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Agitating for success

Kevin Myers, Mark Reeder, Andre Bakker and Martin Rigden explain the importance of impeller selection

Agitation plays a crucial role in the success of many chemical processes. The wide variety of commercially-available impellers practically guarantees that optimal agitation can be provided for any process. However, the difficulty arises in choosing the best impeller from the myriad that are available. Equipment manufacturers provide expert guidance in this area, but it is advantageous if design, development, and process engineers have a fundamental understanding of the impeller choices that face them.

The process objective of agitation is the primary factor influencing impeller selection[1,2]. These objectives include blending of miscible fluids, convective heat transfer, solids suspension, contacting immiscible fluids, and numerous other functions. Physical properties, primarily viscosity, also play a key role in impeller selection, with different impeller designs being used in laminar, transitional, and turbulent operation.

The flow pattern generated by an impeller is closely related to the impeller's ability to meet process objectives. Flow patterns are broadly grouped into the axial and radial types, which are illustrated in Table 1 (p41). In general, the axial flow pattern is optimal for flow-sensitive operations such as blending, heat transfer, and solids suspension, while the radial flow pattern is best suited for dispersion operations that require higher shear levels than are provided by axial-flow impellers. The axial flow pattern of the selection table corresponds to a down-pumping impeller orientation. Up-pumping axial flow is also encountered industrially, but only in specialised applications.

There are a multitude of highly-specialised impellers available to the chemical processing industries. This paper will focus only on those with the broadest applications. The impellers that will be discussed are shown in Table 1. Note that all impellers are intended to rotate clockwise when viewed from the top of the tank. The selection table shows various impeller styles, their flow pattern, preferred usage, and power number and pumping number information.

Pitched-blade turbines

Pitched-blade turbines are multi-purpose impellers that generate a mainly axial flow pattern, but with substantial radial and tangential components. The geometries of pitched-blade turbines are highly-variable, with the four-bladed, 45° P-4 shown in Table 1 being the most common. This impeller has a turbulent power number ($N_p = P/N^3D^5$) of approximately 1.25 (see *Notation* p42).

Because they are relatively efficient at generating flow, pitched-blade turbines are most often used in miscible fluid blending, solids suspension, and convective heat transfer operations. When placed near a free liquid surface, pitched-blade turbines can also create a surface vortex, particularly when baffling is reduced or eliminated. Thus, these impellers are well-suited for drawdown of floating solids or liquids and for incorporation of gas from the vessel headspace. Although pitched-blade turbines do not produce high shear rates, they are sometimes used for dispersion of immiscible fluids.

High-efficiency impellers

Two high-efficiency impellers are shown in Table 1. The narrow-blade HE-3 is typically used in only a three-blade configuration while the wide-blade Maxflo T is used in three, four, five, and six-blade versions. These impellers generate highly-axial flow patterns.

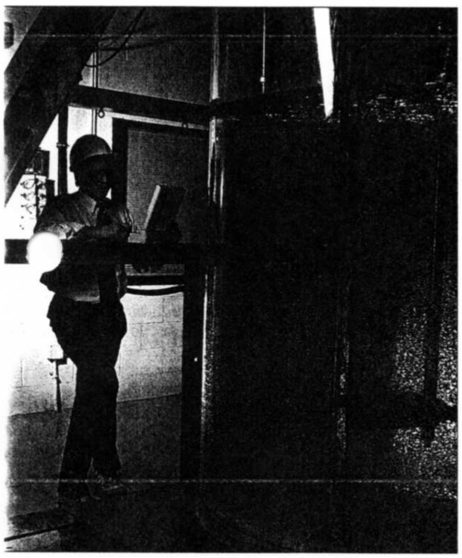
The turbulent power number of the HE-3 is of the order of 0.27, while that of the Maxflo T is typically somewhat higher depending on the number of blades and blade angle. Because of their sensitivity to the pressure head against which they must pump, the power and pumping numbers ($N_q = Q/ND^3$) of high-efficiency impellers are influenced by geometric parameters such as off-bottom clearance and impeller diameter to tank diameter ratio[3].

High-efficiency impellers provide maximum pumping capacity while minimising energy dissipation. Energy dissipation is minimised by using profiled blades that reduce vortex generation on the trailing edges of the blades which in turn reduces form drag. Therefore these impellers are optimal for low-viscosity blending, convective heat transfer, and solids suspension — applications that are sensitive to the flow generated by the impeller.

In addition, wide-blade high-efficiency impellers are often used in side-entering agitators commonly used in pulp and paper, flue gas desulphurisation, and storage tank applications. The axial impeller discharge flow is directed across the vessel base in this instance. Conversely, narrow-blade, high-efficiency impellers are not recommended for highly-viscous applications or as a dispersion impeller. Wide-blade, high-efficiency impellers are suitable for transitional blending. High-efficiency impellers generally do not generate a surface vortex like pitched-blade turbines, so they are not recommended for surface incorporation operations.

High-efficiency impellers share many characteristics with marine propellers (low power number, high pumping capacity, axial flow pattern). However, marine propellers are produced by casting, while high-efficiency impellers are typically fabricated. Further, marine propellers are typically much heavier than a comparable high-efficiency impeller. Consequently, high-efficiency impellers provide material savings, are subject to fewer mechanical design limitations, and find far more use in the chemical processing industries than marine propellers.

Two cautions apply to the use of high-efficiency impellers. First,



(photo: Chemineer)

because of their low power numbers, a large diameter impeller is typically needed for processes that require high power inputs. A large impeller is heavy, and if a long shaft is necessary, critical speed limitations can occur[4]. The second related problem is that the flow pattern of an axial-flow impeller, both high-efficiency impellers and pitched-blade turbines, can change if the impeller diameter is too large or if the impeller is placed too far from the vessel base. This phenomenon, termed flow reversal, leads to radially-inward flow at the vessel base with velocities that are much lower than with the normal axial flow pattern. This leads to poor performance in solids suspension applications[5]. When diameter limitations occur for narrow-blade, high-efficiency impellers, the higher-power number wide-blade versions or pitched-blade turbines are used to reduce the impeller diameter. When this impeller substitution is necessary, the efficiency of the agitator does decrease.

Viscous effects also influence the flow pattern of axial-flow impellers[6], with the discharge flow becoming progressively more radial as the impeller Reynolds number ($N_{Re} = ND^2/v$) is reduced below 400. The use of narrow-blade, high-efficiency impellers is not recommended for impeller Reynolds numbers less than 100 while wide-blade high-efficiency impellers and pitched-blade turbines are not recommended for impeller Reynolds numbers less than 10.

Disc turbines

Both the flat-blade D-6 and concave-blade CD-6 disc impellers generate radial flow patterns, as shown in the selection table.They are not nearly as efficient for pumping as axial-flow impellers because a significant portion of their power input is dissipated through vortices and shear in the impeller region. Therefore the power numbers of disc turbines are substantially higher than those of axial-flow impellers. The D-6 disc turbine has a turbulent power number of approximately 5.5 while that of the CD-6 disc turbine is near 3.2.

The D-6 turbine, often called a Rushton turbine, has been the traditional impeller for dispersion of immiscible fluids (either gas-liquid or liquid-liquid). While the D-6 turbine is still often used for liquid-liquid dispersion, the CD-6 turbine is now the favoured impeller for gas-liquid dispersion, particularly at high gas flows (superficial gas velocities greater than 0.03 m/s). Concave-blade disc turbines are sometimes referred to as Smith impellers after their originator.

As detailed by van't Riet and Smith[7], the D-6 turbine generates a pair of counter-rotating vortices on the back of its blades. These vortices are low-pressure regions that attract gas when it is sparged into the system. This leads to the formation of gas-filled cavities on the back of the blades which in turn reduces the drag on the rotating impeller, causing the gassed power draw of the D-6 to be substantially lower than its ungassed power draw. The design of the CD-6 turbine limits the size of the gas-filled cavities, and this impeller maintains its power draw upon gassing. This and other advantages of the CD-6 are discussed by Bakker *et al*[8].

Flat-blade turbines

Like disc turbines, flat-blade turbines pump radially and produce higher shear rates than axial-flow impellers. The turbulent power number of the four-bladed S-4 in Table 1 is approximately 3.0. Flat-blade turbines can be used for many purposes, but in general do not provide the performance of special purpose impellers. The most common applications of flat-blade turbines are in laminar and transitional blending and to provide local liquid motion. Local liquid motion is particularly important near the base of vessels with steep conical bottoms and when agitation intensity needs to exceed a certain minimum when the liquid level falls below the primary impeller(s) during vessel draining.

High-shear impellers

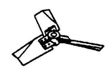
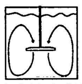
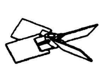
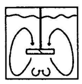
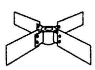
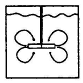
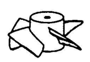
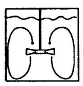
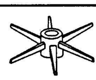
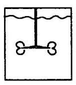
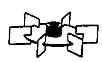
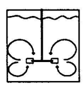
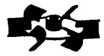
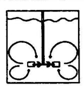
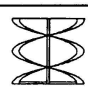
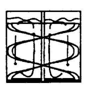
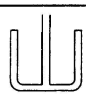
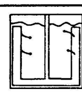
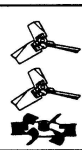
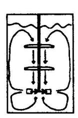
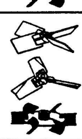
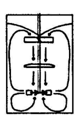
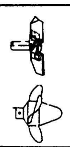
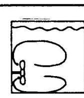
When control of drop or particle size distribution is the primary process objective, high-shear impellers are used. These high-shear impellers typically operate at high speeds, often in excess of 1000 rpm. Because the majority of the energy input to these impellers is dissipated through shear, they produce very limited flow in a small region around the impeller. The high-shear impeller shown in the table, a ChemShear impeller, is one of many designs of high-shear impellers. Other designs include disperser discs and sawtooth impellers.

Laminar-flow impellers

Laminar agitation provides unique challenges. Turbulent flow rapidly transports momentum throughout the vessel volume, yielding high velocities even close to the vessel wall. However, in laminar flow, fluid velocities fall rapidly with increasing distance from the impeller. This problem is particularly acute when the agitated fluid exhibits non-Newtonian, shear-thinning properties as is often the case in industrial processes. Low velocities near the vessel wall or heat transfer coils can lead to poor process performance when rates of heat transfer to or from the agitated fluid are limited. However, because of the low fluid velocities in the vessel wall region, it is usually not necessary to use baffles for laminar agitation.

To eliminate low-velocity regions, large-diameter impellers are often specified for laminar operation. The flat-blade, pitched-blade, and disc turbines discussed previously can all be used in

Table 1: Impellers and flow patterns

Impeller	Flow Pattern	Name and description	Applications	
		HE-3 Narrow-blade, high-efficiency impeller	Blending, Turbulent heat transfer, Solid suspension,	Upper impeller for gas dispersion, $N_p \approx 0.27$, $N_q \approx 0.5$ (turbulent)
		P-4 Pitched-blade turbine	Blending, Dispersion, Solid suspension,	Heat transfer, Surface motion, $N_p \approx 1.25$, $N_q \approx 0.7$ (turbulent)
		S-4 Straight-blade turbine	Local liquid motion for blending, Dispersion, keeping outlets clear from solids,	$N_p = 3.0$
		Maxflo T Wide-blade, high-efficiency impeller	Blending, Transitional flow, Simultaneous gas dispersion and solid suspension (like mining),	N_p and N_q vary with tip angle and number of blades
		ChemShear Narrow-blade turbine	Liquid-liquid dispersion, Solid-liquid dispersion, Local shear	
		D-6 Flat-blade disc turbine (Rushton turbine)	Gas dispersion, low and intermediate gas flows, Liquid-liquid dispersion, $N_p \approx 5.5$, $N_q \approx 0.75$	
		CD-6 Concave-blade disc turbine (Smith turbine)	Gas dispersion, intermediate and high gas flows	
		Helical ribbon (Double flight shown)	Blending and heat transfer in viscous media (μ > 50 Pa-s or N_{Re} <100) -$N_p \approx 350 / N_{Re}$, N_{Re}<100)	
		Anchor	Heat transfer in viscous media $N_p \approx 400 / N_{Re}$, $N_{Re} < 10$	
		CD-6 / HE-3 / P-4	Gas dispersion and blending for tall reactors Fermentations (food products, pharmaceuticals)	
		CD-6 / HE-3	Combined gas-dispersion, blending, and material drawdown (corn wet milling)	
		Side–entering wide blade impeller (HE3-S or Mark II)	Oil storage, Paper pulp, Wastewater circulation, Flue gas desulnurisation	

laminar operation, but this often requires narrow blades to reduce power draw and multiple impellers with small separations to ensure movement throughout the entire vessel.

A number of impellers, such as the helical ribbon and anchor impellers in Table 1, are specifically designed for laminar operation. These impellers are often described as close-clearance impellers because the impeller diameter is typically 95-99% of the vessel diameter ($0.95 \leq D/T \leq 0.99$). Because of their large diameters relative to that of the vessel, close-clearance impellers generate fluid motion at the vessel wall. In some instances the impeller blades are equipped with extensions to physically scrape the vessel wall.

The anchor impeller imparts primarily tangential flow to the fluid, with only limited radial and axial movement. On the other hand, the helical ribbon generates significant axial as well as tangential flow. In general, the helical ribbon is a very efficient laminar blending impeller. However, because of its intricate construction and close tolerance at the vessel wall, it is also an expensive impeller to manufacture.

When viscous forces dominate, very high impeller power numbers occur. To limit power consumption, low speed drives are used. These low speeds result in large gear drives to convert the high-speed, low-torque motor output into the low-speed, high-torque impeller motion. Bakker and Gates[9] have discussed agitator design for laminar operation in detail.

Mixed impeller systems

In many instances a single impeller cannot meet all process objectives. This situation is most commonly encountered when both rapid dispersion and blending are required simultaneously. This goal can be achieved by combining a lower, dispersing impeller with upper, high-efficiency impellers. This configuration is often used in tall gas-liquid reactors such as fermenters where installations as large as 750 kW are commonly encountered. Typically, a lower CD-6 turbine is combined with upper HE-3 impellers. Maxflo T impellers are used if the diameters of the HE-3 impellers are too large at the desired power input. If rapid incorporation of material from the surface is also required, a P-4 turbine can be added.

Use of multiple radial-flow impellers in gas-liquid reactors leads to poor top-to-bottom mixing because of zoning that occurs between impellers. Zoning is eliminated when high-efficiency impellers are used above the dispersing impeller. Myers *et al*[10] demonstrated that these impeller systems reduce gassed blend times to less than half the value of multiple radial-flow impeller systems while maintaining comparable rates of interphase mass transfer. The top-to-bottom flow pattern generated by a mixed dispersing/high-efficiency impeller system is shown in the table.

Another common application of mixed impeller systems is in semi-batch reactors in which both rapid micro-scale and macro-scale blending are important for ensuring the desired product distribution[11]. Also, since high-shear impellers provide very limited pumping, they are sometimes combined with axial-flow impellers. In these mixed impeller systems, the axial-flow impeller creates motion throughout the vessel, moving the vessel contents through the high shear region where the desired dispersed phase size distribution is generated.

Glass-lined reactors

Glass-lined reactors are used for numerous chemical processing applications with highly-corrosive environments. The impellers used in these vessels must meet a wide variety of process requirements including blending, solids suspension, dispersion, and heat transfer. In some instances the impeller must simultaneously meet these process objectives. In others, a single glass-lined vessel may be used in the production of a number of chemical species, each with different requirements of the impeller. A complete line of pitched and straight-blade, high-efficiency, radial-flow, and anchor impellers is now available. Glass-covered impellers used to be supplied as a single piece including both the shaft and impeller. Newer impellers are designed such that the impeller can be removed from the shaft while maintaining glass cover.

Epilogue

Proper impeller selection is critical to the success of agitator design. As detailed here, the selection process must consider both process objectives and fluid physical properties. Axial-flow impellers are ideal for flow-sensitive operations such as blending, solids suspension, and convective heat transfer. Radial-flow impellers are suitable for operations that require more shear such as dispersion of immiscible phases. Laminar operation requires specialised designs such as helical ribbons and anchors. Other specialised designs include high-shear impellers, mixed impeller systems, and impellers used for glass-lined reactors.

Following the impeller selection guidelines presented here will help you choose the impeller system that will achieve your process objectives.■

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Notation

D = impeller diameter, m
N = impeller rotational speed, s^{-1}
N_p = impeller power number (P/rN^3D^5), dimensionless
N_q = impeller pumping number (Q/ND^3), dimensionless
N_{Re} = impeller Reynolds number (ND^2/v), dimensionless
P = impeller power draw, W
Q = impeller pumping capacity, m^3/s
T = vessel diameter, m
v = fluid kinematic viscosity, m^2/s

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