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Original Research Paper

Assessment of the effective viscous dissipation for deagglomeration processes induced by a high shear impeller in a stirred tank

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ABSTRACT

A ring-style high shear impeller Hockmeyer® type (HockD-2R) of practical importance (Hockmeyer® Equipment Corp. D-Blade), commonly used in the paint and coatings industry to rapidly break lumps of powdery material in a liquid was investigated, and its performance compared against the classical Rushton turbine (RT). A numerical and experimental study in an unbaffled tank, operating in the laminar to transitional flow regime ($50 \leqslant Re \leqslant 125$) was carried out. Simulations were conducted using commercial Computational Fluid Dynamics (CFD) solver ANSYS Fluent 14.5. Local hydrodynamics (velocity vectors and viscous dissipation), averaged viscous dissipation values and pumping capacities, obtained from simulations, were firstly used to compare the impeller's performance. After that, experiments were performed to investigate the influence of the viscous dissipation on the amount of fines generation from mineral powders. It was found that the volume swept by the blades is the region of maximum effective viscous dissipation, considering its effects on breakage of particle agglomerates. Further experiments were conducted to investigate the influence of the power input on the powder dispersion efficiency. At the same power draw and higher speeds, the HockD-2R was found to be more efficient than the RT for fine aggregates production.

1. Introduction

High shear impellers (HSIs), also known as dispersers, are a type of mixer commonly used in unbaffled cylindrical tanks for wetting and incorporating powders into liquid, as well as for dispersing particle agglomerates and distributing them uniformly in a liquid vehicle. Size reduction of pigment agglomerates by using HSIs in stirred tanks is an important step in a number of industrial processes involving the processing of powders. The dispersion process can be divided in three main steps: (a) powder wetting, (b) breakdown of particle clusters, and (c) flocculation or stabilization of the dispersed particles [1]. Experience shows that one-powder ingredients may differ from another in one or more of the aforementioned steps. For instance, in many technical applications the wettability of the powder might become the rate-controlling step after the last ingredients have been added, i.e., when a small amount of free vehicle is available to wet the surfaces of the final additions of dry pigments.

Another practical aspect that can influence significantly the overall dispersion process is the incorporation time of floating pigments into the mixing solution. To this end, the vortex formation might be useful to characterize the required operating conditions for floating pigments to be quickly incorporated into the mixing solution. However, in this work the dispersion process will be visualized as an act of moving (circulating) and separating (breaking down) particle agglomerates or other lumps, which are well wetted by the vehicles used, and are incorporated into the liquid in order to generate smaller or individual particles by using the mechanical energy provided by the impeller. Thus, the effects of wetting, stabilizing agents or solid incorporation are not considered. In pigment dispersing processes, the design objective is to achieve a maximum dispersion efficiency, which ideally is attained when agglomerate particles are reduced to its primary particle size with minimum energy consumption.

The preparation of concentrated aqueous pigment dispersions at medium viscosities (well known as high solid slurries) is

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common in the paint, cosmetic and paper industries. The rheological behavior of slurries, which often exhibit shear thinning non-Newtonian flow properties, is strongly dependent on the pigment concentration and the nature of other ingredients (e.g. degassing, wetting and surfactant agents). In technical applications, a typical solid concentration is as high as 75% by weight; effective viscosities commonly used are between 0.8 and 9 Pa s. A common practice in industry is dispersing pigment slurries in unbaffled tanks with the purpose that vortex formation occurs in the free liquid surface. At the right impeller speed and effective viscosity, a doughnut flow pattern (laminar flow) with a vortex around the shaft becomes visible in the gas-liquid interface. This is a signal that the maximum shear stress is being transferred into the slurry by the HSI [2] and, furthermore, that the flow is high enough, so that all the agglomerates will eventually reach the high shear region located in the vicinity of the impeller swept volume. With this purpose, HSIs are commonly operated at low Reynolds numbers ($Re = ND^2\rho/\mu$), i.e., in the laminar to transitional flow regime. Here, N and D are the impeller's rotational speed and diameter, while ρ and μ are the fluid density and viscosity, respectively.

Since local maximum values of shear stress are correspondent to maximum values of viscous energy dissipation in laminar flow and, qualitatively, the local distribution of shear stress is similar to the local distribution of viscous dissipation [3], both hydrodynamic parameters are commonly related to the ultimate particle size in actual pigment dispersion processes [3–8].

In practice, choosing the right mixer impeller for an application depends on the process requirements [9]. Thus, a particular impeller is more efficient than standard impellers when its design (hydrodynamic performance) is best suited for a specific purpose and requires less energy consumption. Impellers with particular designs, as HSIs, provide substantial improvements in pigment dispersing processes, where very specific requirements of shear and pumping are desirable. In principle, any mixer impeller device can be classified by its capabilities of circulating (pumping) and shearing (head). The pumping capacity determines the degree of system homogeneity and dispersion time, whilst maximum values of shear stress (or viscous dissipation for laminar flow) determine the ultimate particle size in solid-liquid dispersions [4]. Thus, in principle, if the maximum shear stress values are kept constant in scale-up or scale-down solid dispersion processes, then the same smallest agglomerate size will be achieved. A further objective of HSIs, is attaining the desired degree of homogeneity in the particle size distribution of the system, by providing sufficient effective circulation of the liquid throughout the high shear zone induced by the impeller, but investing most of the power input in shear force [10]. To this end, HSIs are designed for operating at high speeds, which means imparting high local shear to a system volume but consuming minimum power [10], i.e., with low power number (N_P) values.

Despite the practical importance of HSIs operating at low to moderate Reynolds numbers in unbaffled tanks, the knowledge of their hydrodynamics and performance in this flow regime is very limited and literature information is very scarce. General information about their recommended operating conditions is discussed in [2,5] and in patents [10–12], and can also be found in the technical information provided by suppliers. In our literature review, only two previous academic experimental works [7,13] and one numerical study [3] were found on HSIs operating at low to moderate Reynolds numbers.

Duquesnoy et al. [13] introduced a new high shear device, i.e., a rod turbine rotating at the free surface, whose performance was validated by using a dispersion of high solids slurries of calcined and delaminated clays (up to a solids content of 66.7% by weight). According to their experimental observations, low power consumption and very effective powder incorporation are two of the main advantages of this mixing device. Furling et al. [7] evaluated the performance of two new HSIs, namely Deflo and Sevin. Their power consumption and dispersing efficiency were compared against the performance of the well known Cowless sawtooth impeller. Their experiments were carried out with kaolin clays at solid concentrations up to 72% by weight, i.e., a non-Newtonian fluid with apparent viscosities between 0.38 and 9 Pa s. They reported that although the dispersing efficiency of the three impellers is very similar, the power draw of the Cowless impeller is drastically higher than that of the other impellers. They pointed out that this is due to the higher speed required for the Cowless impeller to maintain the vortex flow in the tank when non-Newtonian properties of the slurries are developed.

The results of Furling et al. [7] suggest that, in proportion, an excessive amount of the power draw by the Cowless impeller is invested in pumping instead of in shearing. However, for cohesive powders, such as kaolin clays, dispersing efficiency depends on the shear rate, and the rotation rate is a very important operation variable [8]. Therefore, it is unclear why the Cowless sawtooth impeller, still rotating at higher speeds than the other two impellers studied by Furling et al. [7], produces similar dispersion efficiencies.

Ramírez-Gómez et al. [3] studied numerically the hydrodynamics produced by the same ring-style impeller of two rings evaluated in this study, and compared its performance against a similar impeller of four rings and with the standard Rushton Turbine (RT). They found that the condition of higher speed at the same or higher power draw is not enough to assert higher local viscous dissipation values. They suggest that higher tangential velocities and poor axial pumping (i.e., the suppression of the doughnut type circulation flow) create a compact body of fluid rotation in the region near the impeller swept volume, which produces a sudden low radial acceleration. This is the main cause of the lower viscous dissipation values. These results provide fundamental insight to the experience where satisfactory pigment dispersion is obtained only when a rolling-doughnut type of circulation (laminar flow) is induced by the rotation of the impeller [2,5].

Considering the broad spatial distribution of the local energy dissipation in a mechanically stirred vessel, the maximum dispersion efficiency will not be achieved until all particle agglomerates experience the highest shear stress, coincident with the highest energy dissipation region in the tank. Thus, a question that naturally arises is which volume should be chosen in order to compute the region of maximum dissipation? In the turbulent flow regime, with conventional impellers and for liquid-liquid dispersions, the best order-of-magnitude estimate of the maximum dissipation uses the swept volume by the impeller [14]. In the viscous regime, the region to be considered is the subject of the present work, as well as a recent study by our team [3].

Ramírez-Gómez et al. [3] divided the impeller swept volume into two regions, the impeller blades swept volume and the impeller center swept volume. They suggested the average viscous dissipation in the impeller blades swept volume as the maximum effective dissipation region for solid-liquid dispersions, and they pointed out that it is likely that the ultimate particle size due to the breakage of particle agglomerates is carried out mainly in the blades swept volume rather than in the whole impeller swept volume. However, there is no experimental evidence on the effect of the maximum viscous dissipation obtained from simulations in fine aggregates production. It should be highly valuable to carry out experiments, as in this work, to gain insight into the effective maximum dissipation region for solid dispersion processes for the impellers considered in this study.

The performance of a commercial ring-style HSI of two rings Hockmeyer® type (HockD-2R) operating in an unbaffled cylindrical tank was firstly investigated with the commercial Computational