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SIMULATION AND EXPERIMENTAL VERIFICATION OF LIQUID - SOLID AGITATION PERFORMANCE

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The results of the Ghost! and Fluent computational models of liquid-solid agitation have been compared with experimental solids concentration profiles obtained using a conductivity probe. Both models predict experimentally-observed local maxima and minima in the solids concentration profiles. Qualitatively and quantitatively, the three-dimensional Fluent model is the most promising, but currently its run times are excessive.

INTRODUCTION

Traditionally, the design of liquid-solid agitators has relied upon laboratory testing and generalized correlations of extensive experimental data [1]. However, computational tools are now having a significant impact in this arena, and their importance is certain to increase in the future [2]. Although complex, modeling of multiphase systems has shown promise, primarily in gas-liquid systems [3]. However, to date, computational investigations of liquid-solid agitation have been limited [4]. This work investigates the performance of the Ghost! and Fluent™ models of liquid-solid agitation through comparison with experimental solids concentration profiles.

EXPERIMENTAL APPARATUS

All experiments were performed in a flat-bottomed vessel with a diameter of 0.29 meters. The solid phase was glass beads with a nominal diameter of 200 microns (ranging from 160 to 250 microns), while tap water was used as the liquid. The glass beads had a density of 2500 kg/m^3 and a measured settling velocity of 0.028 m/s. A five volume percent (11.6 weight percent) slurry was studied.

Chemineer HE-3 impellers of standard construction were used, and the impeller diameter to tank diameter ratios studied were 0.20, 0.35, and 0.57. Agitation speeds equal to 0.80, 0.90, 1.00, 1.25, and 1.50 times the just-suspended speed were considered. For one test, a four-bladed, forty-five degree pitched-blade turbine was used. Its impeller diameter to tank diameter ratio was thirty-five percent and its blade width to impeller diameter ratio was twenty percent. Square batch geometry (liquid level equal to tank diameter) was used with a fixed impeller off-bottom clearance of twenty-five percent of the vessel diameter.

Axial solid concentration profiles were measured with a two-electrode conductivity probe. The probe was positioned in the baffle plane, midway between the vessel centerline and wall ($r/R = 0.5$). Maxwell's equation [5] was found to describe the relation between the probe response and solids volume fraction.

COMPUTATIONAL MODELS

Early attempts to describe solids concentration profiles in agitated slurries most often relied on the sedimentation-dispersion model. Both deterministic [6] and probabilistic [7] formulations of this model have been investigated. Typically, a one-dimensional model that ignores radial and angular effects is considered. However, as computational speed has increased, the use of models that are more closely linked to the system hydrodynamics has become possible. Recently, the network of zones model [8] has been extended to liquid-solid systems.

The current generation of liquid-solid agitation models directly incorporate system hydrodynamics. The two models that are considered in this study are Ghost! and Fluent. Both two-dimensional and three-dimensional models were tested. In the two-dimensional model an axisymmetric flow pattern is assumed. In the three-dimensional model the baffles are modeled explicitly. However, this more accurate modeling comes at the cost of increased calculation times.

The Ghost! model uses Fluent to calculate a liquid-only flow pattern with impeller boundary conditions supplied from laser Doppler velocimetry. This single-phase flow pattern is then assumed to be unchanged by the presence of solids, an assumption that limits its applicability to low solids fractions. Further, particle-particle interactions are not taken into account.

Ghost! calculates the solids spatial distribution using the continuity balance for the solids. The continuity equation includes turbulent transport of solids with the turbulent diffusivity being modeled in analogy with kinetic gas theory. Rather than solving the solid momentum balance for the solid velocity field, Ghost! assumes that the solids have a constant slip velocity relative to the liquid in the axial direction, and that this slip velocity is equal to the terminal settling velocity [4].

The Fluent model is a beta version that uses a fully-coupled Eulerian two-phase approach to simultaneously determine the liquid and solid velocity and concentration fields. Continuity and momentum equations for both phases are solved simultaneously, with momentum transport between the phases being modeled with a Reynolds number-dependent, spherical-particle drag coefficient. At its current stage of development, the Fluent model requires transient simulations.

Although the Fluent model is clearly closer to first principles, its excessive run times currently limit its use to only the most critical designs. Three-dimensional simulations require two to three days on a HP-755 workstation. For this reason, the simpler, but less fundamental Ghost! model was studied in hopes that it could provide rapid simulations under some conditions.

EXPERIMENTAL RESULTS

Before comparing model simulations with experimental data, the data will be presented and examined. In the figures that present solids concentration profiles, the term dimensionless vertical position represents the distance above the base of the vessel normalized with respect to the liquid level. The average and impeller lines on the figures indicate the average solids volume percent (five) and the plane of the impeller (located one-fourth of the liquid level from the vessel base).

Figure 1 compares the solids concentration profiles of the HE-3 and pitched-blade impellers at just-suspended conditions (6.45 s^{-1} for the pitched-blade turbine and 9.78 s^{-1} for the HE-3 impeller). In this instance, the two profiles are essentially identical. It should be noted that the pitched-blade turbine requires twenty percent more power and eighty percent more torque than the HE-3 to achieve just-suspended conditions. Figure 1 also demonstrates that local maxima and minima exist in the solids concentration profiles [9].

Figure 2 illustrates the influence of the impeller diameter to tank diameter ratio on the solids concentration profile of the HE-3 impeller at just-suspended conditions (the just-suspended speeds are 28.3, 9.78, and 5.17 s^{-1} for the smallest to the largest impeller). Clearly, larger impellers produce a higher cloud height, but they also require more torque to achieve suspension [10]. Also, the local maxima and minima become more pronounced as the size of the impeller increases.

Figure 3 presents the solids concentration profiles of the smallest HE-3 impeller ($D/T = 0.20$) at various speeds. A significant increase in the cloud height occurs as the speed is increased from just-suspended conditions to 1.25 times the just-suspended speed. Further increase in the speed to 1.5 times the just-suspended speed does not significantly change the solids concentration profile. Also, as the speed is increased to produce a more uniform suspension, the maxima and minima in the profiles become more pronounced.

The influence of speed on the profiles of the HE-3 impeller with a diameter equal to thirty-five percent of the vessel diameter ($D/T = 0.35$) is shown in Figure 4. These results are similar to those of the smaller impeller except that an increase in the speed from ninety to one-hundred percent of the just-suspended speed does not cause much change in the solids concentration profile. This is most likely due to the fact that at ninety percent of the just-suspended speed only about three to five percent of the solids are not suspended.

As shown in Figure 5, the largest HE-3 impeller (D/T = 0.57) exhibits dramatically different behavior than the smaller impellers at eighty percent of the just-suspended speed. Under these conditions the solids that are suspended form a relatively uniform, dilute suspension throughout the vessel. As the speed is increased, the cloud height actually decreases as more solids are lifted into suspension. This behavior was verified visually during experimentation.

COMPARISON OF DATA AND SIMULATIONS

Figure 6 compares the solids concentration profiles predicted by Ghost! and Fluent with the experimental data obtained with the HE-3 impeller at just-suspended conditions at an impeller diameter to tank diameter ratio of thirty-five percent (D/T = 0.35). The Ghost! two-dimensional simulation shows reasonable qualitative agreement with the data, particularly relative to the cloud height. However, the three-dimensional formulation of Ghost! predicts a much more pronounced maximum concentration near the middle of the vessel and a higher cloud height, neither of which are observed experimentally.

The two-dimensional Fluent prediction does not compare well with the experimental data. In particular, this model predicts a settled solids bed over the bottom five percent of the vessel (not indicated in Figure 6). Conversely, the three-dimensional formulation of Fluent shows reasonable agreement with the experimental data. Although its concentration maximum is exaggerated and it predicts somewhat higher concentrations throughout most of the vessel, these differences are not great, and the model accurately predicts the cloud height.

The Ghost! and Fluent predictions of the complete solids concentration field in the baffle plane are presented in Figure 7, while the liquid velocity profiles of the two models are presented in Figure 8. The liquid velocity used by Ghost! is assumed to be unaffected by the presence of the solids. However, examination of the Fluent velocity profile indicates that the liquid velocity is altered by the solids. In particular, the liquid velocity above the solids cloud is dramatically reduced. Not taking this into account is most likely why the three-dimensional Ghost! model predicts cloud heights that are higher than those observed experimentally.

CONCLUSIONS

This work has yielded a number of results that impact both our knowledge of solids concentration profiles in agitated slurries and our ability to model the behavior of these systems. First, at just-suspended conditions and an intermediate impeller diameter to tank diameter ratio (D/T = 0.35), the solids concentration profiles of the pitched-blade and high-efficiency impellers are essentially identical. Also, larger impellers provide greater solids uniformity at just-suspended conditions. Further, large impellers (D/T = 0.57 for the HE-3 impeller) can yield uniform distribution of the suspended solid material throughout the vessel at levels of agitation below just-suspended conditions.

The solids concentration profile often exhibits local maxima and minima, behavior that cannot be modeled by the sedimentation-dispersion model. However, this behavior was predicted by both the Ghost! and Fluent models in their two- and three-dimensional formulations. Also, three-dimensional simulations predict higher solids suspension than do two-dimensional simulations. This was found both with Fluent and Ghost!.

Comparison of simulation predictions with experimental solids concentration profiles indicates that the quantitative accuracy of the models must be improved. Comparison of Ghost! and Fluent indicates that the influence of the solid on the liquid-phase velocity profile can probably not be ignored. Of the models tested, the three-dimensional formulation of Fluent appears to be the most promising, but its long run times make its use impractical for all but the most critical designs.

TRADEMARKS

Fluent™ is a trademark of Fluent, Inc. (Lebanon, New Hampshire 03766).

ACKNOWLEDGMENTS

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NOTATION

D = impeller diameter, m
N_{js} = just-suspended speed, s^{-1}
r = radial position, m
R = tank radius, m
T = tank diameter, m

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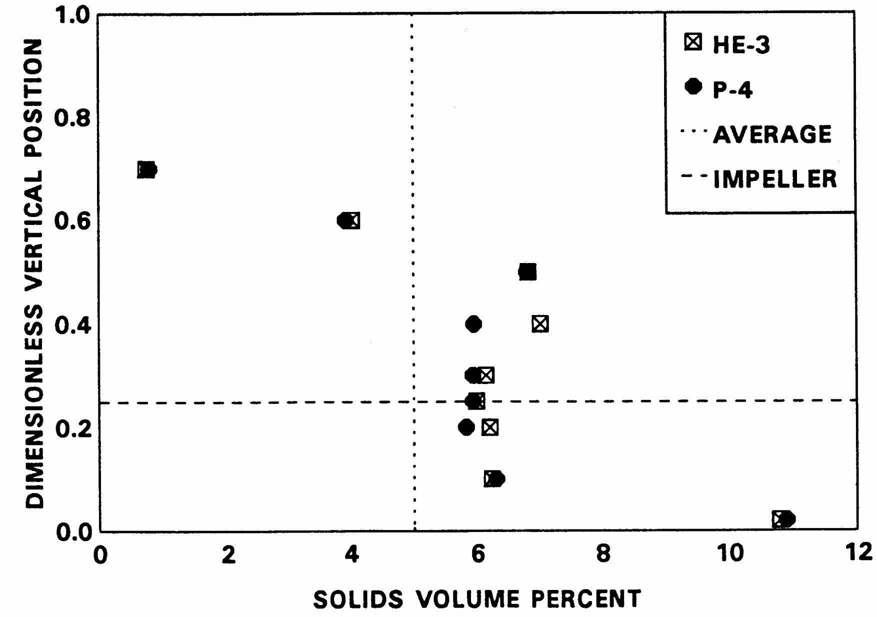

FIGURE 1: COMPARISON OF EXPERIMENTAL SOLIDS CONCENTRATION PROFILES OF HIGH-EFFICIENCY AND PITCHED-BLADE IMPELLERS AT JUST-SUSPENDED CONDITIONS FOR AN IMPELLER DIAMETER TO TANK DIAMETER RATIO OF THIRTY-FIVE PERCENT (D/T = 0.35)

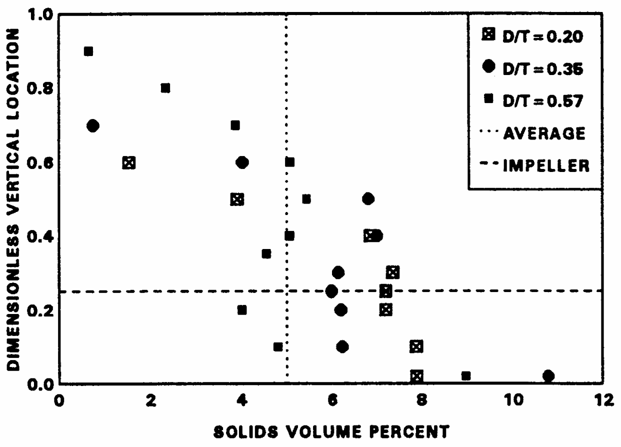

FIGURE 2: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF THE IMPELLER DIAMETER TO TANK DIAMETER RATIO (D/T) AT JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER

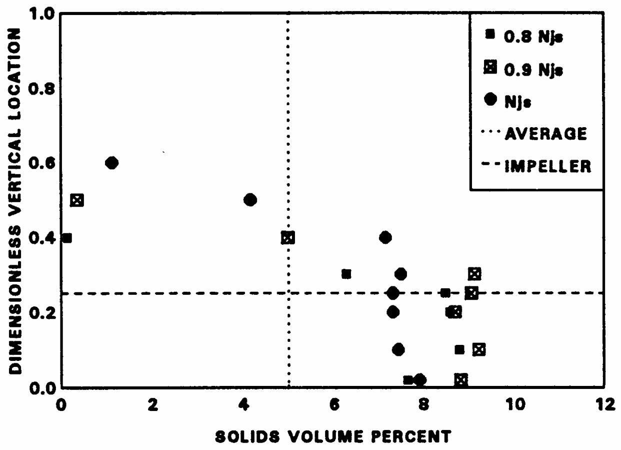

FIGURE 3A: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND BELOW JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.20

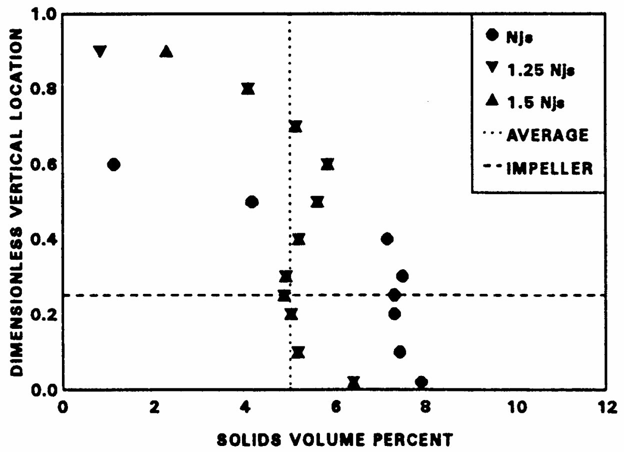

FIGURE 3B: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND ABOVE JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.20

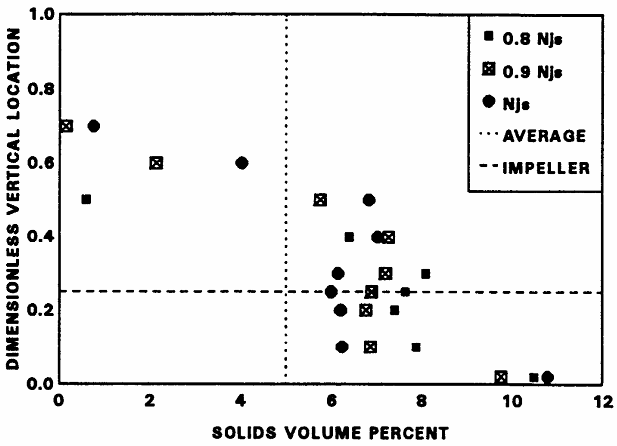

FIGURE 4A: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND BELOW JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.35

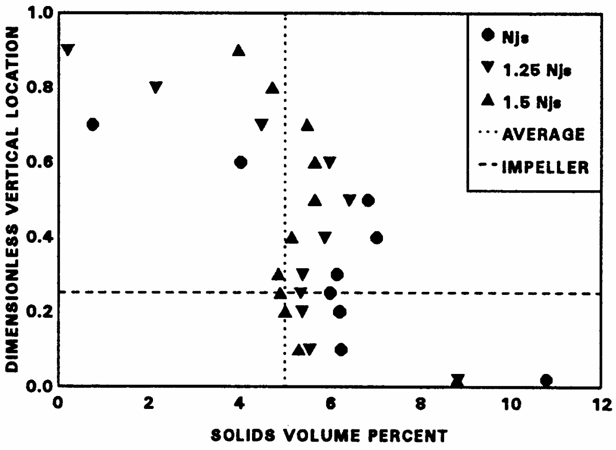

FIGURE 4B: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND ABOVE JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.35

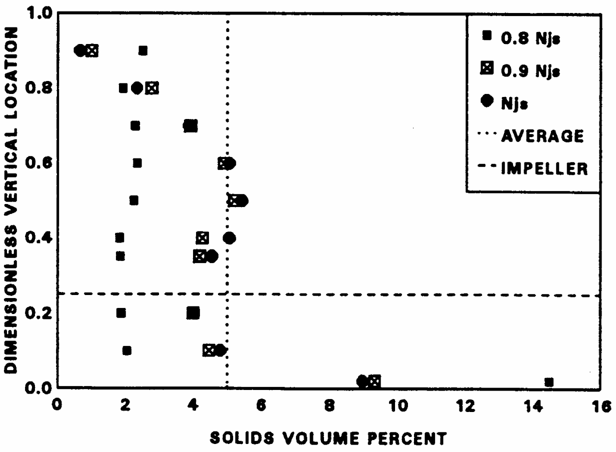

FIGURE 5A: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND BELOW JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.57

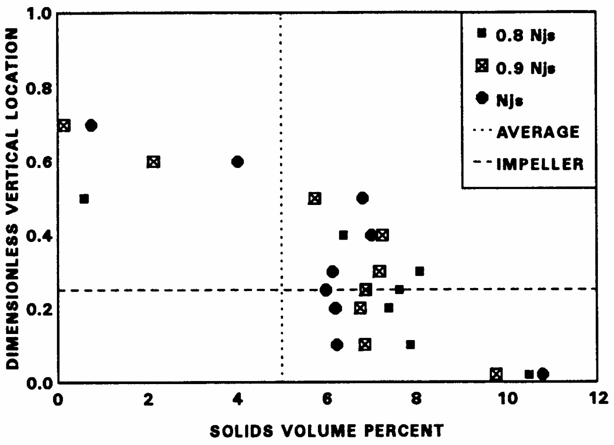

FIGURE 4A: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND BELOW JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.35

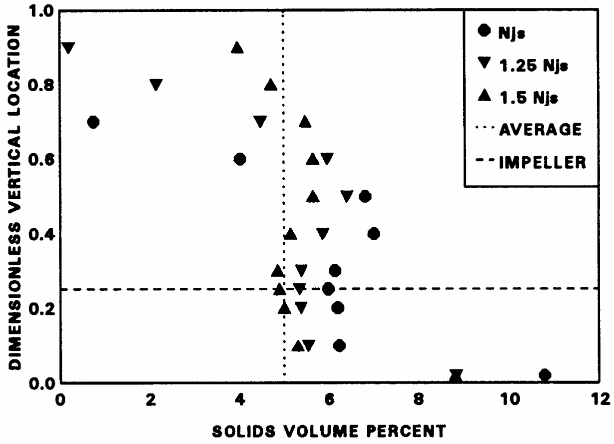

FIGURE 4B: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND ABOVE JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.35

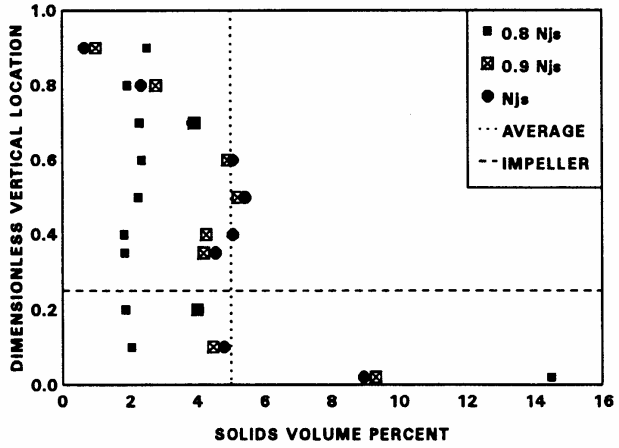

FIGURE 5A: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND BELOW JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.57

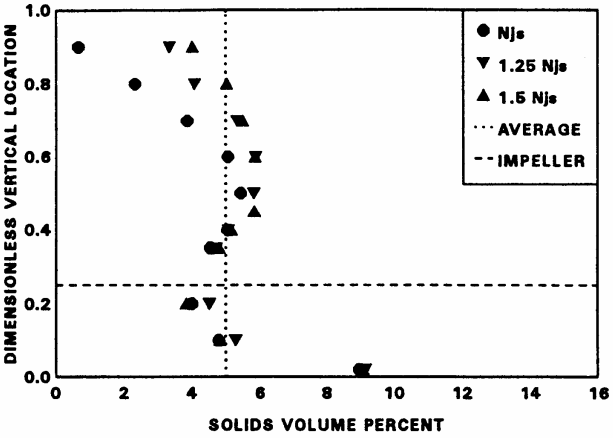

FIGURE 5B: EXPERIMENTAL SOLIDS CONCENTRATION PROFILES ILLUSTRATING THE INFLUENCE OF SPEED AT AND ABOVE JUST-SUSPENDED CONDITIONS FOR THE HIGH-EFFICIENCY IMPELLER WITH D/T = 0.57

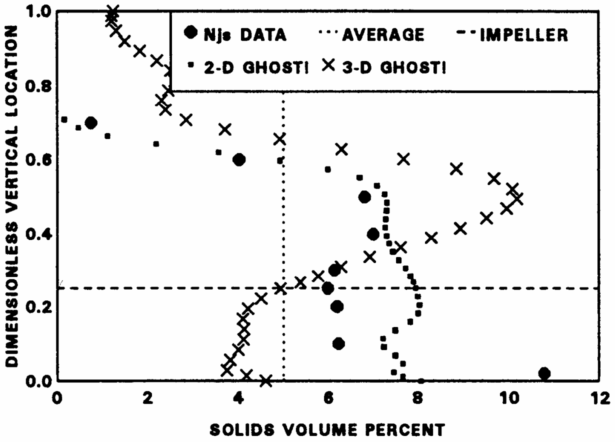

FIGURE 6A: COMPARISON OF TWO- AND THREE-DIMENSIONAL GHOSTI PREDICTIONS WITH THE EXPERIMENTAL SOLIDS CONCENTRATION PROFILE OF THE HIGH-EFFICIENCY IMPELLER AT JUST-SUSPENDED CONDITIONS WITH D/T = 0.35

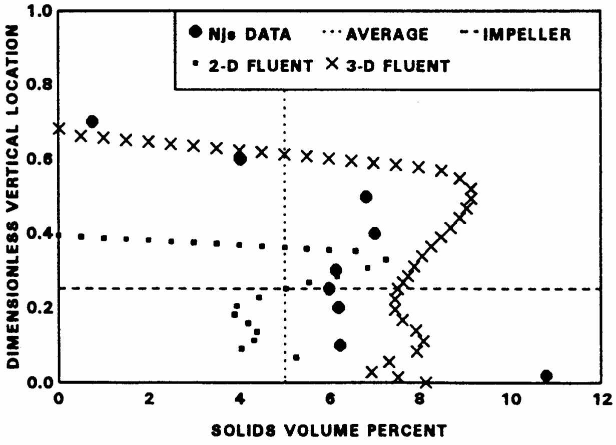

FIGURE 6B: COMPARISON OF TWO- AND THREE-DIMENSIONAL FLUENT PREDICTIONS WITH THE EXPERIMENTAL SOLIDS CONCENTRATION PROFILE OF THE HIGH-EFFICIENCY IMPELLER AT JUST-SUSPENDED CONDITIONS WITH D/T = 0.35

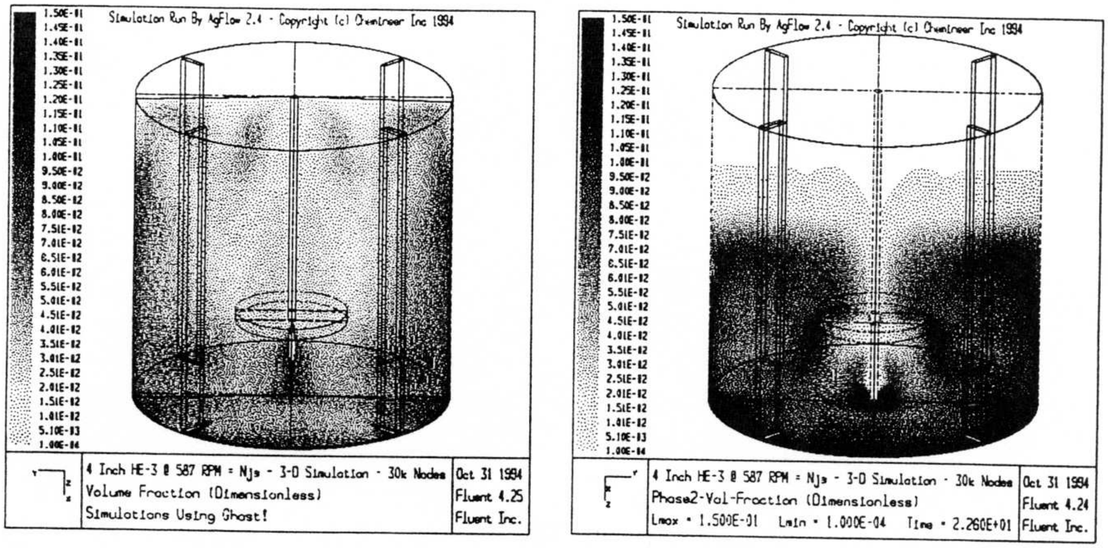

FIGURE 7: THREE-DIMENSIONAL GHOST! (LEFT) AND FLUENT (RIGHT) SOLIDS CONCENTRATION FIELD PREDICTIONS FOR THE HIGH-EFFICIENCY IMPELLER AT JUST-SUSPENDED CONDITIONS WITH D/T = 0.35

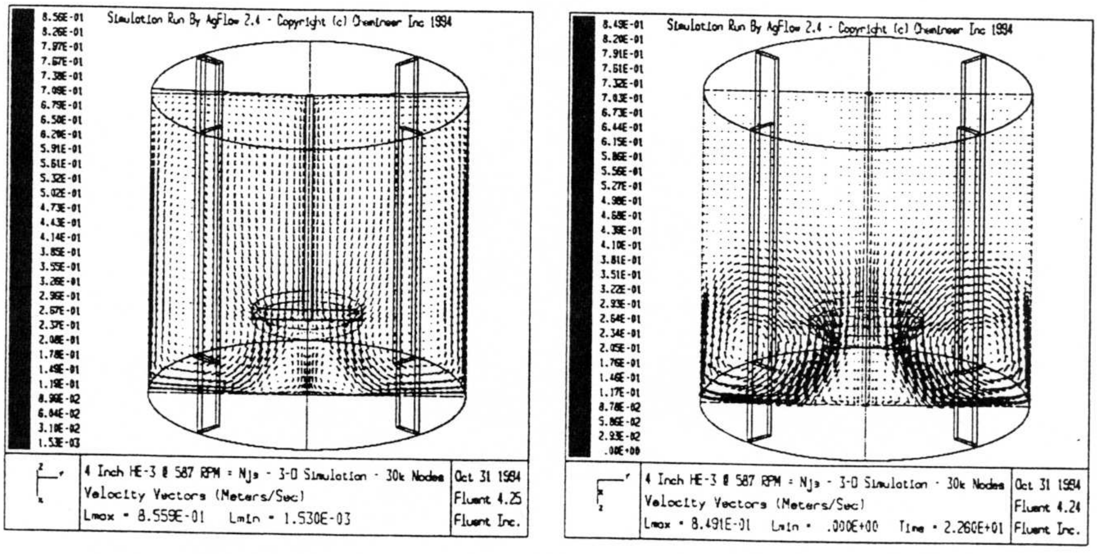

FIGURE 8: THREE-DIMENSIONAL GHOST! (LEFT) AND FLUENT (RIGHT) LIQUID VELOCITY FIELD PREDICTIONS FOR THE HIGH-EFFICIENCY IMPELLER AT JUST-SUSPENDED CONDITIONS WITH D/T = 0.35