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GAS DISPERSION USING MIXED HIGH-EFFICIENCY/DISC IMPELLER SYSTEMS

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Mixed impeller systems that combine the gas-dispersing capabilities of a radial-flow impeller with the pumping of high-efficiency impellers have been finding increased use in gas-liquid agitation. Under gassed conditions, mixed impeller systems have been found to provide blend times that are less than one-half of those of radial-flow impeller systems. The gassed power draw of mixed impeller systems can be approximately predicted from knowledge of the gassed power draw of the individual impellers in single-impeller operation. The gas holdup generated by mixed impeller systems is lower than that of radial-flow impeller systems when compared at the same gassed power input and superficial gas velocity. Despite this lower gas holdup, mixed impeller systems exhibit similar or improved interphase mass transfer performance at high gas flows and high power inputs.

1. INTRODUCTION

Because of the practical upper limit on tank diameter of about four meters, many industrial vessels are designed with aspect ratios (fluid level to tank diameter ratios) significantly greater than one to achieve desired capacities. Such geometries require the use of multiple impellers to ensure adequate agitation throughout the vessel, and for more than five years mixed impeller systems have been used for gas-liquid agitation in these instances. Mixed impeller systems combine a lower gas-dispersing impeller with upper axial-flow impellers to achieve the desired mixing performance.

Despite the industrial importance of mixed impeller systems in gas-liquid agitation, their characteristics have not been reported in much detail. Kuboi and Nienow [1] have reported the power draw characteristics of mixed impeller systems using pitched-blade turbines as the upper impellers. However, they focused on the up-pumping mode of operation rather than the down-pumping mode of interest in this work. Eliezer [2] studied a mixed D-6/high-efficiency impeller system, but aeration numbers were limited to a maximum value of 0.03, below the range of interest for most industrial applications.

This paper reports the results of a study of gas-liquid agitation with a mixed CD-6/HE-3 impeller system at aeration rates and power inputs of practical interest. Blend time, gas holdup, gassed power draw, and interphase mass transfer are considered. Both experimental results and those obtained using the computer program Ghost! are reported.

2. EXPERIMENTAL APPARATUS AND METHOD

All experiments were performed with air and tap water, a coalescing system, in an acrylic dished-bottom tank with an internal diameter of 0.40 meters. Rotational speeds in the range of 2 to 15 s^{-1} and gassing rates of 4.7 x 10^{-4} to 1.4 x 10^{-2} m^3/s were studied. The impellers used were Chemineer's D-6, CD-6, and HE-3, all of standard design. These impellers are shown in Figure 1. Two mixed CD-6/HE-3 impeller systems were considered: a dual-impeller system with one CD-6 and one HE-3, and a four-impeller system with one CD-6 and three HE-3s. The gas-dispersing impellers, either the D-6 or CD-6, had diameters of 0.16 meters, corresponding to an impeller diameter to tank diameter ratio of forty percent. The diameter of the HE-3 impellers was varied, but was most often 0.20 meters which corresponds to an impeller diameter to tank diameter ratio of fifty percent. The HE-3 impellers were studied only in the down-pumping mode. The off-bottom clearance of the gas-dispersing impellers was twenty-five percent of the tank diameter and the separation between impellers was one-half of the tank diameter. When a dual-impeller system was studied, the ungassed liquid level was 1.2 times the tank diameter, and when a four-impeller system was studied, the ungassed liquid level was two times the tank diameter. Air was introduced below the lowest impeller through a ring sparger with a diameter of 0.076 meters. At the power inputs and superficial gas velocities of these experiments, all impeller systems operated in the completely-dispersed regime.

Agitation speed was measured with a zero-velocity magnetic pickup while torque was measured by a strain gauge. Gas holdup was measured visually by noting the increase in liquid level during gassing. Blend times were studied using an acid-base reaction technique in which the color change of an indicator provided a visual indication of blend time. The blend times reported here are for addition on the upper surface of the gas-liquid mixture. The gassed power draw of the HE-3 impeller was determined in a simulated environment, similar to that above a gas-dispersing impeller, using a perforated rubber membrane to provide uniform gas dispersion. Fasano et al. [3] have discussed this technique in greater detail.

3. COMPUTATIONAL METHOD

Fluent™ was used to calculate single-phase flow patterns, with impeller boundary conditions provided by experimental laser Doppler velocimetry. To simulate gas-liquid mixture behavior, the single-phase flow patterns were used as input for Ghost! which then calculates the spatial distribution of gas holdup, bubble size, and interphase mass transfer coefficient based upon conservation principles including a force balance on the gas bubbles. Details, including justification of the model, are provided by Bakker [4] and Bakker and Van den Akker [5].

4. RESULTS

4.1 Blend Time

The primary reason for using mixed impeller systems for gas-liquid agitation is the improved blending performance provided by the high-efficiency impellers. This effect can clearly be seen in the results of Figure 2 which indicate that the blend time of a mixed CD-6/HE-3 impeller system can be less than half of that of an all D-6 impeller system. The longer blend time of the D-6 impeller system is due to the compartmental flow pattern created by this impeller system, with each impeller establishing its own zone of influence as shown in the computed ungassed flow patterns of Figure 3. When HE-3 impellers are used in a mixed impeller system, they pump liquid axially with no zoning between impellers, leading to good top-to-bottom mixing of the vessel contents.

As the diameter of the HE-3 impellers is increased, the blend time continually decreases. However, this decrease in blend time is accompanied by an increase in the relative standard deviation of the blend time (the values reported in Figure 2 are the average of six to eight individual blend time experiments). In the extreme case in which the HE-3 diameter is 1.51 times that of the CD-6, two distinct blend times are observed - one that is eighty percent of the mean (observed five times) and one that is one hundred and thirty percent of the mean (observed three times). This behavior is most likely due to fluctuations in the flow pattern that have been noted in ungassed streakline videos of these systems. The computed ungassed flow patterns of a mixed impeller system shown in Figure 3 also support this reasoning. As the size of the HE-3 impellers is increased, less of the discharge flow from the lowest high-efficiency impeller reaches the gas-dispersing impeller. Therefore, it is recommended that the diameter of the HE-3 impellers in mixed impeller systems be approximately 1.3 times the diameter of the gas-dispersing impeller. It should be noted that no attempt was made to determine if the observed variations in blend time were accompanied by fluctuations in power draw.

4.2 Gas Holdup

The measured gas holdups for single, dual, and four-impeller systems are shown in Figure 4. In both cases, the gas holdup generated by the all D-6 and all CD-6 impeller systems is very similar. The holdup generated by the mixed impeller systems is less than that of the all radial-flow impeller systems and is not influenced by the size of the high-efficiency impeller.

The difference in the gas holdup generated by the all radial-flow and mixed impeller systems is greater for the four-impeller systems than for the dual-impeller systems. This is due to a greater portion of the power input being provided by the high-efficiency impellers in the four-impeller system than in the dual-impeller system (the high-efficiency impellers are estimated to be responsible for twenty-five percent of the ungassed power draw in the dual-impeller system and fifty percent in the four-impeller system). Since the high-efficiency HE-3 impellers provide maximum pumping with little shear, they would not be expected to contribute substantially to the generation of gas holdup. Although it is a simplistic interpretation of the situation, the gas holdup generated by the mixed impeller systems is similar to that of a single gas-dispersing impeller operating at the same gassed power input for both the dual and four-impeller systems.

4.3 Gassed Power Draw

Gassed power draw was measured for both dual and four-impeller systems as shown in Figures 5 and 6. Prediction of the gassed power draw in multiple impeller systems is not a simple matter, but a straightforward approach was found to provide reasonable estimates of the gassed power draw of mixed CD-6/HE-3 impeller systems.

Elucidation of the gas cavity structure behind the blades of D-6 impellers by Bruin et al. [6] and Nienow and Wisdom [7] led to rational approaches to correlation and prediction of the gassed power draw of single impellers. However, as suggested by Hicks and Gates [8] and Smith et al. [9], the upper impellers in multiple-impeller systems experience a different environment than the lowest, gas-dispersing impeller. Nienow and Lilly [10] hypothesized that very little gas passes through upper impellers and that their decreased power draw upon gassing can be attributed to the decreased density of the gas-liquid mixture. They supported this hypothesis with data demonstrating that the power draw of dual D-6 impeller systems drops much less on a relative basis than that of a single D-6 impeller upon gassing (the later study of Kuboi and Nienow [1] did not support this contention, however).

Fasano et al. [3] previously found that, upon exposure to a well-dispersed gas environment, the power draw of an HE-3 impeller drops dramatically, more than can be attributed to density reduction. Therefore, the technique of Nienow and Lilly [10] is not applicable to prediction of the gassed power draw of mixed CD-6/HE-3 impeller systems. The approach used here is to study the power draw of a single HE-3 impeller in the well-dispersed gas environment generated by a rubber membrane sparger and to couple this with the experimentally-determined power draw of a single gas-dispersing CD-6 impeller in the following manner.

$$\left(\frac{P_g}{P_o}\right)_{CD-6/HE-3} = \alpha\left(\frac{P_g}{P_o}\right)_{CD-6} + (1 - \alpha)\left(\frac{P_g}{P_o}\right)_{HE-3}$$

α represents the fraction of the ungassed power draw attributed to the CD-6 impeller which is estimated to be seventy-five percent for the dual-impeller system and fifty percent for the four-impeller system (note that the CD-6 impeller has a diameter that is forty percent of the tank diameter and the HE-3 impellers have diameters that are 1.27 times that of the CD-6 for all data in Figures 5 and 6).

Examination of the experimental data illustrates that this approach provides a reasonable approximation to the gassed power draw of mixed CD-6/HE-3 impeller systems, exhibiting an average absolute error of less than five percent when applied to the current data. One clear inadequacy of the proposed technique is that it consistently overpredicts the power draw at low gassing rates (aeration numbers below about 0.1). This is likely due to unaccounted-for interactions between the impellers that would tend to reduce the power draw of the multiple impeller system. At higher gas flows these impeller interactions diminish, and the proposed technique provides better estimates of the power draw.

4.4 Interphase Mass Transfer

Very little work has been done relative to the interphase mass transfer characteristics of mixed impeller systems. Using a dynamic physical absorption technique, Weir [11] compared the gas-liquid mass transfer capabilities of dual D-6/D-6, CD-6/CD-6, and CD-6/HE-3 impeller systems. His results, obtained at a fixed power input of 3 kW/m^3, are presented in Figure 7. They indicate that the use of the mixed impeller system should be considered at high gassing rates where it provides enhanced interphase mass transfer capabilities.

The Ghost! predictions of Figure 8 illustrate a clear advantage of the CD-6/HE-3 impeller system -a much more uniform spatial distribution of the interphase mass transfer coefficient. This behavior can be critical to the success of processes such as fermentations in which it is necessary to maintain sufficiently high dissolved oxygen concentrations throughout the liquid. Further, the Ghost! results agree very well with experimental data. At a gassed power input of 3 kW/m^3 and a superficial gas velocity of 0.03 m/s, Ghost! predicts a gas holdup of 0.168 for the all D-6 impeller system and a gas holdup of 0.152 for the mixed impeller system. Examination of Figure 4a indicates that this is in excellent agreement with the experimental gas holdup data. Ghost! also predicts nearly identical interphase mass transfer coefficients for the two impeller systems, 0.28 s^{-1} for the all D-6 impeller system and 0.29 s^{-1} for the mixed impeller system, which agrees with the mass transfer data of Figure 7. Ghost! was originally justified for low gassing rates (gas holdups below about five percent)[4,5], but these results indicate that its applicability may not be that restricted. Further work on the extension of Ghost! to high gassing rates is therefore warranted.

5. CONCLUSIONS

Mixed impeller systems should be considered for gas-liquid agitation when rapid liquid blending is required. The gassed power draw of mixed impeller systems can be estimated from knowledge of the gassed power draw of the individual impellers in single-impeller operation. Although the high-efficiency impellers do not contribute substantially to the generation of gas holdup, mixed impeller systems provide similar or enhanced mass transfer capabilities at high power inputs and high gas flows. Comparison of experimental data and computational simulations indicates that Ghost! provides reliable prediction of the behavior of agitated gas-liquid dispersions.

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TRADEMARKS

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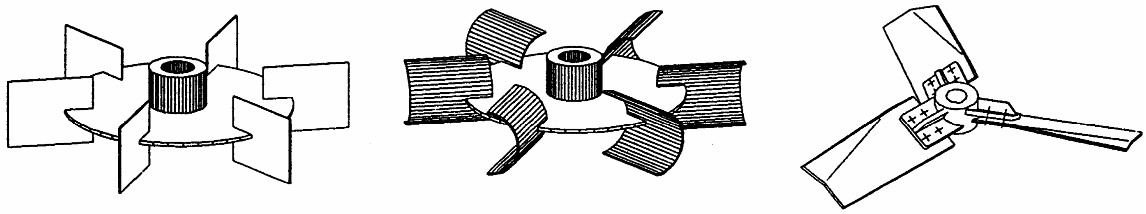

Figure 1: Impeller Types Studied. D-6 (left), CD-6 (center), and HE-3 (right)

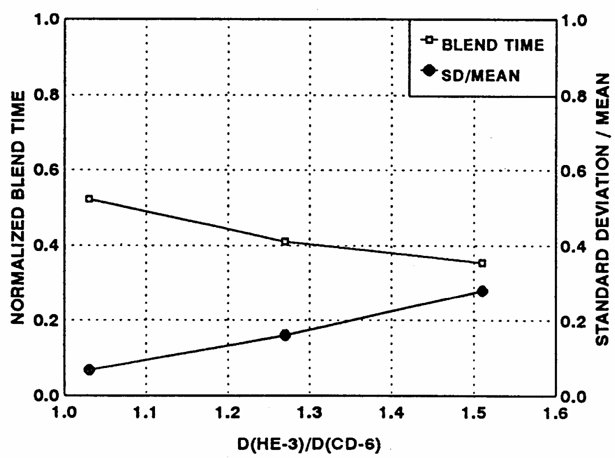

Figure 2: Blend Time of Mixed Four-Impeller System (1 CD-6 and 3 HE-3s). Normalized blend time is unity for a four-D-6 impeller system. Basis of comparison is equal power input and superficial gas velocity (2 kW/m^3 and 0.030 m/s). CD-6 diameter is fixed at forty percent of the tank diameter.

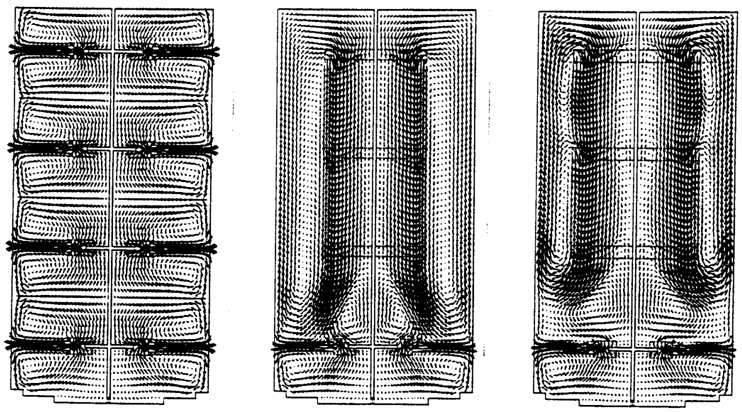

Figure 3: Computed Ungassed Flow Patterns of Four-Impeller Systems. All D-6 (left), CD-6/HE-3 with HE-3 diameter being 1.3 times the CD-6 diameter (center), and CD-6/HE-3 with HE-3 diameter being 1.6 times the CD-6 diameter (right).

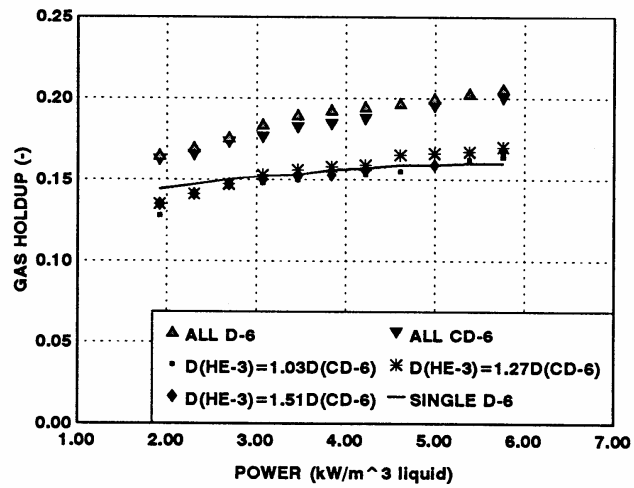

Figure 4a: Gas Holdup of Four-Impeller Systems. Superficial gas velocity is fixed at 0.03 m/s.

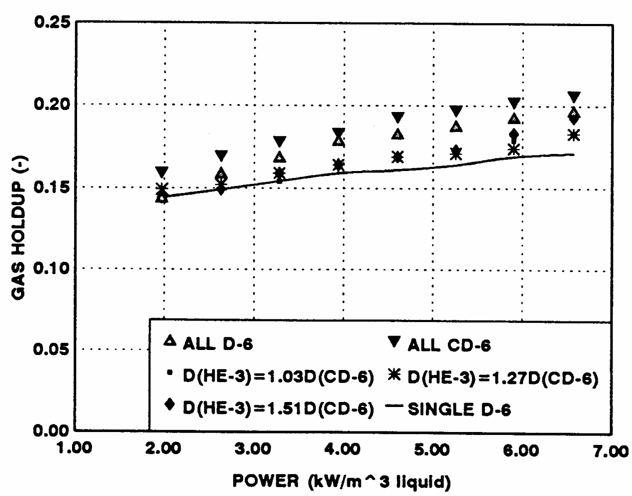

Figure 4b: Gas Holdup of Dual-Impeller Systems. Superficial gas velocity is fixed at 0.03 m/s.

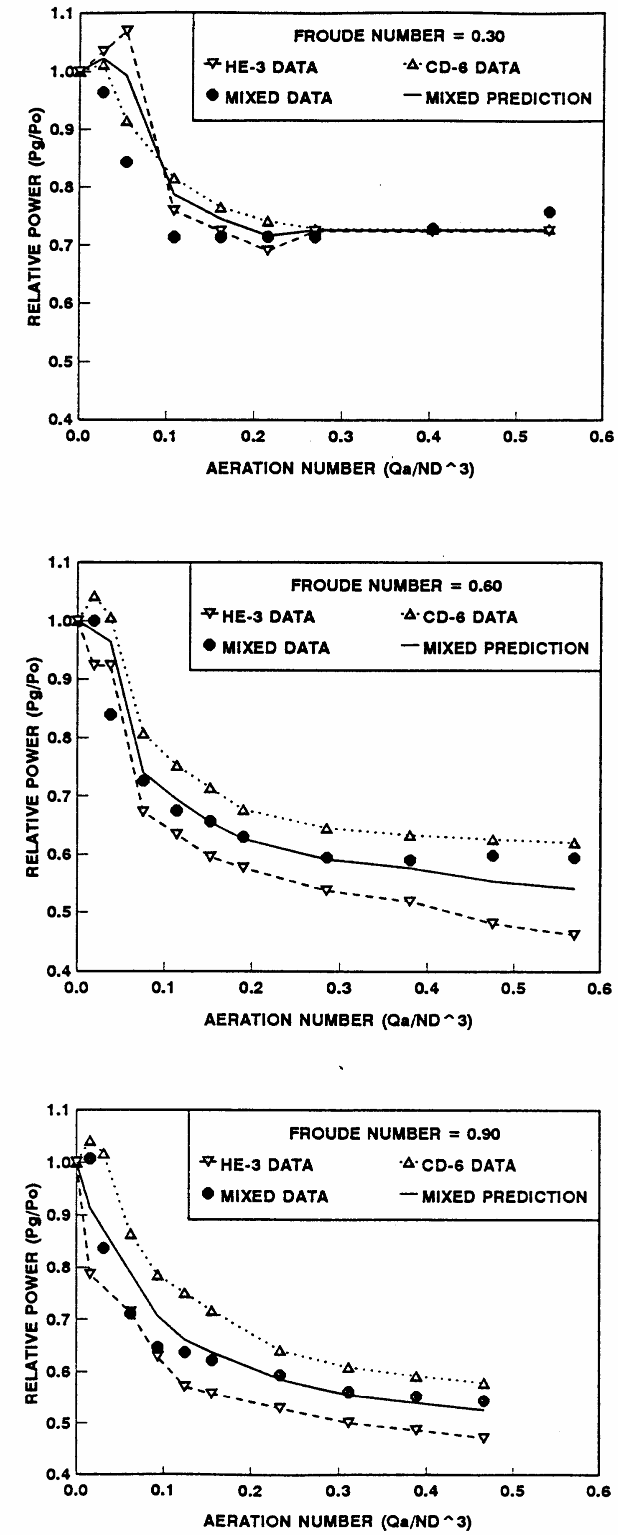

Figure 5: Gassed Power Draw of a Four CD-6/HE-3 Impeller System at Various Froude Numbers HE-3 diameter is 1.27 times the CD-6 diameter. Froude and aeration numbers are based on the CD-6 impeller and the experiments were performed at fixed agitation speed with varying gas flow.

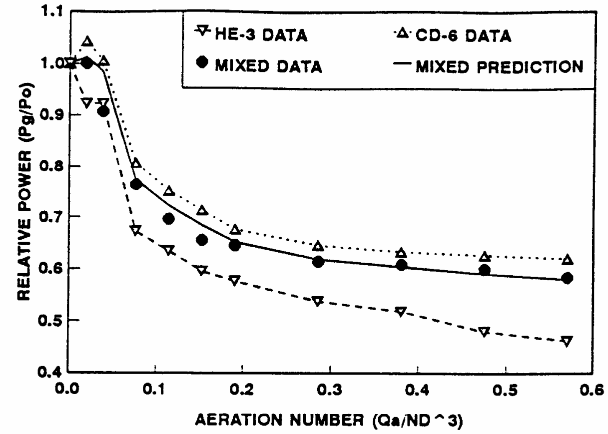

Figure 6: Gassed Power Draw of a Dual CD-6/HE-3 Impeller System at a Froude Number of 0.6. HE-3 diameter is 1.27 times the CD-6 diameter. Froude and aeration numbers are based on the CD-6 impeller and the experiments were performed at fixed agitation speed with varying gas flow.

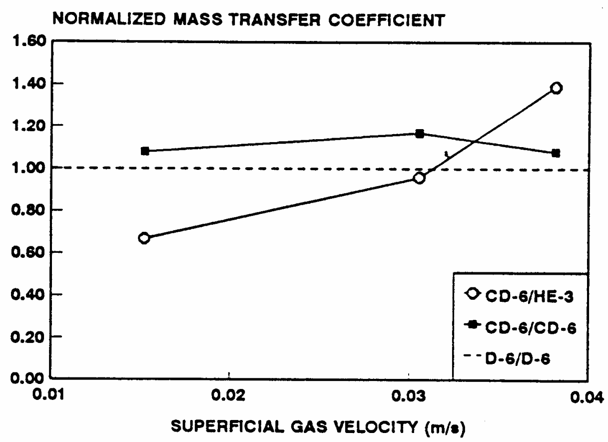

Figure 7: Gas-Liquid Mass Transfer Coefficient of Dual CD-6/HE-3 and CD-6/CD-6 Impeller Systems. Data is normalized relative to a dual D-6/D-6 impeller system at the same gassed power input (3 kW/m^3 liquid) and superficial gas velocity.

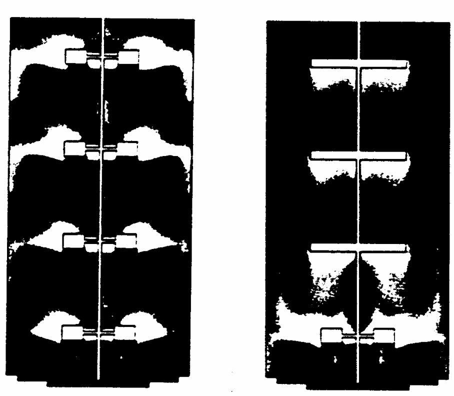

Figure 8: Ghost! Mass Transfer Coefficient Predictions of Four-impeller Systems. All D-6 (left) and CD-6/HE-3 with HE-3 diameter being 1.3 times the CD-6 diameter (right). Basis of comparison is equal power input and superficial gas velocity (3 kW/m^3 and 0.03 m/s). Light regions indicate high mass transfer coefficients and dark regions indicate low mass transfer coefficients.