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Retrofit of CD-6 (Smith) Impeller in Fermentation Vessels

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Abstract

We extended prior studies on the influence of impeller type on fermentation performance to include a novel low-power-number, high-efficiency radial flow impeller, the CD-6, possessing six curved blades on a disk turbine. Dual impeller combinations of CD-6/CD-6, CD-6/Maxflo T, and CD-6/HE-3 were compared with Rushton/Rushton and Maxflo T/Maxflo T base cases. Qualitative comparisons of unaerated and aerated power draw in both water and glycerol were conducted. These suggested minimal power drops with aeration for dual CD-6 impellers and hybrids containing the CD-6 impeller design. We also examined fermentation performance for *Streptomyces* and *Glarea* secondary metabolite fermentations. A qualitative comparison of the data suggested that dual CD-6 impellers and hybrids containing the CD-6 impeller design resulted in reasonable power draws, improved mass transfer rates with airflow increases, and acceptable peak titers. These arrangements may warrant further study under a wider range of production conditions.

Index Entries: CD-6; hydrofoil; impeller, axial; impeller, radial; impeller, power; fermentation.

Introduction

Since the mid-1980s, substantial research has been conducted in the Fermentation Pilot Plant at Merck Research Laboratories comparing radial and axial flow impellers *(1–5)*. The aim of this research was to evaluate various impeller designs for the mixing of highly viscous aerobic secondary metabolite cultivations. These studies have resulted in the recommendation and installation of low-power-number, axial flow hydrofoil impellers in both our pilot plant and factories, resulting in cost-effective improvements in mixing performance at the large scale.

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Table 1
Axial Flow vs Radial Flow Impeller Comparisons

Impeller type	N_p (power number)	Characteristics of mixing
Rushton	5–6.5 *(5,12,24)*	Radial flow, impeller-associated well-mixed zone, formation of air-filled cavities behind blades *(5)*
CD-6	3.2 *(16)*	Radial flow, curved blades with smaller air-filled cavities
6SRGT	1.8 *(8)*	Radial flow, curved blades with smaller air-filled cavities
HE-3	0.32 *(16)*	Axial flow, top-to-bottom blending, long blades with bent leading edge
Prochem Maxflo T	1–1.6 *(5)*	Axial flow, top-to-bottom blending, greater bulk flows and mechanical loads on shaft and tank *(5)*

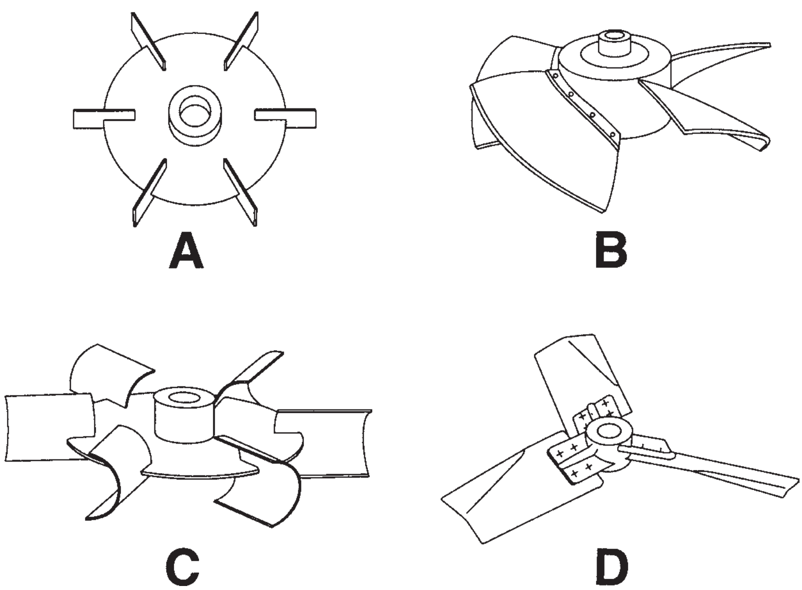

Fig. 1. Types of impellers (clockwise direction of rotation): (a) Rushton, (b) Maxflo T, (c) CD-6, (d) HE-3 *(1,13,23)*.

This effort was continued at the 600-L scale through the evaluation of an additional novel impeller design, a low-power-number, radial flow CD-6 impeller. This impeller was used in the following dual impeller arrangements: CD-6/CD-6, CD-6/Maxflo T and CD-6/HE-3. CD-6/Maxflo T, and CD-6/HE-3 combinations were expected to favor better liquid uniformity, heat transfer, and lower shear whereas the CD-6/CD-6 combination was expected to favor higher k_La. These three trial systems were compared with the Rushton/Rushton and Maxflo T/Maxflo T base cases studied previously *(6,7)*. Table 1 gives the characteristics of individual impeller types and Fig. 1 *(1,13,23)* gives sketches of each impeller type. Power draw was compared qualitatively using water and glycerol model systems. Impeller performance was evaluated during actual secondary metabolite cultivations. Qualitative relationships for the effect of agitation speed and airflow rate on mass transfer coefficients, power draws, and off-gas CO_2 concentrations were generated.

Background

Prior research has focused on novel impeller designs for both single and multiple impeller systems with similar and mixed impellers installed. The Scaba 6SRGT (SCABA AB, Taby, Sweden) and Gasfoil (ICI) impellers are similar to the CD-6 (Chemineer) impeller. Each design has six curved blades on a disk rotating with the open concave portion at the lead. Prior experiments by Saito et al. *(8)* determined that the 6SRGT had a gassed power ratio of 0.8 (vs 0.4 for a standard Rushton impeller) for moderate viscosity solutions. Also, they demonstrated a threefold greater holdup prior to the onset of flooding. The use of Scaba impellers both in model media and in *Aspergillus* fermentations resulted in substantially higher mass transfer rates for viscous systems *(9)*. For this novel curved blade impeller, the gassed-to-ungassed power ratio, P_g/P_o, vs Reynolds number, N_{Re}, curve passed through a minimum, the value of which depended on the rheological properties of the broth *(10)*.

Below power draws of 1 kW/m^3, Rushton ($D_I = 0.57D_T$) and CD-6 ($D_I = 0.5D_T$) impellers were superior to HE-3 ($D_I = 0.68D_T$) and 6SRGT ($D_I = 0.5D_T$) impellers with respect to the lower size of caverns developed while mixing Carbapol solutions at the 350-L scale *(11)*. For impeller speeds of 2.5 s^{-1} and a 0.5 vvm airflow rate, gassed power drops were highest for the Rushton impeller, yet similar for the CD-6, HE-3, and 6SRGT geometries. Serrano-Carreon and Galindo *(11)* suggested that the CD-6 impeller might be most suitable for yield stress fluids, and, specifically, that cavern volume was a function of impeller geometry and spacing.

The major advantage of the curved blade impeller design is that the large gas-filled cavities characteristic of Rushton impellers form only at higher gas flow rates *(8)*, and therefore, there is often a minimal power drop on gassing *(12)*. They have slightly lower shear than the flat-bladed Rushton impellers *(12)*. Vibrations can be lower than for hydrofoil impellers, but their extent depends on the broth viscosity, because significant vibrations were noted for the mixing of xanthan broth *(10)*.

Mixed impeller systems have been examined to fully optimize agitator performance for a specific application. In one example, the gas-dispersing abilities of a radial flow impeller were combined with the pumping of a higher-efficiency axial flow impeller *(12,13)*. Although this arrangement lowered the overall gas holdup, it still improved performance especially under unaerated or viscous conditions *(13,14)*. Specific types targeted for comparison included dual Rushton (D-6), dual CD-6, and the combination of CD-6/HE-3 *(13)* and three Rushtons with a combination of Rushton and two axial flow three-bladed LE20 (APV Baker Ltd Pump and Mixer Division) with each of the two LE20 impellers sized to draw the same power as the Rushton at a similar revolution per minute *(14)*. Another study demonstrated that Rushton/CD-6 combinations had larger cavern volumes than dual HE-3 impellers *(11)*.

In another study, based on the magnitudes of resulting mass transfer coefficients, dual Rushton impellers were preferred over Rushton/hydrofoil and Rushton/marine propeller combinations at low agitation rates whereas Rushton/hydrofoil combinations were preferred at the higher agitation rates for aerated cellulose fiber solutions in 20- and 65-L vessels *(17)*. Power draws were highest for the dual Rushton agitator, followed by the Rushton/hydrofoil and the Rushton/propeller arrangements for these same diameter impellers in water at airflow rates of 0.5 and 1.0 vvm *(17)*. A significant power savings can occur by designing the upper impeller to be the lower-power-number impeller and to draw less power than the bottom impeller *(18)*. A final study comparing dual Rushton, hydrofoil, and Scaba impellers for xanthan gum fermentation concluded that the favored impeller was largely dependent on the analytical criterion applied, specifically either power consumption or gum quality *(15)*.

Materials and Methods

Vessels

Experiments were conducted at the 0.8-m^3 scale in stainless-steel fermentors equipped with 5.6-kW motors. Five sets of different impeller combinations were present comprised of these four impeller types (Fig. 1): flat-blade disk turbines (Rushton; Lightnin, Avon, NY), curved-blade disk turbines (CD-6; Chemineer, Dayton, OH), axial flow hydrofoils (Maxflo T; Prochem, Brampton, Ontario), and axial flow high-efficiency impellers (HE-3; Chemineer). Vessels possessed four 6.4-cm wide baffles positioned at 90° from one another and offset 2.5 cm from the tank wall. The sparger was an open pipe with a diameter of 2.5 cm. Details of each tank are listed elsewhere *(6)*. Impellers were statically and dynamically balanced prior to installation. Impellers were spaced approx 55 cm apart.

CD-6/Maxflo T, CD-6/CD-6, and CD-6/HE-3 impeller combinations were sized based on recommendations from Chemineer. For the axial/radial combinations, impellers were sized such that 70% of the total power was drawn by the lower radial impeller, which is similar to tapered power draw approaches described elsewhere. For the radial/radial combination, impellers were sized such that 55% of the power was drawn by the lower impeller. Impellers were mounted on 7.5 × 5 cm shafts without key ways with the step down from 7.5 × 5 cm occurring in between the two impellers.

Instrumentation

Power was measured using a variable frequency watt transducer (Ohio Semitronics P Series; Columbus, OH) from an inductance coil wrapped around the power supply lines of Square D (Raleigh, NC) variable frequency drives. Because of their measurement of electrical power draw, watt transducers are generally considered less accurate than strain gages and are prone to interferences such as bearing gearbox losses and shaft vibration. Nevertheless, these devices are industrially rugged and have been found to be useful qualitatively to analyze power draw advantages of various impeller designs. Impeller speed was measured and controlled through a tachometer directly mounted on the impeller shaft. Sparger airflow rate was sensed by a thermal mass flowmeter (Model 60; Thermal Instrument, Trevose, PA). Dissolved oxygen was measured with a polarographic probe (Mettler/Toledo Process Analytical—Ingold, Wilmington, MA) calibrated such that 100% saturation corresponded with air at atmospheric pressure.

Test Liquids

Two test liquids were used experimentally (Table 2): water and glycerol (99.7% pure; Henkel, Cincinnati, OH). Test liquid experiments were conducted at a controlled temperature of 25°C, a typical cultivation temperature for a secondary metabolite fermentation. Fermentation broths from a *Streptomyces hygroscopicus* cultivation at 28°C *(19)* and a *Glarea lozoyensis* cultivation at 25°C *(20)* in a low-suspended-solids medium also were evaluated.

Methods of Power Measurement and Analysis

To qualitatively obtain the relationship between power draw and agitation rate, agitation rates were varied, in the absence of pressure and aeration, from 1.7 to 4.6 s^{-1} at a typical tank working volume of 0.6 m^3 that covered both impellers. Liquid levels were significantly above the impellers (at least 0.22 m at 0.6 m^3) so as to minimize air entrainment from the liquid surface.

The aeration rate then was varied from 1.7 to 8.3×10^{-3} m^3/s (0.17–0.83 vvm) for a liquid volume of 0.6 m^3 in the absence of pressure for an agitation rate of 4.6 s^{-1} (4.25 s^{-1} for glycerol in the case of the dual Rushton impeller). Gassed power, P_g, was measured for a specific air volumetric flow rate. The influence of pressure on gassed power was negligible for a pressure change of 0.07 MPa. Standard deviations of power readings as a function of agitator speed, impeller type, and liquid were found to be ±5%. Reproducibility of measurements for similar tanks was found to be ±5%. There was no correction made for power losses through the gear boxes. Because of dissimilar diameters of some of the dual impeller combinations studied (Table 3), Reynolds, power, and aeration numbers were not able to be calculated. Typical values for these dimensionless groups for this system are available *(6)*.

Table 2
Slope/Intercept Obtained from Linear Regression of P_o vs N^3 for N [=] s^{-1} and P_o [=] kW for Water and Glycerol and Linear Regression of P_g vs N^3 for N [=] s^{-1} and P_g [=] kW at Airflow of 8.3×10^{-3} m^3/s for *Streptomyces* and *Glarea* Cultivations

Impeller type	Slope	Intercept	r^2
Water			
Rushton/Rushton	0.050	0.43	0.999
Maxflo T/Maxflo T	0.046	0.38	0.999
CD-6/CD-6	0.034	0.42	0.998
CD-6/Maxflo T	0.043	0.39	0.997
CD-6/HE-3	0.046	0.45	0.994
Glycerol			
Rushton/Rushton	0.055	0.46	0.996
Maxflo T/Maxflo T	0.062	0.39	0.999
CD-6/CD-6	0.044	0.38	0.999
CD-6/Maxflo T	0.054	0.47	0.998
CD-6/HE-3	0.061	0.42	0.998
Streptomyces fermentation @ 270–300 h			
Rushton/Rushton	0.028	0.95	0.998
Maxflo T/Maxflo T	0.034	0.66	0.998
CD-6/CD-6	0.029	0.47	0.995
CD-6/Maxflo T	0.037	0.30	0.999
CD-6/HE-3	0.035	0.63	0.999
Glarea fermentation @ 550–580 h			
Rushton/Rushton	0.035	1.06	0.996
Maxflo T/Maxflo T	0.036	0.55	0.998
CD-6/CD-6	0.033	0.51	0.996
CD-6/Maxflo T	0.034	0.56	0.996
CD-6/HE-3	0.039	0.54	0.998

Table 3
Fermentor Vessel Dimensions (lower/upper impeller)

Impeller type	Number of blades	D_I (m)	D_T/D_I
Rushton/Rushton	6/6	0.305/0.305	2.7/2.7
Maxflo T/Maxflo T	6/6	0.406/0.406	2.0/2.0
CD-6/CD-6	6/6	0.346/0.343	2.4/2.3
CD-6/Maxflo T	6/6	0.394/0.406	2.1/2.0
CD-6/HE-3	6/3	0.394/0.533	2.1/1.5

Streptomyces *and* Glarea *Fermentations*

Identical *Streptomyces (19)* and *Glarea (20)* fermentations were performed using each impeller combination. During the fermentation, variations were made in agitation rate (3.6–4.9 s^{-1}) and airflow rate (4.2 to 8.3×10^{-3} m^3/s and 0.42–0.83 vvm, respectively) to determine the qualitative effect on power draw, mass transfer rate, and off-gas CO_2 concentration. The mass transfer rate was calculated on-line by dividing the oxygen uptake rate by the difference between the saturated and measured dissolved oxygen concentrations obtained using Henry's law coefficient. Fermentations of both organisms were filamentous in nature with neither cultivation being notably shear sensitive after the initial growth phase was completed. *Glarea* fermentations generally exhibited non-Newtonian viscosities about 50% greater than *Streptomyces* fermentations.

Results

Qualitative Comparison of Ungassed Power Draw as Function of Agitation Rate for Water and Glycerol Model Systems

Power increased as the cube of the impeller agitation rate with linear regression coefficients above 0.99 (Table 2). Substantial rises in dependency for all impellers occurred on switching from water to glycerol, with the Rushton impeller dependency increasing the least by only the expected amount of 10% corresponding to the increased density of glycerol. Dual CD-6 impellers had the lowest power draw increase with agitation rate as well as the lowest power draw in both the water and glycerol model systems, substantially lower than that of the dual Rushton impellers. Hybrid CD-6 arrangements with either Maxflo T (CD-6/Maxflo T hybrid) or HE-3 (CD-6/HE-3 hybrid) raised the rate of increase with agitation rate toward that of the dual Maxflo T and dual Rushton cases.

Figure 2A demonstrates that the dual CD-6 impellers had the lowest power draw and the dual Rushton impellers had the highest power draw for water. The dual Maxflo T impellers and the two hybrid systems are similar but in between the CD-6 and Rushton cases. In contrast to the glycerol model system, Fig. 2B shows that all the impellers were similar except for the dual CD-6 arrangement, which had a notably lower power draw for an equivalent agitator speed.

Variation of Ungassed-to-Gassed Power Draw with Aeration Rate for Water and Glycerol Model Systems

The gassed-to-ungassed power draw ratio did not change appreciably for the water model system, declining to only 0.9 with maximum aeration for the dual CD-6 impellers as well as for the CD-6/Maxflo T and CD-6/HE-3 hybrids (Fig. 3A). More substantial declines to 0.75–0.8 were observed for the dual Rushton and dual Maxflo T cases. For the glycerol model system, the largest gassed power ratio decline to 0.7 was for the dual Maxflo T case, followed by the dual Rushton case at 0.75, and the CD-6/Maxflo T and CD-6/HE-3 hybrids at 0.8 (Fig. 3B). Although unexpected, these results are consistent with those reported elsewhere *(12)* and are believed to be due to the larger diameter of the dual hydrofoil impellers and the use of an open pipe sparger in these studies. In addition, the rise of this ratio above 1.0 at

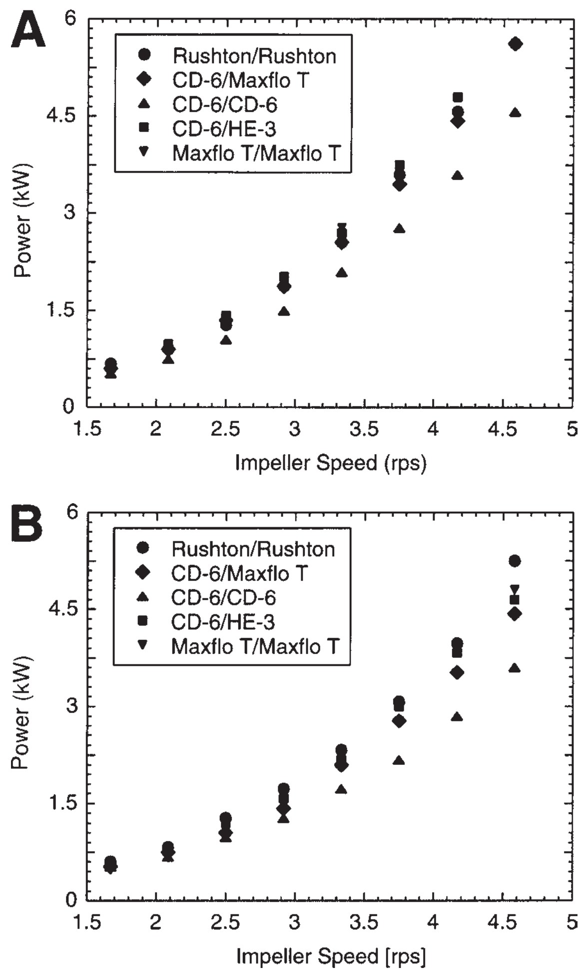

Fig. 2. Unaerated total power draw vs agitation rate for **(A)** water and **(B)** glycerol at 0.6 m^3 and 30°C (based on uncorrected power measurements).

low airflow rates is consistent with published results *(13)*. The dual CD-6 impellers had the highest gassed-to-ungassed ratio at 0.9, similar to the value observed for the water model system. Interestingly, the slight increase in holdup seen at lower flow rates for the dual CD-6 and CD-6 hybrid impellers in the water model system was not evident in the glycerol model system.

Performance During Secondary Metabolite Streptomyces *Cultivation*

Gassed Power Draw with Agitation Rate

The slope of gassed power draw (P_g) with the cube of agitation rate (N^3) during *Streptomyces* cultivations at a constant peak airflow rate of 8.3×10^{-3} m^3/s was calculated and compared (Table 2). This comparison appeared to indicate that the dual CD-6 impellers behaved similarly to the

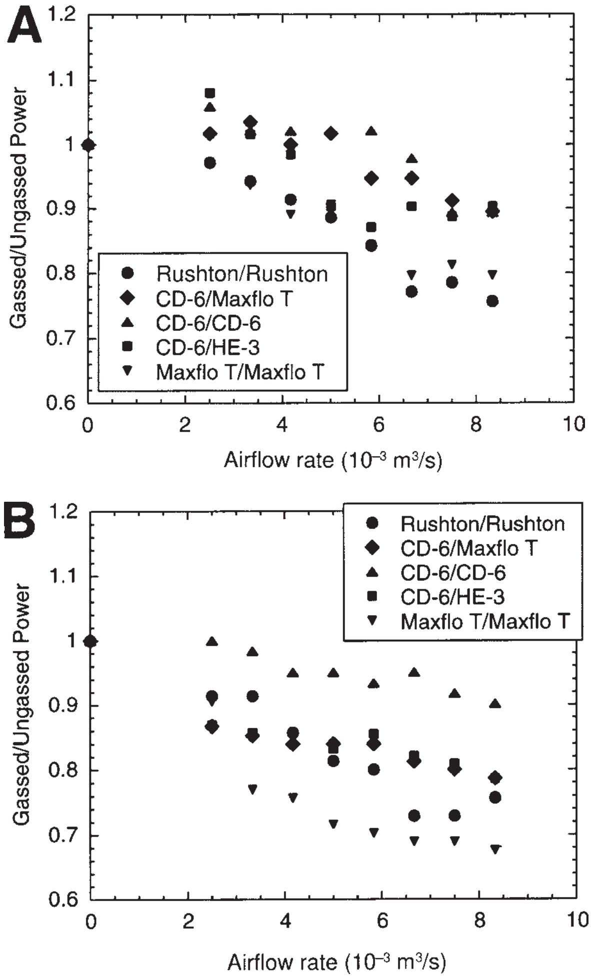

Fig. 3. Gassed-to-ungassed power ratio vs aeration rate at impeller speed of 4.6 s^{-1} for **(A)** water and **(B)** glycerol (impeller speed of 4.25 s^{-1} for glycerol with dual Rushton impellers).

dual Rushton impellers whereas the CD-6/Maxflo T and CD-6/HE-3 hybrids behaved similarly to the dual Maxflo T impellers. There was less of a significant difference between the dual CD-6 arrangement and the other impeller types in a gassed system, potentially owing to the lower effective fluid density.

Peak power draws during the cultivation were 13% lower for the dual CD-6 combination and 7% higher for the CD-6/HE-3 hybrid than for the other three combinations (Table 4). The gassed power decline with a 50% decrease in airflow rate was lower for the dual Maxflo T and the CD-6/Maxflo T hybrid than the other three combinations at a cultivation time of 220–230 h (Table 5). Later in the cultivation, as viscosity increased, the gassed power declines increased for the dual Rushton, dual Maxflo T,

Table 4
Influence of Impeller Type on *Streptomyces* Fermentation Performance in Range of 250–300 h

Impeller type	Peak titer (g/L)	Oxygen uptake rate (OUR) (mmol/[L·h])	Power draw, P_g (kW) @ 4.9 s^{-1} and 8.3×10^{-3} m^3/s	$K_La = AP_g^B$ for V_L = 600 L
Rushton/Rushton	1.1	32	4.6 (0.2)	$K_La = 1.6P_g^{0.41}$ ($r^2 = 0.88$)
Maxflo T/Maxflo T	1.1	34	4.6 (0.2)	$K_La = 2.0P_g^{-0.18}$ ($r^2 = 0.48$)
CD-6/CD-6	0.9	32	4.0 (0.1)	NA[a]
CD-6/Maxflo T	1.2	27	4.6 (0.2)	$K_La = 1.3P_g^{0.69}$ ($r^2 = 0.83$)
CD-6/HE-3	0.9	30	4.9 (0.1)	$K_La = 1.6P_g^{0.32}$ ($r^2 = 0.83$)

[a]Data not obtainable for CD-6/CD-6 arrangement owing to the inability to vary agitation speed for this cultivation without reducing dissolved oxygen below acceptable levels.

Table 5
Influence of Impeller Type on *Streptomyces* Fermentation Response to Airflow Rate Decrease from 8.3×10^{-3} to 4.2×10^{-3} m^3/s at Agitation Rate of 4.9 s^{-1}[a]

	P_g ratio		K_La ratio		Off-gas CO_2 ratio	
Impeller type	220–230 h	320–330 h	220–230 h	320–330 h	220–230 h	320–330 h
Rushton/Rushton	0.97	0.93	1.1	1.20	0.5	0.4
Maxflo T/Maxflo T	0.95	0.92	0.9	0.90	0.5	0.5
CD-6/CD-6	0.99	0.99	1.3	NA[b]	0.6	0.6
CD-6/Maxflo T	0.94	0.94	1.3	1.25	0.5	0.5
CD-6/HE-3	0.98	0.95	1.0	1.20	0.5	0.4

[a]Data are presented as the ratio of the parameter value at an airflow rate of 8.3×10^{-3} m^3/s to its value at an airflow rate of 4.2×10^{-3} m^3/s.
[b]Data not obtainable for CD-6/CD-6 arrangement for this time interval.

and CD-6/Maxflo T cases, but were similar to the earlier values for the dual CD-6 and CD-6/Maxflo T hybrids. Interestingly, there was little effect on the dual CD-6 impellers, which was consistent with their earlier behavior in the water and glycerol studies (Fig. 3A,B).

Mass Transfer Rate

The CD-6/Maxflo T hybrid appeared to have the strongest relationship between gassed power and mass transfer coefficient when compared with the CD-6/HE-3 hybrid and the dual Rushton impeller combinations (Table 4). The lower dissolved oxygen levels obtained for the agitation ranges studied of the dual CD-6 impellers prevented this analysis for the *Streptomyces* fermentation without compromising batch performance. There was little dependence (as evidenced by the low correlation coefficient) of the mass transfer coefficient of the dual Maxflo T combination on gassed power, which was unexpected; this behavior was not able to be confirmed by the subsequent *Glarea* fermentations owing to equipment problems. These results supported the conclusion of other researchers *(21)*, who found that the mass transfer coefficient was more dependent on aeration rate than agitation rate for axial flow pitched-blade impellers. Values obtained for the exponent *B* in the relationship of gassed power to mass transfer coefficient are generally in the range of the wide variations summarized *(22)*.

Peak oxygen uptake rates were similar, averaging 31 ± 2.6 mmol/(L·h). Slightly higher values were obtained for the dual Maxflo T combination, and slightly lower values were obtained for the CD-6/Maxflo T hybrid system.

Increases in airflow rate had the largest effect on the mass transfer coefficient obtained for the dual CD-6 and CD-6/Maxflo T combinations (Table 5). However, the effectiveness of the HE-3 impeller at improving mass transfer ratio increases in this study seemed to improve for the later cultivation time.

Off-Gas CO_2 Concentration

All of the impeller combinations tested appeared to permit a substantial reduction in off-gas CO_2 with increasing flow rate in the range of 40–60% for this cultivation. This result is expected and can be used to evaluate the similarity of cultivation conditions among the various *Streptomyces* batches.

Peak Titer

Peak titers were similar for all five impeller combinations with the fermentor using the CD-6/Maxflo T hybrid attaining the highest value for this particular set of experiments. Additional studies are required to determine whether the lower titers from the dual CD-6 and CD-6/HE-3 hybrid combinations are significant in comparison with normal experimental variation. From this one set of experiments, however, it appears that the CD-6/Maxflo T combination might warrant further study.

Performance During Secondary Metabolite Glarea *Cultivation*

Gassed Power Draw with Agitation Rate

The dependence of gassed power draw on agitation rate during the *Glarea* cultivation at a constant peak airflow rate of 8.3×10^{-3} m^3/s appeared to indicate similar behavior among the dual CD-6 impellers, the dual Rushton impellers, the dual Maxflo T impellers, and the CD-6/Maxflo T hybrid. The CD-6/HE-3 hybrid seemed to have a slightly greater dependence of power on agitation speed (Table 2).

Peak power draws near the end of the cycle were 9% lower for the CD-6/CD-6 combination, and 4% lower for the CD-6/Maxflo T hybrid when compared with the dual Maxflo T arrangement (Table 6). The dual Rushton case and CD-6/HE-3 hybrid were similar to each other and 8% higher than for the dual Maxflo T impellers. Thus, it appears that the use of a CD-6 impeller can lead to lower power draws both as a dual combination and in a hybrid installation with a Maxflo T impeller for *Glarea* broth. Interestingly, the dual CD-6 impeller also exhibited a lower power draw for the *Streptomyces* broth, and the CD-6/HE-3 hybrid had the highest power.

Mass Transfer Rate

The relationship between gassed power draw and mass transfer coefficient in the *Glarea* cultivation appeared to indicate similar behavior among the dual CD-6 impellers, the dual Rushton impellers, the CD-6/Maxflo T hybrid, and the CD-6/HE-3 hybrid. Data were not obtainable for the dual Maxflo T impellers. This dependency was stronger for the *Glarea* cultivations than for the *Streptomyces* fermentations, potentially owing to the substantially higher viscosity of the *Glarea* broth, which dampens turbulence in certain areas of the vessel. Values for the exponent of the gassed power all were similar at about 1.0.

Increases in airflow rate had the largest effect on the mass transfer coefficient obtained for the dual CD-6 and the CD-6/HE-3 combinations (Table 7). The dual CD-6 combination performed consistently better in this regard. It appears that the use of the lower power number radial flow impeller as the lower impeller was effective in certain combinations at breaking up and distributing gas bubbles for this culture. In other combinations and for other broths, the effectiveness was not as dramatic. The variability might have been due to the role of the upper impeller for the particular broth/impeller combination.

Off-Gas CO_2 Concentration

As in the case of the *Streptomyces* cultivations, all of the impeller combinations tested appeared to permit a substantial reduction in off-gas CO_2 with increasing flow rate in the range of 55–60% for this cultivation. This result is expected and can be used to evaluate the similarity of cultivation conditions among the various *Glarea* batches.

Table 6
Influence of Impeller Type on *Glarea* Fermentation Performance in Range of 550–580 h

Impeller type	Peak titer (U/L)	Oxygen uptake rate (OUR) (mmol/[L·h])	Power draw, P_g (kW) @ 4.9 s^{-1} and 8.3×10^{-3} m^3/s	$K_La = AP_g^B$ for V_L = 600 L
Rushton/Rushton	19	8.1	5.2 (0.3)	$K_La = 4.2P_g^{1.05}$ ($r^2 = 0.98$)
Maxflo T/Maxflo T	20	8.5	4.8 (0.2)	NA[a]
CD-6/CD-6	18	9.1	4.4 (0.1)	$K_La = 5.2P_g^{1.04}$ ($r^2 = 0.98$)
CD-6/Maxflo T	24	8.7	4.6 (0.1)	$K_La = 4.8P_g^{0.96}$ ($r^2 = 0.98$)
CD-6/HE-3	22	8.9	5.2 (0.1)	$K_La = 5.6P_g^{1.04}$ ($r^2 = 0.99$)

[a]Data not obtainable for Maxflo T/Maxflo T arrangement owing to faulty dissolved oxygen sensor.

Table 7
Influence of Impeller Type on *Glarea* Fermentation Response to Airflow Rate Decrease from 8.3×10^{-3} to 4.2×10^{-3} m^3/s at Agitation rate of 4.9 s^{-1}[a]

Impeller type	P_g ratio @ 570 h	K_La ratio @ 570 h	Off-gas CO_2 ratio @ 570 h
Rushton/Rushton	0.99	1.0	0.4
Maxflo T/Maxflo T	0.91	NA[b]	0.4
CD-6/CD-6	0.96	1.4	0.45
CD-6/Maxflo T	0.89	1.1	0.45
CD-6/HE-3	0.99	1.3	0.5

[a]Data are presented as the ratio of the parameter value at an airflow rate of 8.3×10^{-3} m^3/s to its value at an airflow rate of 4.2×10^{-3} m^3/s.
[b]Data not obtainable for Maxflo T/Maxflo T impeller arrangement for this time point.

Peak Titer

Peak titers were similar for all five impeller combinations with the fermentor using the CD-6/Maxflo T hybrid, again attaining the highest value for this particular set of experiments. Additional studies are required to determine whether the lower titers from the dual CD-6 and Rushton combinations are significant in comparison with normal experimental variation. From this second set of experiments, however, it appears that the CD-6/Maxflo T combination might warrant further study.

Discussion

The low-power-number radial flow CD-6 impeller was evaluated both as a dual impeller system and in two hybrid systems with low-power-number axial flow Maxflo T and HE-3 impellers. In model systems using water and glycerol, ungassed power draws had the lowest value as well as the smallest increase with agitation rate for dual CD-6 impellers. Increases in power draw with the cube of the agitation rate all were linear when plotted in a semilog fashion. Dual CD-6 impellers also possessed the highest gassed-to-ungassed power ratio of all the combinations tested. In actual fermentation systems, peak power draws were lowest for the dual CD-6 and the two CD-6 hybrid arrangements. The effectiveness of increases in airflow rate improving mass transfer for the dual CD-6 and its hybrids also was greater. Peak titers were slightly more attractive for the CD-6/Maxflo T hybrid for the two fermentation systems examined, but titers for all impeller systems were within typical experimental ranges, with no single impeller system emerging as a clear favorite.

These results suggest that the use of novel impellers in hybrid arrangements might be a useful method of providing a versatile impeller installation for multiple-use facilities. Often removal and exchange of impellers for different processes is difficult to justify during piloting studies for processes early in their development cycle. Using such a hybrid installation, the strengths of each portion of the hybrid might then be available for the various processing scenarios encountered. The specific case of the CD-6/Maxflo T hybrid arrangement is one worthwhile option to pursue for secondary metabolite broths.

Nomenclature

D_I = Impeller diameter (tip to tip) (m)
D_T = Fermentor vessel diameter (m)
k_La = Mass transfer coefficient (h^{-1})
N = Impeller speed (s^{-1})
N_P = Newton or power number ($P_o/[\rho N^3 D_I^5]$)
N_{Re} = Reynolds number for impeller ($ND_I^2\rho/\mu$)
P_o = Ungassed power draw (kW)
P_g = Gassed power draw (kW)
Q = Volumetric gas flow rate (m^3/s)
S = Impeller spacing (m)
V_L = Ungassed liquid volume of tank (m^3)
μ = Viscosity (MPa·s)
ρ = Liquid density (g/cm^3)

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