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OPERATING CHARACTERISTICS OF AN AGITATOR WITH A DRAUGHT TUBE

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ABSTRACT

A mechanical agitator is important device for mixing process in many industrial plants. In general, helical screw type agitator is appropriate to mix high viscous fluids; and it has been known that the agitator with a draught tube is more efficient than the others. The draught tube has functions of intermixing between the tube and screw by obstructing radial flows, and making some circulation regime. There are many parameters which affect the performance of the agitator, such as, the shapes of mixing chamber and helical screw impeller, the number of screw pitches, and the existence of draught tube, etc. In this study, mixing efficiency was investigated with various geometrical configurations by tracking the fractions of particle distributions. Numerical analyses were carried out, using a commercial CFD code, Fluent, to find the velocity, pressure and particle distributions. From these results, mixing characteristics and performance of an agitator have been examined, and results are graphically depicted.

NOMENCLATURE

d_p	diameter of solid particle
H_i*	dimensionless parameter (H_i*=h_i/r_2)
n	number of turns of helix
R_i*	dimensionless parameter (R_i*=r_i/r_2)
r_2	characteristic shape factor
Re	Reynolds number
$\boldsymbol{u_i}$	x_i-direction velocity
μ	viscosity [kg/m-s]
ρ	density [kg/m^3]
σ^2	variance of particle suspension
$\phi_{vf,h}$	volume fraction at measured height
ϕ_{vf}	average volume fraction of total volume

INTRODUCTION

The important point of the fluid-solid multiphase systems is the suspension and dispersion of solid particles inside the working fluids. Here, solid particles are such as an intermediate or a final product of reaction. The uniform suspension and dispersion of solid particles in the reacting fluids are capable of being the main parameter which determines the elevation of processing efficiency and the quality of the final goods.

In these days, the prediction of mixing process inside agitators becomes possible with the improvement of computer technology and the development of algorithm which can calculate the solid suspension and mixing characteristics. Specially, HSA (Helical Screw Agitator) that is applied in the present study is suitable to mix high viscous fluids, and ordinary, it has been known that one possessing with a draught tube (baffle) is superior to others.

The previously published studies are as following. Patterson et al. (1979) and Yap et al. (1979) tested mixing performance of HRA (Helical Ribbon Agitator) on the Newtonian and non-Newtonian fluids by experimental methods. Carreau et al. (1993) dealt with the effect of flow characteristics on power consumption with six different shapes of HRA models. Based on experimental investigation, Rai et al. (2000) studied on the heat transfer mechanisms of HRA with Newtonian and non-Newtonian fluids. For the recent studies, Bao et al. (2005) executed numerical study on the suspension of buoyant particles in a three-phase flow mixing chamber. Wang et al. (2005) performed numerical and experimental investigations of liquid-liquid two-phase flow stirred systems. And Ochieng and Lewis (2006) investigated solids off-bottom suspension and cloud height based on numerical simulations.

There were relatively fewer studies about HSA. Jiříĉková et al. (1994) investigated experimentally on the effects of draught tube (baffle) of solid suspension in the turbine type mixer with six blades. Rieger (1993, 1997) made an experiment on the operating characteristics of agitators with a draught tube, and investigated the pumping efficiency of a screw impeller in a draught tube with different Reynolds numbers at the turbulent and laminar regions based on experimental research.

In this manner, it has not been examined closely yet about the flow characteristics and mixing capacity of the helical screw agitator with a draught tube. The objective of the present study is to draw the optimum mixing condition and appropriate design parameters.

NUMERICAL METHODOLOGY

Governing Equations

The fluid flow generated in the helical screw agitator is governed by the mass and momentum conservation principles. If we adopt the classical Eulerian description, this flow can be described by the well-known Navier-Stokes equations as follows:

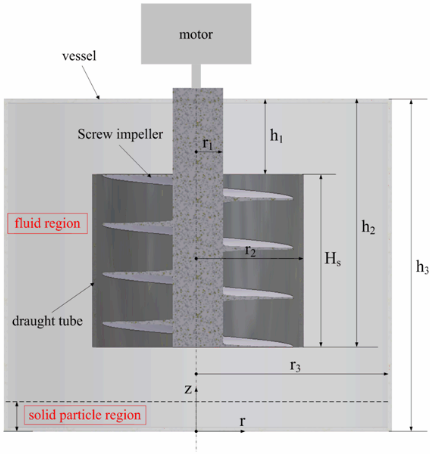


Figure 1: Schematic diagram of HSA model.

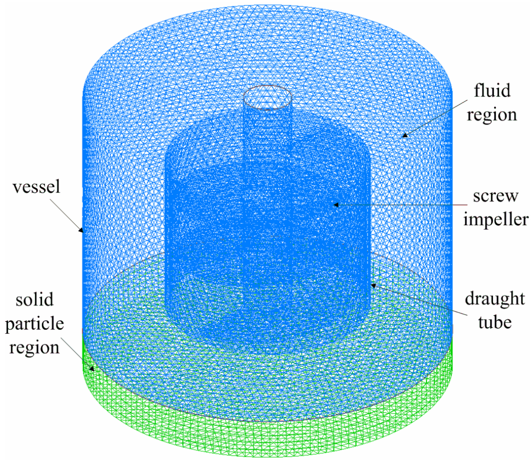


Figure 2: Grid systems of HSA.

continuity equation:

$$\frac{\partial}{\partial x_i}(\rho \mathbf{u}_i) = 0 \tag{1}$$

momentum equation:

$$\rho\frac{\partial \mathbf{u}_i}{\partial x_i} + \rho\left(\mathbf{u}_j \cdot \frac{\partial}{\partial x_j}\right)\mathbf{u}_i = -\frac{d\mathbf{p}}{dx_i} + \mu\frac{\partial^2}{\partial x_i^{\,2}}\mathbf{u}_i \tag{2}$$

here, x_i is the component of Cartesian coordinate systems and $\boldsymbol{u_i}$ is the velocity of x_i-direction. **P** is the pressure, ρ is the density and μ is the viscosity coefficient, respectively.

In order to calculate the particle distribution in the agitator, the following Eulerian multiphase model was used:

continuity:

$$\frac{\partial}{\partial t}(\alpha_s\rho_s) + \nabla\cdot(\alpha_s\rho_s\vec{v}_s) = \sum_{l=1}^{n}\dot{m}_{ls} \tag{3}$$

here, α_p, ρ_p, $\vec{v}_p$ are the volume fraction, density and velocity of each phase, and the subscription l means the liquid phase and s means the solid phase, respectively. And also $\dot{m}_{ls}$ indicates the mass transfer rate from liquid to solid phase.

momentum:

$$\frac{\partial}{\partial t}(\alpha_s\rho_s\vec{v}_s) + \nabla\cdot(\alpha_s\rho_s\vec{v}_s\vec{v}_s) = -\alpha_s\nabla p_s + \nabla\cdot\bar{\bar{\tau}}_s + \alpha_s\rho_s\vec{g}$$
$$+\alpha_s\rho_s(\vec{F}_s + \vec{F}_{lift,s} + \vec{F}_{vm,s}) + \sum_{l=1}^{N}(K_{ls}(\vec{v}_l - \vec{v}_s) + \dot{m}_{ls}\vec{v}_{ls}) \tag{4}$$

where, $\vec{g}$ is the gravitational term, $\bar{\bar{\tau}}_s$ is the stress-strain tensor and K_{ls} is the fluid-solid exchange coefficient. And $\vec{F}_s$, $\vec{F}_{lift,s}$, $\vec{F}_{vm,s}$ are the external body force, the lift force and the virtual mass force, respectively.

Model and Grid Systems

The numerical model for prediction of the mixing characteristics of agitators in tube is depicted in Fig. 1. The three-dimensional HSA model was made by Inventor which is the 3-D CAD tool. The combination of geometrical parameters is based on the prior study by 2-D simulation (Lhota et al., 1980). Its arrangement and specification are shown in Table 1.

The three-dimensional grid systems for the simulation are formed by the CFD pre-processor, GAMBIT (see Fig. 2). Since the shape of helical screw impeller inside the draught tube is relatively complex, unstructured grid generation method and especially fine grid system were applied near the screw impeller. And solid particle region which has 10 mm height from the bottom of the vessel is made by structured grids. As a result totally hybrid mesh creation method was used.

Numerical Analysis

In order to elucidate the effect of the number of screw pitches, two different number of turns of helix, n=2.5 and 3.5 were selected at the same size of mixing vessel. Also, two different angular velocities, respectively, 60 and 90 rpm were applied to examine the effect of rotational frequency.

In the numerical analysis it the angular velocity was assigned to the screw wall by rotating momentum to display the rotational effect of the screw impeller. Also, the Eulerian multiphase model was applied to calculate the particle distribution because liquid and solid particles are coexisted in the mixing vessel. Since the state of flux in

Arrangement (by definition, $R_2^* \equiv 1$)	$R_1^* = 0.24$, $R_3^* = 1.8$, $H_1^* = 0.7$, $H_2^* = 2.3$, $H_3^* = 3$
Notation (dimensionless parameters)	$H_1^* = h_1/r_2$, $H_2^* = h_2/r_2$, $H_3^* = h_3/r_2$, $R_1^* = h_1/r_2$, $R_2^* = r_2/r_2$, $R_3^* = r_3/r_2$
Dimensions (when, $r_2 = 25$) [mm]	$r_1 = 6$, $r_3 = 45$, $h_1 = 17.5$, $h_2 = 57.5$, $h_3 = 75$

Table 1: Specification of the modelled HSA.

the agitator is low Reynolds number flowage ($Re=\rho ND^2/\mu<20$, where, ρ is density, N is revolution per second, D is diameter, and μ is viscosity) like creeping flow regime, the calculation was carried out under laminar condition. The room temperature glycerine (ρ=1259.9 kg/m^3, μ=0.799 kg/m-s) was used as working fluid and carbon (ρ=2000 kg/m^3, $\mu=1.72\times10^{-5}$ kg/m-s, d_p=100 μm) was used as solid particle.

Numerical simulations were carried out, using a commercial CFD code, Fluent, to obtain the flow and mixing characteristics. Governing equations were discretized by FVM (Finite Volume Method) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm. Convergence was determined until residuals were the order of 10^{-4} and the calculations were executed about 10,000 iterations. An elapsed time for computation per each case was taken over 20 hrs in the workstation with Intel Pentium 4A CPU 2GHz and 1GB memory.

RESULTS AND DISCUSSION

Flow Characteristics

Totally the flow pattern is marked similar trends for two different shapes of HSA as shown in Figs. 3 and 4. We could confirm the circulation region is formed by draught tube which has the function of disturbing the radial flow from rotating the screw impeller. It is seen that Type 2 has relatively higher values of pressure and velocity than the case of Type 1. Therefore, it seems that Type 2 has brisker mixing action between the screw and draught tube than Type 1. Also, in the results of velocity distribution, relatively clear circulation region is shown.

case	Type 1		Type 2	
	60 rpm	90 rpm	60 rpm	90 rpm
σ^2	2.06×10^{-5}	1.61×10^{-6}	2.46×10^{-6}	7.53×10^{-6}

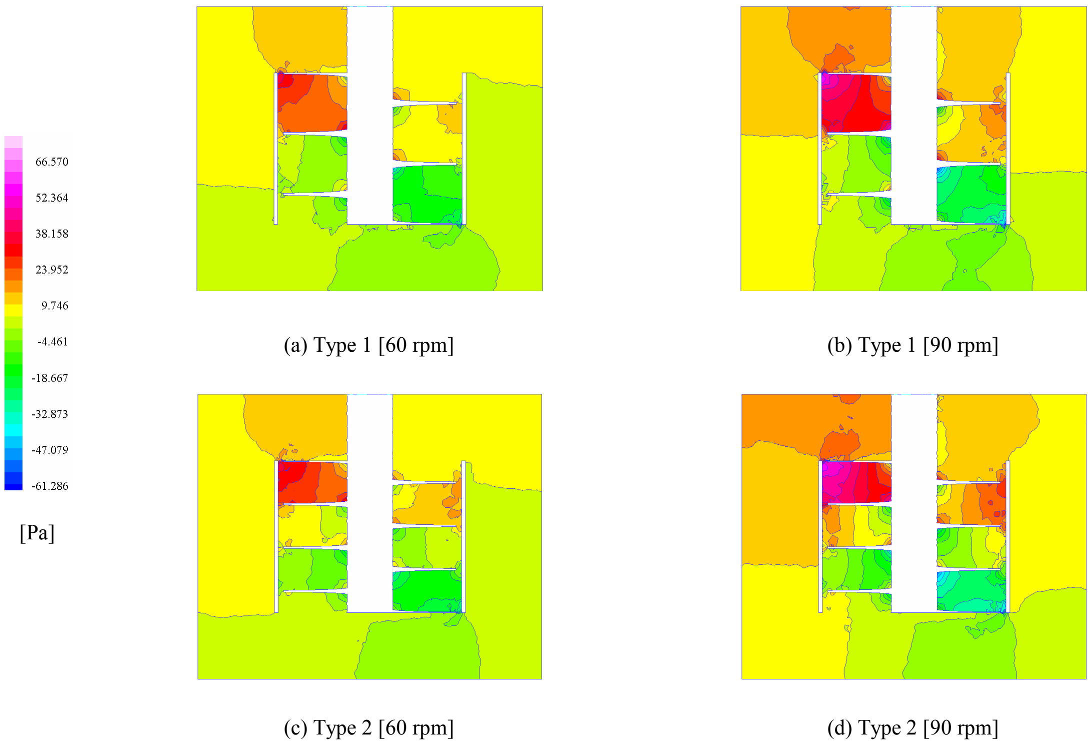
Table 2: Variances (σ^2) for the solid particle distribution.

Solid Particle Distribution

The characteristics of solid particle distribution were obtained in the agitator with draught tube and the mixing performances were evaluated with respect to the effects of the number of screw pitches and angular velocity. The characteristics of particle distributions are depicted in Fig. 5. These figures indicate that solid particles distribute uniformly for Type 2. For the quantitative analysis the variance (σ^2) which is the representative statistical parameter was calculated as shown in Table 2. The variance is defined as follows:

$$\sigma^2 = \frac{1}{N}\sum_{1}^{N}\left[\left(\phi_{vf,h}/\phi_{vf}\right)-1\right]^2 \qquad (5)$$

where, $\phi_{vf,h}$ is the volume fraction of solid particles at the height (h) from bottom of the vessel and ϕ_{vf} is the average volume fraction of solid particles in the whole volume. From the values of variance we know that there are about five to ten times differences between 60 and 90 rpm. It is also noted that, for the case of 90 rpm, more uniform distribution of solid particles was drawn for the mixing process. As a result, it seems that the case of 90 rpm has superior capacity to the case of 60 rpm.



(a) Type 1 [60 rpm] (b) Type 1 [90 rpm]

(c) Type 2 [60 rpm] (d) Type 2 [90 rpm]

Figure 3: Pressure distribution on the vertical direction of HSA models.

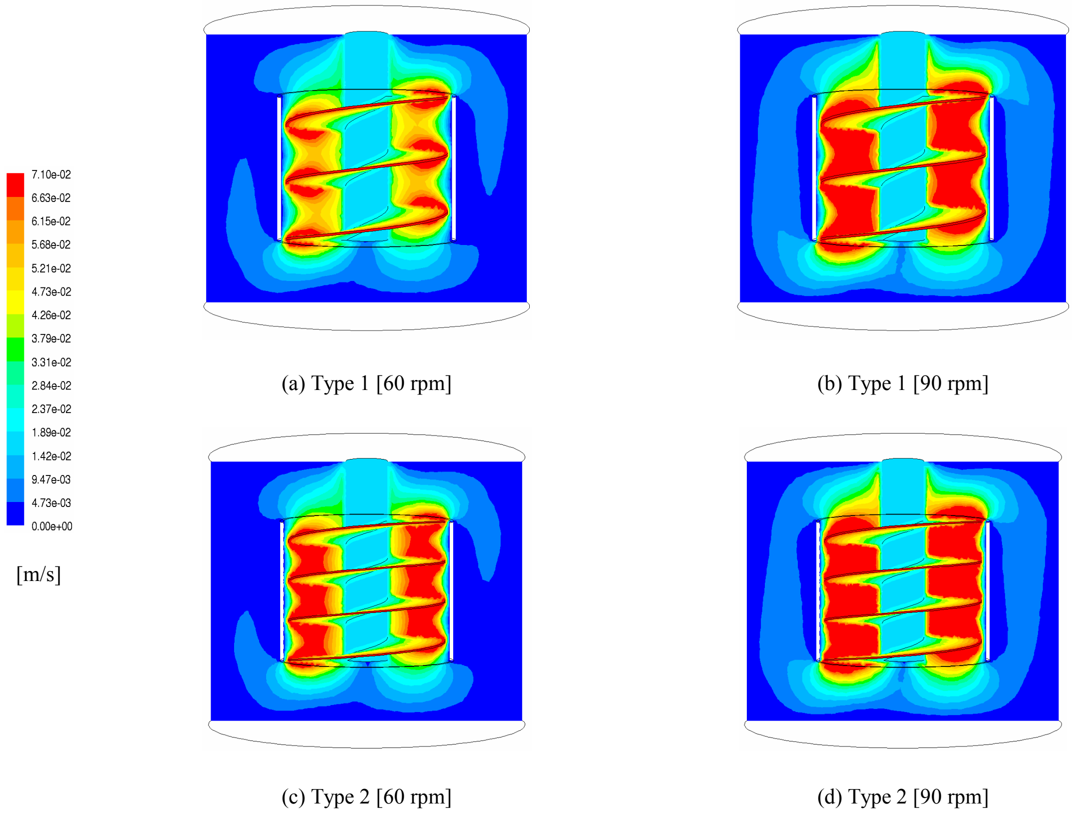


Figure 4: Velocity distribution on the vertical direction of HSA models.

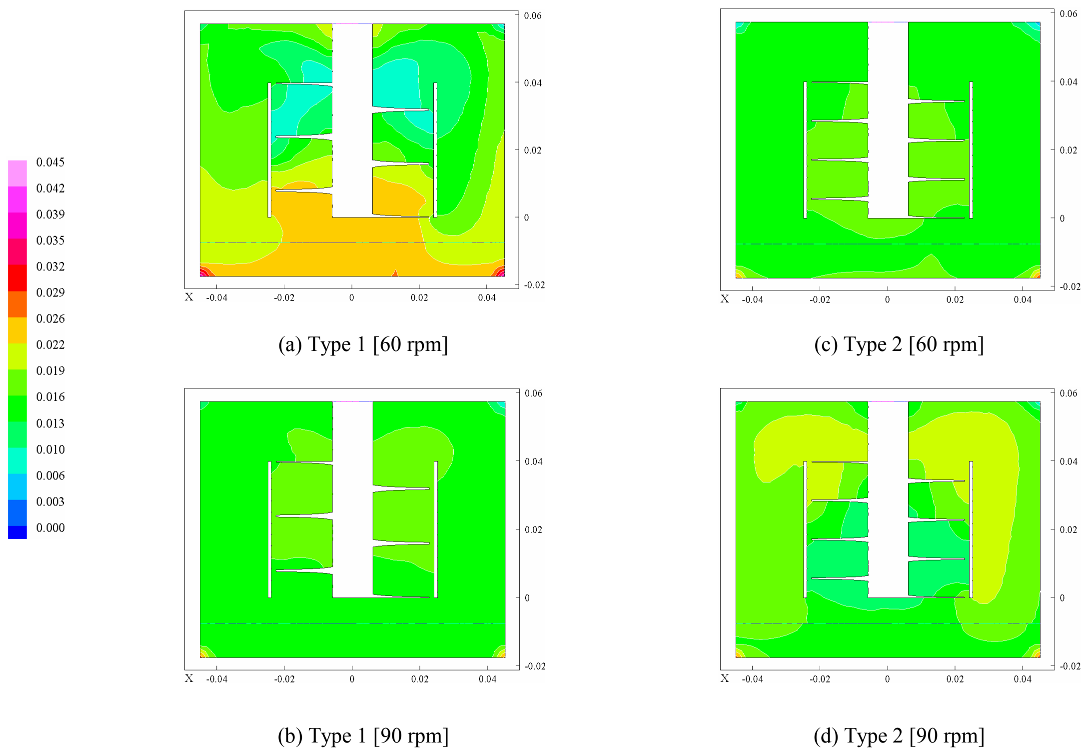
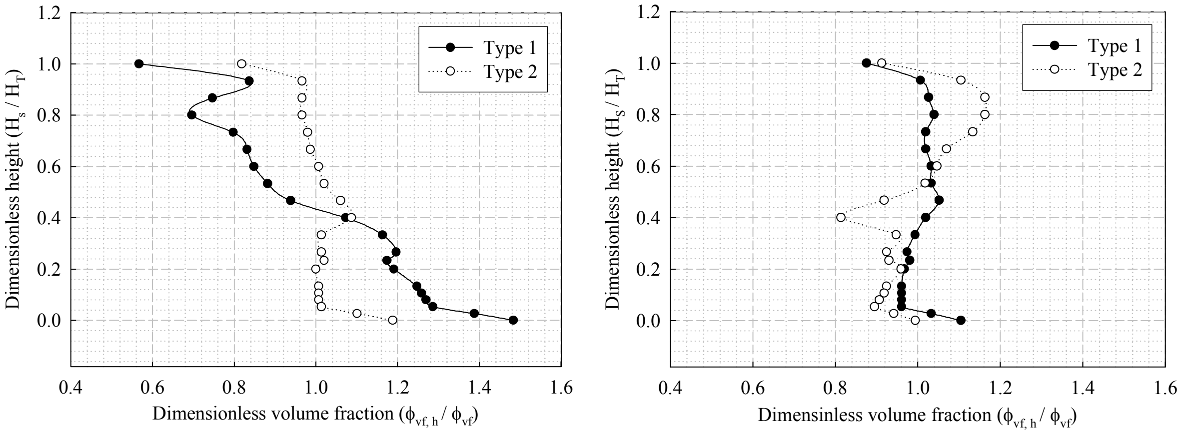


Figure 5: Solid particle distribution on the vertical direction of HSA models.



(a) 60 rpm

(b) 90 rpm

Figure 6: Effect of the number of screw pitches on the mixing performance.

From the results of particle distribution as shown in Fig. 5, Type 2 indicates valuable pattern of particle dispersion. From the graphical point of view, the case of Type 2 with 60 rpm has the most regular particle distribution in the mixing vessel. It is a little encouraging phenomenon because power consumptions for increasing the rotational frequency can be reduced. Judging from this, Type 2 with 60 rpm has higher efficiency than the other cases within the mixing process. Also, we could find out partial particle concentration in the corner of mixing vessel. It is required further study for eliminating these useless spaces by altering into the shape of the vessel.

Effect of Screw Pitches

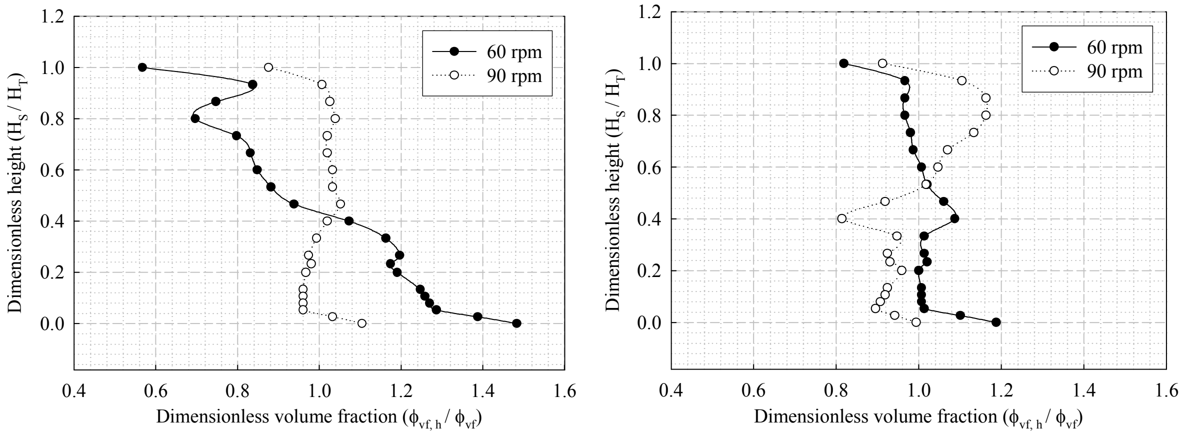
General mixing performance of HSA models was derived by numerical analysis for two different values of screw pitch and rotational frequency. Typical shapes of these correlations were shown in Fig. 6. In this diagram, horizontal axis represents the dimensionless values of the volume fraction of solid particles, which were divided by the average volume fraction. The ordinate axis is the values of dimensionless height which were divided by the total height of stirred vessel. It can be seen from this diagram that the mixing capacity of Type 2 is higher than Type 1. Since the value of dimensionless volume fraction nearby the value of 1 manifests the index of uniformity.

Effect of Rotational Frequency

The numerical results are illustrated in Fig. 7 where the mixing characteristics for two different values of screw pitch and angular velocity are depicted. From these results it can be seen that Type 2 is more efficient to stir its reactants than Type 1 and also the case of Type 2 with 60 rpm was reflected the nearest value of 1 on the x-axis. It is noted that the case of Type 2 with 60 rpm has the optimum conditions out of four cases with regard to the efficiency.

On the other hand, for the case of 90 rpm, it has large volume fraction in the upper part of the mixing vessel while small volume fraction in the lower part. It is noted that the case of 90 rpm has higher mixing and pumping capacity than the case of 60 rpm. However, the power consumptions should be enlarged to increase the angular velocity since the large shear forces are induced due to high viscous liquid in the mixing vessel. Furthermore, the efficiency is closely related to the operating cost, so that this is one of the important factors for selecting the agitator. Therefore, it is necessary to find out the compromise between opposite motives, i.e., the power consumption and efficiency.

Aforementioned, there were some of particle concentrated regions in the lower part of the vessel and some of particle shortage regions in the top of the vessel. It was



(a) Type 1

(b) Type 2

Figure 7: Effect of the rotational frequency on the mixing performance.

caused by the geometrical configuration of the mixing vessel. Therefore, it is required further study to investigate the effect of changing vessel shapes, e.g., round shape by fillet corners or the spherical chamber, and so on.

CONCLUSIONS

In this study, the flow and mixing characteristics of HSA models were investigated using numerical simulations. Numerical calculation of both characteristics was based on the investigation of functional relationships changing the shape of screw and the angular velocity in total four cases of HSA arrangements. From these results, the following conclusions are obtained.

1) The flow patterns were totally similar to every case but Type 2 has higher pressure and velocity values. Specially, for the cases of Type 2, the components of velocity in the draught tube were higher than Type 1. Therefore it is noted that Type 2 has more active intermixing in the draught tube and superior mixing efficiency to the case of Type 1.

2) As the statistical parameter, the variances of solid particle distribution were calculated for analysing the characteristics of particle distribution quantitatively. From the comparison of the variances, it is seen that Type 2 has a little better mixing performance than Type 1.

3) From the results of solid particle distributions, it is seen that Type 2 has overall superior capacity to Type 1. It is also noted that the case of 90 rpm has higher capacity than the case of 60 rpm. However, we must consider the relationship between the power consumption and efficiency.

4) Judging from the result of the mixing characteristics, it is noted that Type 2 with 60 rpm has the optimum mixing condition out of total four cases. Also it is required further numerical studies that minimize some of dead spaces like stagnation region in the upper and lower part of the mixing vessel.

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