of the liquids, which showed that the power input increased as the Reynolds number increased. In the range investigated, it is well-known that the power number of the Rushton turbine is almost constant, as reported in several studies [10,12,16]. Hence, as can be seen from Eqs. (2) to (3), the power input P follows the relationship \( P \propto \text{Re}^\alpha \) for a constant impeller diameter. The experimental data agreed well with this correlation (with \( R^2 = 0.9992 \), see Fig. 5).

The power characteristic of the Rushton turbine is shown in Fig. 6. In agreement with expectations, the power number \( N_p \) decreased at low Reynolds numbers (100 < Re < ≈500) before it increased again above Re ≈ 200. Under fully turbulent conditions (Re > 10⁴), an almost constant power number of \( N_p = 4.17 ± 0.14 \) was obtained. These observations showed good qualitative agreement with data reported by Shiue and Wong [12] and Ibrahim and Nienow [16] for the Re range investigated (see Fig. 6). These authors have determined the power input of a single Rushton turbine in 20 and 40 L working volumes, respectively.
However, some discrepancies were found in a more quantitative comparison. The power numbers for \( Re < 300 \) seem to be overestimated by up to a factor of 2. Although such low Reynolds numbers are unlikely in animal cell cultures (even at very low impeller speeds) they may be relevant in plant cell cultivations, where increases in the broth viscosity by up to a factor of 40 have been reported [40], resulting in a considerably lower \( \text{Re} \).

Furthermore, the power number for fully turbulent conditions is up to 25% lower than that provided by reference data of \( N_p = 4.7 \) [16] and \( N_p = 5.5 \) [12]. As can be seen from Table 3, other researchers found \( N_p \) values for Rushton turbines in baffled vessels in a range of 3.6–5.9 [10,14–17,20,27,35,36,48], depending on the stirrer and vessel geometry used. Furthermore, an even lower \( N_p \) value of 3.36 has been reported for an unbaffled Rushton turbine agitated minibioreactor [35].

### Table 3. Summary of determined power numbers \( N_p \) for Rushton turbines under fully turbulent conditions for different geometries reported in the literature

| \( d/D \) (−) | \( z_d/D \) (−) | \( s/d \) (−) | \( t/d \) (−) | \( a/d \) (−) | \( b/d \) (−) | Baffles (−) | \( N_p \) (−) | Ref. |
|---|---|---|---|---|---|---|---|---|
| 0.43 | 0.41 | 0.027 | 0.026 | 0.29 | 0.20 | 3 | 4.17 ± 0.14 | This work |
| 0.25–0.75 | 0.16–0.75 | n.a. | 0.013–0.11 | 0.25 | 0.20 | 4 | 3.6–5.9<sup>a</sup> | [10] |
| 0.31 | 0.31 | 0.016 | 0.024 | 0.25 | 0.20 | 4 | 4.6 ± 0.4<sup>a</sup> | [48] |
| 0.33 | 0.33 | 0.075 | n.a. | 0.25 | 0.20 | 0 | 3.36 ± 0.09<sup>a</sup> | [35] |
| 0.33 | 0.33 | n.a. | n.a. | 0.25 | 0.20 | 4 | 5.10 ± 0.06<sup>a</sup> | [20] |
| 0.33 | 0.33 | 0.031 | n.a. | 0.25 | 0.20 | 4 | 5.1<sup>a</sup> | [15] |
| 0.33 | 0.25 | 0.008 | n.a. | 0.25 | 0.20 | 4 | 5.27 ± 0.05<sup>a</sup> | [14] |
| 0.41 | 0.33 | 0.009–0.076 | n.a. | 0.25 | 0.20 | 4 | 5.58<sup>b</sup> | [27] |
| 0.52 | 0.25 | n.a. | 0.013 | 0.25 | 0.20 | 4 | 4.6 ± 0.28<sup>a</sup> | [17] |
| 0.33 | 0.20 | n.a. | n.a. | n.a. | n.a. | 4 | 5.5<sup>b</sup> | [36] |
| 0.50 | 0.25 | n.a. | 0.05 | 0.25 | 0.20 | 4 | 5.0<sup>b</sup> | [16] |

In all literature studies, flat-bottomed vessels were examined, whereas the bottom was torospherical in the present work.

<sup>a</sup>These data were determined from (logarithmically scaled) graphs in the references given.

<sup>b</sup>No information is provided about the relationship between impeller thickness and the power number.

n.a. = not available.

However, it should be emphasized that direct comparison is difficult because of the differences in the geometrical details. The majority of data that has been published is for flat-bottomed tanks with four baffles, whereas in the present study, only three baffles were installed in a vessel with a torospherical bottom. The number and position of the baffles was given by the pre-configured ports in the head plate of the SmartGlass bioreactor. Furthermore, it has been demonstrated that the power number depends on the diameter ratio \( d/D \) [10,49] and the blade thickness [10,50], with a relationship of \( N_p \propto (s/d)^{−0.22} \) being reported [50]. This was confirmed by our own measurements in a 10 L scale vessel, where \( N_p \propto (s/d)^{−0.33} \) was determined (data not shown). Finally, it has been stated that the disc thickness also has a notable influence on the power number [10], but not all references from Table 3 provide the blade thickness used in their studies.

#### 3.3.2 SmartGlass bioreactor

Figure 6 also shows the power characteristic of the SmartGlass bioreactor, which is agitated by a combination of a top-mounted axial flow segment blade impeller (also known as an elephant ear impeller) and a modified disc blade turbine with tapered blades (i.e. a modified Rushton turbine), where the latter exhibits a predominantly radial flow in CFD simulations (data not shown). In the baffled vessel, the total power number continuously decreased from \( N_p \approx 6.5 \) for \( Re \approx 10^4 \) to \( N_p \approx 4.46 \) for \( Re > 10^4 \). This indicates that the reduced drag at the disc blade, compared to a classic Rushton turbine, is equalized by the second impeller.

In contrast, the power number in the unbaffled SmartGlass bioreactor decreased over the complete \( Re \) range investigated. Because this behavior has also been described for various other unbaffled agitators [1,49], it agreed with expectations and can be explained by centrifugal forces that result in fluid rotation and finally the formation of a vortex.

#### 3.3.3 SmartVessel bioreactor

Not entirely surprisingly, a very similar power characteristic for the SmartVessel bioreactor (Finesse Solutions, Inc.), the...
single-use counterpart of the SmartGlass 3L bioreactor, was also
determined (see Fig. 7). In the unbaffled vessel, a power num-
ber of \( N_P = 2 \) was determined for \( Re = 10^4 \). Small deviations
(with relative values in the range of \(-25 \) and \(+40\%\), depending
on the Reynolds number) between the single-use and multiuse
vessel can be explained by differences in the impeller designs.
Even though the shape of the impellers and their main geometric
parameters (\( d, z_R, z_M, b, \alpha \) in Table 2) were identical for both
the stainless steel and the plastic impellers, small modifications
resulting from the manufacturing process could not be avoided.
The blades of the plastic impellers were thicker (2 vs. 1.5 mm)
and their edges were rounded compared to the sharp-edged steel
blades. The bottom-mounted shaft holder in the SmartVessel
bioreactor may also have an impact on the flow structure below
the impellers.

Measurements with lower filling volume, where only the lower
impeller was covered, revealed a power number of 1.3 for \( Re =
10^4 \) (data not shown). Assuming negligible interactions between
the impellers, something that has been found for systems with
\( z_R/d > 1.2 \) \([49–51]\), the power number of the upper impeller
would be 0.65. This value is comparable to data for a
similarly shaped elephant ear impeller \([51]\) and also to data from
the two-stage segment blade impellers in the UniVessel 2L SU
bioreactor (see discussion below).

3.3.4 UniVessel 2L SU bioreactor
For the UniVessel 2L SU bioreactor, power numbers of between
5.08 and 1.13 were determined, depending on the Reynolds num-
bers \((1.5 \times 10^{2} < Re < 1.78 \times 10^{4})\). These \( N_P \) values are some-
what lower than experimental data reported by van Eikenhorst
et al. \([32]\), e.g. \( N_P = 1.9 \) for \( Re = 1.4 \times 10^{4} \). Interestingly,
their data showed the same relationship of \( N_P \propto Re^{-0.336} \) as
found in the present study for comparable Reynolds number
ranges. The different absolute values may be explained by the
different measurement techniques. While the dead torque in the
present study was considerably lower than the effective torque,
it was higher for the two experiments presented in the reference
study \([32]\), which presumably caused higher experimental er-
rors. However, the overall agreement between the two studies was
satisfactory.

3.3.5 Mobius CellReady 3L bioreactor
Finally, the power input of the Mobius CellReady 3L biore-
actor was determined for Reynolds numbers between \( 2.75 \times
10^{2} \) and \( 3.06 \times 10^{4} \). Due to the low blade angle of the ma-
nine impeller, the power numbers obtained were only between
0.82 and 0.31. Again comparable experimental values have been
reported \([32]\) and were also obtained from numerical CFD
models \([46]\).

3.4 Power input for standard and single-use agitators
under aerated conditions
The influence of aeration on the power input was studied for the
single-use Mobius CellReady 3L and the reusable SmartGlass 3L
bioreactors over a wide range of aeration rates \((0.125–1 \text{ vvm})\).
In Fig. 8, the ratio of gassed power input to ungassed power
input \((P_G/P_L)\) that was obtained from the torque measurements
is shown as a function of the gas flow number \( F_G \), which was
defined as:

\[
F_G = \frac{F_G}{N \cdot d^2}
\]

where \( F_G \) is the volumetric gas flow rate. As expected, the
gassed power input in both bioreactors decreased as gas flow
rates increased. At flow numbers of \( F_G \approx 0.04 \), the \( P_G/P_L \) ra-
tio became constant, which has also been reported for tradi-
tional impellers, such as Rushton turbines \([14, 31]\) and curved
blade impellers \([21]\). Surprisingly, the Mobius CellReady marine
impeller showed a higher dependency on the flow rate \( (P_L/P_G \propto \text{Fl}^{-0.15}) \) than the SmartGlass bioreactor impellers \( (P_L/P_G \propto \text{Fl}^{-0.08}) \), which may be explained by the lower gas dispersion efficiency of the marine impeller. Furthermore, \( P_L/P_G \) ratios slightly above one were determined for low gas flow numbers in the Mobius CellReady bioreactor, which has also been demonstrated for hydrofoil impellers [30]. It has been stated that the rising gas–liquid plume opposes the impeller pumping action at low impeller speeds and, therefore, the power numbers under aeration conditions (typically high aeration rates and low impeller speeds).

Finally, it should be emphasized that the results only consider the measured power input based on the torque, whereas the power input from the gas, which can be calculated from Eq. (6), assuming isothermal gas expansion, was not considered.

\[
P_{\text{C,h}} = F_G \cdot (\rho_G - \rho_L) \cdot g \cdot H_{CL}.\tag{6}
\]

In fact, the power input released from gas expansion exceeded the measured power input under certain operation conditions (typically high aeration rates and low impeller speeds). Nevertheless, it should be noted that aeration rates and gas flow numbers above 0.25 vvm and 0.015 are typically not used for cell culture applications based on protocols developed in our laboratory. Therefore, it can be concluded that the influence of aeration on power input in the investigated systems is negligible.

4 Concluding remarks

Even though the (specific) power input is an important parameter for engineering characterization and scaling-up/down of bioreactors, only limited experimental data for benchtop scale systems is available in the literature. In particular, little data on power input for laboratory-scale single-use bioreactors, which come ready to use from the manufacturers, has been published to date. This study has closed some gaps for commercially available single-use systems at benchtop scale, namely the UniVessel 2L SU, the Mobius CellReady 3L, and the SmartVessel 3L bioreactors. The determined power numbers cover a wide range of Reynolds numbers between very low and moderate turbulence and are regarded as useful for defining suitable operating conditions for most cell culture applications (or even microbial processes with a requirement of \( \text{Re} < 1000 \)).

To the best of the author’s knowledge, there are only a few commercially available sensors with lower measurement ranges (e.g. with a nominal torque of 0.1 Nm [44]). However, none of these were used because of the additional investment costs.

This may also limit the use of the current experimental setup for smaller bioreactors with volumes of below one liter (and geometrically similar agitators). For instance, a 10% smaller impeller diameter results in an approximately 40% lower impeller torque for a given impeller speed and shape (i.e. power number), because of the \( M \propto d^4 \) relationship between torque and impeller diameter. Consequently, the torque meter and the experimental setup must be carefully considered. Further work is planned to establish an experimental setup for measuring torque in vessels with volumes of 1 L and less.

Practical application

Measuring power input in small-scale bioreactors is still challenging because of the limited accuracy and resolution of common measurement techniques. The torque-based method that currently dominate are often limited by the relatively high friction losses of the bearings that are usually used. Consequently, there is still a lack of data on power inputs in benchtop scale bioreactors, in particular for single-use bioreactors, which are preassembled, sterilized, and delivered ready to use from the manufacturers. The present study shows that air bearings can be used to effectively reduce the friction losses and, thus, enable accurate measurements for a wide range of operational conditions. Based on reference measurements with a conventional Rushton turbine, which agreed well with literature data, the power inputs in different single-use and single-use bioreactors were determined for low-to-moderate turbulence, which is often found in cell culture based processes with low agitation.

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## Nomenclature

| Symbol | Unit | Description |
|--------|------|-------------|
| \(a\)  | [m]  | Impeller blade width |
| \(a_b\) | [m]  | Baffle thickness |
| \(b\)  | [m]  | Impeller blade height |
| \(B_s\) | [m]  | Baffle width |
| \(d\)  | [m]  | Impeller diameter |
| \(D\)  | [m]  | Vessel diameter |
| \(g\)  | [m s\(^{-2}\)] | Gravitational acceleration |
| \(F_{\text{lg}}\) | [m\(^3\) s\(^{-1}\)] | Gas flow rate |
| \(H\)  | [-] | Flow number |
| \(H_{\text{gbl}}\) | [m] | Gas bubble rising height in liquid |
| \(H_b\) | [m] | Baffle height |
| \(M_D\) | [N m] | Dead torque (measured in air) |
| \(M_{\text{eff}}\) | [N m] | Effective torque |
| \(M_L\) | [N m] | Torque measured in liquid |
| \(N\)  | [s\(^{-1}\)] | Impeller rotational speed |
| \(N_P\) | [-] | Power number (Newton number) |
| \(P_l\) | [W] | Power input, ungassed |
| \(P_l^G\) | [W] | Power input, gassed |
| \(P_{l,b}\) | [W] | Power input by gas expansion |
| \(\text{Re}\) | [-] | Reynolds number |
| \(s\)  | [m]  | Impeller blade thickness |
| \(t\)  | [-] | Impeller tip speed |
| \(\mu_{\text{exp}}\) | [m s\(^{-1}\)] | Impeller disc thickness |
| \(V_L\) | [m\(^3\)] | Liquid volume |
| \(x\)  | [-] | Sucrose mass fraction |
| \(\varepsilon_M\) | [m] | Off-bottom clearance |
| \(\Delta\) | [m] | Distance between impellers |

## Greek symbols

| Symbol | Unit | Description |
|--------|------|-------------|
| \(\alpha\) | [°] | Impeller blade angle |
| \(\eta_l\) | [Pa s] | Liquid dynamic viscosity |
| \(\pi\)  | [-] | Mathematical constant |
| \(\rho_c\) | [kg m\(^{-3}\)] | Gas density |
| \(\rho_L\) | [kg m\(^{-3}\)] | Liquid density |

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