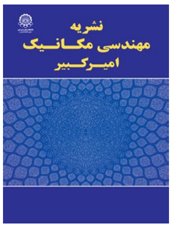

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The Drag Coefficient Prediction of a Rising Bubble through a Non-Newtonian Fluid

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ABSTRACT: In the present research, the drag coefficient of a single bubble rising in the non-Newtonian fluid has been investigated. Polyacrylamide solutions were selected with different concentrations as a Non-Newtonian fluid. As known, these solutions have viscoelastic properties which strongly influence the drag coefficient. The experiments have been done with different nozzle diameters, for three types of gas (Air, and) at different injection flow rates. Hence, the results are more comprehensive than in previous studies. A comparison between the obtained results and the equations in other studies showed that none of these relationships can predict the drag coefficient of a bubble rising in a non-Newtonian fluid with a viscoelastic property. Therefore, two new correlations have been presented to predict the drag coefficient based on Reynolds, Archimedes and Eötvös dimensionless number by dimensional analysis. The first equation which obtained directly from the dimensional analysis was simpler than the second equation. The average error of the first equation was 3.26%, while, the average prediction error of the second equation was about 1.7%, which is more complex in terms of formulation. In addition, new equations for predicting terminal velocities and the behavior of bubble rising in a non-Newtonian viscoelastic fluid are presented.

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1- Introduction

So far, many theoretical and experimental studies have been carried out in order to obtain a comprehensive understanding of the bubble movement through a quiescent fluid. Drag is one of the most important forces in controlling this phenomenon. Hence, a significant amount of researches has been performed to predict the drag coefficient of a rising bubble and its terminal velocity [1-3]. The results of these researches lead to the suggestion of a new empirical correlation more accurate than the previous. In contrast to the Newtonian fluids, the study of the bubble motion in non-Newtonian liquids has more variety and difficulty because of the complicated rheological behavior of these fluids [4, 5].

In most non-Newtonian studies, the same rheological model has been used and the effect of bubble type and its injection velocity has not been studied. Therefore in the present paper, a rising bubble behavior through a non-Newtonian fluid has been studied to find a more comprehensive drag coefficient correlation. Hence, gas bubbles of air, CO2 and O2 ascending in a viscoelastic fluid (aqueous solutions of polyacrylamide) have been studied. The experiments were carried out in different nozzle diameter and injection rates. The results lead to a new correlation conforming to the experimental results.

2- Methodology

The designed experimental set up is shown schematically in Fig. 1. The set-up was consists of a vertical Plexiglas column with a height of , internal cross-section of and thickness of which was filled up to a height of by the liquid. The bubble diameter was controlled by the nozzle. The nozzles used in this experiment had an internal diameter of , and . Experiments were carried out at various gas velocities of $0.4\,\mathrm{ml/min}$, $0.4\,\mathrm{ml/min}$ and $0.4\,\mathrm{ml/min}$.

An aqueous solution of Polyacrylamide (PAAm), a viscoelastic non-Newtonian shear-thinning liquid with weight percentages of 0.1%, 0.2% and 0.4% was used as a fluid. Geometric parameters, as well as single bubble location, are calculated by analyzing the collection of images obtained by image processing.

The studies show that PAAm solutions exhibit shear-thinning and viscoelastic behavior. The rheological properties of the PAA solution were measured by Sosa et al. [6] by rheometer. The viscosity can be expressed by the Carreau-Yasuda equation:

$$\mu(\dot{\gamma}) = \mu_\infty + \left(\mu_0 - \mu_\infty\right)\left[1 + \left(\lambda\dot{\gamma}\right)^{a_1}\right]^{\frac{(a_2-1)}{a_1}} \tag{1}$$

The drag coefficient is a function of three dimensionless quantities: Reynolds number, Archimedes number, and Eötvös number. In this study, the values of each parameter are determined and the effect on the drag coefficient has been studied. The first problem is the definition of Reynolds number and other non-dimensional parameters, due to the change in viscosity of the fluid as a function of shear rate. Thus, with the definition of the average shear rate as $2V/d_{eq}$, the Reynolds number is obtained as follows:

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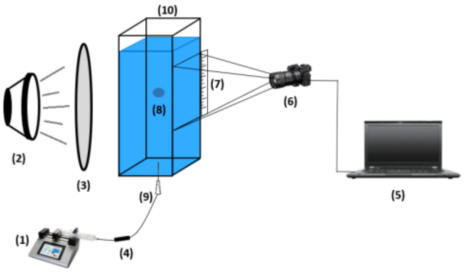

Fig. 1. Schematic of experimental apparatus, 1: Syringe pump, 2: LED lamp, 3: Diffuser, 4: One -way valve, 5: Image processing system, 6: Camera, 7: Ruler, 8: Bubble rising In the liquid column, 9: nozzle, 10: liquid column

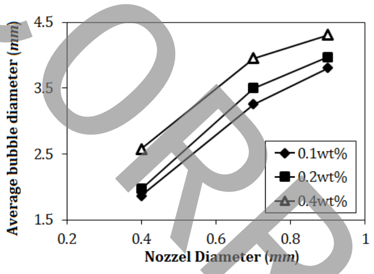

Fig. 2. Bubble equivalent diameter at different concentrations of PAAm

$$\mathrm{Re}=\frac{\rho_l d_{eq} V}{\mu_\infty+\left(\mu_0-\mu_\infty\right)\left[1+\left(\lambda\left(\frac{2V}{d_{eq}}\right)\right)^{a_1}\right]^{\frac{(a_2-1)}{a_1}}} \quad (2)$$

In addition, the Eötvös number is also calculated for the Carreau fluid as follows:

$$Eo=\frac{\rho_l^2 g d_{eq}^3}{\left(\mu_\infty+\left(\mu_0-\mu_\infty\right)\left[1+\left(\lambda\left(\frac{2V}{d_{eq}}\right)\right)^{a_1}\right]^{\frac{(a_2-1)}{a_1}}\right)^2} \quad (3)$$

3- Results and Discussion

3- 1- Bubble diameter equivalent

Fig. 2 shows the bubble equivalent diameter at different concentrations of PAAm. As can be seen, the diameter of the bubble varies in the range of 1.8 and 4.4 mm. The equivalent diameter of the bubble increases with the increasing the nozzle diameter and concentration of the solution.

3- 2- Terminal velocity of bubble

A new equation has been found to predict the limit velocity in the non-Newtonian fluid by the curve fitting and taking into account the liquid density, liquid viscosity and the diameter of the bubble as independent variables.

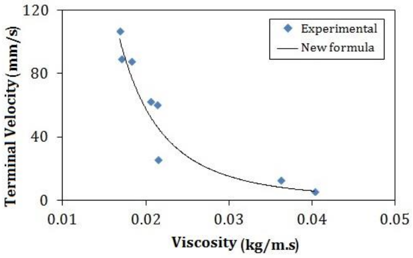

Fig. 3. Validation of the proposed equation for predicting the terminal velocity

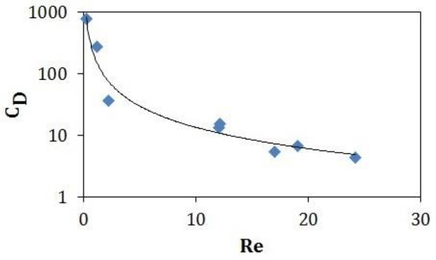

Fig. 4. Drag coefficient calculated for a single bubble rising in PAAm solution vs. Reynolds number

$$V_T=0.2393\frac{d_{eq}}{\rho_l^{0.0118}\mu_l^{2.887777}} \quad (4)$$

The comparison of the predicted values of this equation and laboratory values are shown in Fig. 3. The maximum predicted error value by the equation is about 20%, which is related to the produced bubble with the smallest diameter of the nozzle ($0.4\mathrm{mm}$).

3- 3- Drag coefficient

Fig. 4 shows the relationship between the drag coefficient calculated in this study and the Reynolds number. According to Lee et al. [7], this trend can be attributed to the bubble deformation. Thus, for the shape of the bubble is almost spherical with a diameter ratio of 0.9 to 1.1, while the bubble shape begins to change in flattening shape or spherical-cap shaped for $\mathrm{Re}>10$.

Now, we will try to provide a new empirical equation for the drag coefficient in a non-Newtonian fluid according to the experimental results. According to the dimensional analysis results we have:

$$C_D=5.461478\,\mathrm{Re}^{-1.82973}Ar^{0.23571}Eo^{0.7282} \quad (5)$$

The equation constants are obtained by means of the curve fitting by the least squares method. The average error was 3.26% between experimental data and predicted values. We also obtained a nonlinear correlation for the drag coefficient based on the Reynolds number, Archimedes number, and Eötvös number. Thus, another new equation for predicting the drag coefficient is arrived at on a single bubble rising in a non-Newtonian fluid with a viscoelastic property as follows:

$$C_D = \frac{24}{\mathrm{Re}}\left(1-\frac{\mathrm{Re}^{1.9584}}{4240}\right)\left(\frac{Ar^{0.307511}Eo^{0.64601}}{2.868\,\mathrm{Re}^{0.7782}}\right) \quad (6)$$

Comparison between the values predicted by this equation and the experimental data related to the PAAm solution at different concentrations indicate that the average relative error of the equation is 1.7%.

4- Conclusions

In this paper, the motion of a single bubble in a non-Newtonian fluid with viscoelastic properties was investigated. The operational variables include liquid concentration, bubble type, bubble-producing nozzle diameter, and bubble-entry velocity to the liquid column. Two equations for predicting the drag coefficient of bubble rise in a non-Newtonian viscoelastic fluid are provided by analyzing experimental data.

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