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Technical Paper

Prediction of vortex height from mechanical mixing in metal matrix nanocomposite processing by means of dimensional analysis and scaling

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ABSTRACT

Mechanical mixing can be used for initial dispersion and distribution of nanoparticle agglomerates in metal matrix nanocomposite (MMNC) fabrication. As vortex height increases, flow is enhanced as well as the risk of oxidate melt contamination. The goal of this study was to examine and predict vortex height using dimensional analysis while varying fluid and the angular speed of a pitched square-blade impeller. An equation proposed by Markopoulos et al. was verified for the present experimental conditions. The relevant dimensionless numbers were the Reynolds (*Re*), Froude (*Fr*) and Galilei (*Ga*) numbers. A modified *Fr* was defined (Fr^*) including the shaft and blade angles of the impeller. Experiments allowed calculation of the dimensionless numbers. Two fluids, water and 50 vol% aqueous glycerine, were used. Angular clockwise speed varied from 200 to 900 rpm in 100 rpm increments. Vortex height was measured in lateral view digital images. Correlations of the dimensionless numbers yielded, first, a linear relationship of the product of dimensionless vortex height (*H*) and specific gravity (ρ^*) with respect to Fr^*. A polynomial relationship was found between *H* and $ReFr^*$ for each fluid. The polynomial coefficients, in turn, follow a power law behavior with respect to *Ga*. This allows a prediction of vortex height in other Newtonian fluids that satisfy the single-phase isothermal flow condition. Perhaps, molten aluminum used in MMNC fabrication, can be analyzed based on a simple, room temperature, low cost transparent fluid system. For the experimental conditions in this study, the equation proposed by Markopoulos et al. was valid. The predicting methodology was verified with experimental results using 25 vol% aqueous glycerine, resulting in an absolute percent error of 5.29%, comparable and lower than an error of 9.12% obtained by predicting vortex height with Markopoulos' equation.

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1. Introduction

A significant improvement in the mechanical properties of metal matrix nanocomposites (MMNCs[1]) requires a homogeneous distribution of nanoparticles in the solidified metal matrix. Mechanical mixing can be used as an initial step to distribute and disperse large nanoparticle agglomerates. However, during this process, a vortex is formed which could be both beneficial for mixing and unsatisfactory due to oxides from air entrapment at the surface. The higher the vortex, the more pronounced the two effects become [1–3]. The measurement of vortex development in the metal matrix is a complex effort. The high temperatures required to reach the molten stage, the opaqueness of the fluid and the elevated experimental cost hinder vortex height measurement and prediction.

Several parameters are involved in mechanical mixing, related to geometric factors, processing variables and physical and material properties. Such complexity makes this system a perfect candidate for dimensional analysis. This numerical technique lumps all the variables of the system into dimensionless groups [4,5]. This method simplifies the study of phenomena occurring in the system and allows scaling while disregarding dimensions.

Research effort has been done on dimensional analysis of mixing and vortex formation, finding strong relationships between mixing time and Reynolds number (*Re*), as well as between vortex height (h_v) and Froude number (*Fr*), Reynolds number and Galilei number (*Ga*). These dimensionless numbers are ratios that establish which effects dominate particular physical phenomena. In mixing processes, it is fundamental to quantify the influence of gravitational, viscous and inertial effects. The Reynolds number (*Re*) gives an indication of the relative importance of inertial and viscous forces in a

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[1] *Abbreviations*: Metal Matrix Nanocomposites (MMNCs); 50 vol% aqueous glycerine (gly50); 25 vol% aqueous glycerine (gly25).

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fluid system [6]. The Froude number (*Fr*) on the other hand determines the rule of inertial and viscous forces in a process. The Galilei number (*Ga*) predicts the importance of gravitational forces and viscous effects.

Markopoulos and Kontogeorgaki [7] proposed an equation for dimensionless vortex height generated by a pitched four-blade turbine, in terms of the Froude number and the Galilei number, and the ratio of tank to impeller diameter, D/d:

$$\frac{h_v}{d} = K_1\, Ga^{0.05}\, Fr \left(\frac{D}{d}\right)^{-0.1} \quad (1)$$

where K_1 is a constant parameter that depends on the type of impeller. Eq. (1) was validated for *Fr* between 0.168 and 0.46, and D/d between 1.90 and 2.37.

Previous studies in our research group have approached dimensional analysis and vortex height [8]. Our past research found a methodology narrowed to vortex generation due to geometrical, dynamic and kinematic effects in Newtonian-type fluids. The current study extends our previous effort strengthening three main aspects. First, a required validation from the previous model is accomplished with a successful prediction of experimental data. Second, we extend *Fr* intervals of the Markopoulos model (Eq. (1)) by purposely choosing parameters from the industry of molten aluminum. Our technique shows higher accuracy compared to the Markopoulos model. Third, technical benefits of four-blade impeller vs. three-blade propeller in vortex formation are discussed.

The present results are initial steps in the prediction of vortex formation in the field of molten metals, considering certain assumptions. It is valid for Newtonian behavior and it only includes geometrical, dynamic and kinematic effects. Aluminum for example, behaves as a Newtonian fluid in the molten stage. Considering isothermal and single phase flow conditions, this model will give insight into the geometrical and dynamic influence in the vortex formation of molten aluminum. Two drawbacks of such results are the exclusion of thermal effects and other aluminum phases such as the semisolid stage, where a non-Newtonian behavior occurs.

The purpose of this study is to use dimensional analysis to study vortex height using a pitched square-blade impeller in a stirring tank while varying fluid and angular speed. These results could potentially be scaled to other Newtonian fluids, such as molten aluminum, a common matrix material for MMNCs. In addition, Eq. (1) will be verified and compared with our model, which offers a wider interval for *Fr* and higher accuracy for the conditions of our study.

2. Methods

2.1. System description and dimensionless groups

The system under study consists of a stirring tank with diameter D (Fig. 1), containing a fluid with density and dynamic viscosity ρ and μ, respectively. An impeller with diameter d rotates with clockwise angular speed n at an angle ϕ with respect to the vertical axis. The blades are at an angle α with respect to an axis perpendicular to the shaft as shown in Fig. 2 [8]. As the impeller rotates, a vortex of height h_v is formed in the fluid. Based on the Buckingham-Pi theorem [9,10], the independent variables involved in the system were defined in terms of their dimensions and lumped in dimensionless groups. The parameter of interest in this study is the dimensionless vortex height, H, defined in Eq. (2) as

$$H = \frac{h_v}{d} \quad (2)$$

To account for the kinematic effects in mechanical mixing and vortex formation systems, Reynolds number, *Re*, and Froude number, *Fr* are the most relevant parameters. These are described by Eqs. (3) and (4), respectively:

$$Re = \frac{\rho u d}{\mu} = \frac{\rho n d^2}{\mu} \quad (3)$$

$$Fr = \frac{u^2}{dg} = \frac{n^2 d}{g} \quad (4)$$

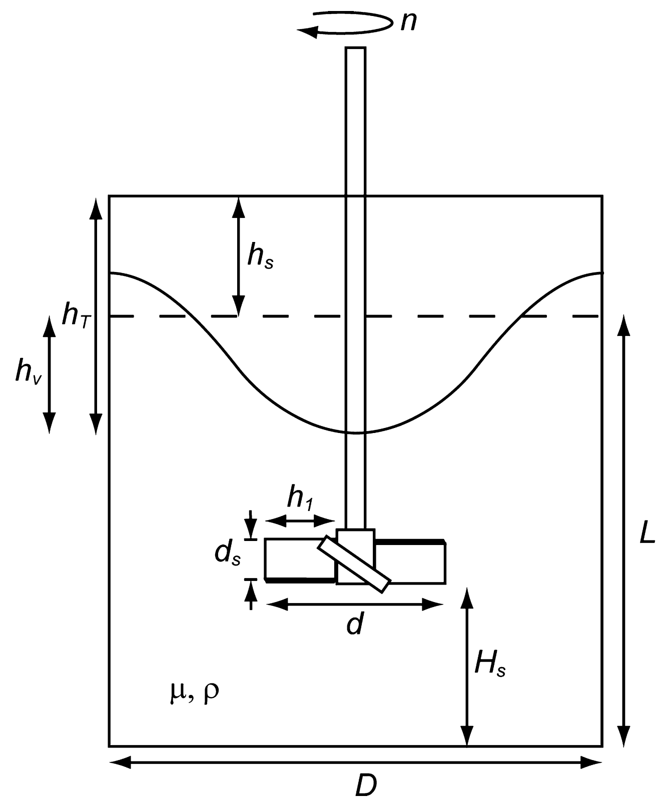

Fig. 1. Schematic of the mechanical mixing system and related variables.

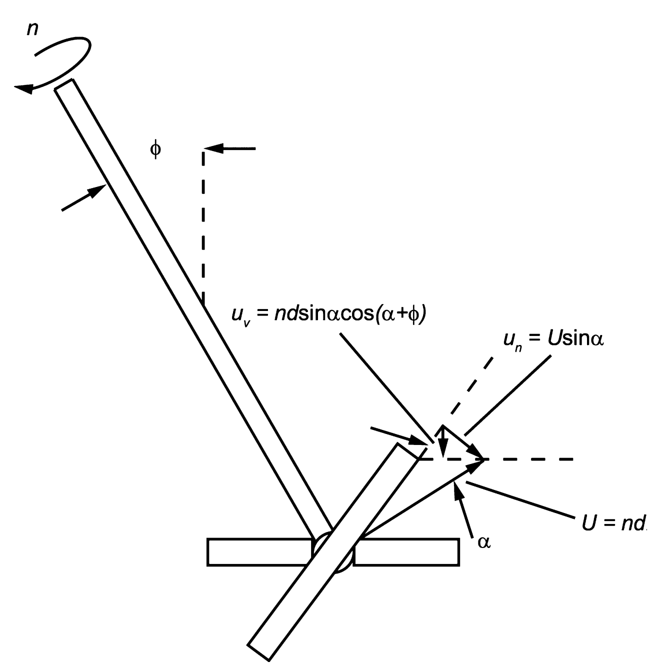

Fig. 2. Definition of system variables in the vicinity of the impeller [8].

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