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# Eulerian Simulation of Bubble Columns Reactors and Effect of Various Parameters on the Gas Holdup

*Gas holdup and bubble size are important parameters for simulation and designing in bubble column reactors. Because based on these parameters, the available gas-liquid interfacial area is defined for mass transfer. In this paper, the results of applying magnetic fields on the velocity field and volume fraction of gas holdup are reported. Hydrodynamics of the bubble column in the reactors is investigated numerically using Euler-Euler model, standard k-ε turbulence model considering axisymmetric assumption, and the control volume technique. The results show that the magnetic fields have minor effects on increasing the volume fraction of gas holdup, but it causes to change in the flow field and vortex. In addition, effects of other parameters as well as rotation of the fluid, bubble size, and variation of inlet velocity on the volume fraction of gas holdup have been presented.*

*Keyword:* Gas holdup, Magnetic field, Velocity field, Bubble size, Euler-Euler model

## 1 Introduction

Bubble columns which are cylindrical vessels wherein gas is sparged via a distributor in the form of bubble into liquid or liquid-solid suspension, are widely used in industry because of their simple construction and operation such as applications includeoxidation, halogenations, hydrogenation, hydrohalogenation, ammonolysis, hydroformylation, Fischer-Tropsch, reaction,ozonolysis, carbonylation, carboxilation, alkylation, fermentation, wastewater,treatment, hydrometallurgical operations, column flotation in bubble column reactors [1-3].

There are many studies in the literature on bubble columns: D. Pfleger and S. Becker [4] have been investigated the liquid phase measurement focus on the local liquid phase velocities and volume fraction of gas in the bubble column reactor in three dimensional using dynamic Eulerian-Eulerian two phase model and standard k-ε turbulence model. In other work, R.F.

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Mudde and O. Simonin [5] use full two-phase model including turbulence modeling for two dimensional and three dimensional cases. In this study, the interfacial forces between two phases the drag and virtual mass have been taken into account and it has been shown that if only the drag force used both the amplitude and the oscillations the flow much smaller than observed experimentally and changing the standard k-ε model to a low Reynolds k-ε ones does not alter the flow behavior significantly.

The behavior of the air-water system characterizes with low gas void fraction for both the laminar and turbulent model has been investigated by D. Pfleger and S. Gomes [6]. Based on their obtained results, the laminar model shows a chaotic behavior and cannot show a harmonic oscillation observed in experiments but turbulent model can show this behavior. The effects of the sparger design and height to diameter ratio and radial gas hold-up profiles have been simulated by M.T. Dhotre and K. Ekambara [7].They have simulated three different gas-liquid systems (i.e., air-water, aqueous solution of butanol, and air-aqueous solution of carboxyl methyl cellulose).

A. sokolichin and G. Eigenberger[8] simulated laminar and turbulent models of Euler-Euler type in two and three dimensions and showed that by applying the 2D laminar model for calculations the dynamic character the simulation results depend strongly on the space resolution used, but for 2D k-ε turbulent model the grid independent solution can be achieved on a relatively coarse grid.V.V.Buwa et al [9] investigated experimentally and numerically the effects of gas velocity sparger design and coalescence suppressing additives on dynamics of gas-liquid flow in a rectangular bubble column. The gas-liquid flow in a square cross sectioned bubble column with LES and k-ε model using Euler-Euler simulations has been studied by M.T. Dhotre et al [10]. In this work an extra contribution in the effective viscosity for turbulence induced by bubbles has been taken into account using the Sato model.

It should be mentioned that there are a few studies for the effects of magnetic field on the two phase flow; the effect of an applied magnetic field on the two phase flow characteristics such as distributions of void fraction, pressure and temperature has been investigated numerically by S. kamiyama et al [11]. Also recently, T. Tagawa [12] studied numerically dynamics of a falling droplet of liquid metal into a horizontal liquid metal layer and of a rising air bubble in water subject to a magnetic field.

It should be mentioned that the above mentioned studies for the bubble reactors mainly focused on increase gas holdup in reactors using numerical Euler-Euler method; therefore in this study the effects of various parameter such as bubble size, velocity inlet, rotation of reactor and magnetic field on the gas holdup as 2D axisymmetric model have been presented. Also, in the following the effects of rotation and magnetic field on velocity field in the reactor have been investigated. In next section the basic theoretical formulation including the governing equations has been presented, boundary conditions and numerical method results are discussed in section 3 and finally section 4 contains some conclusions.

## 2 Theoretical formulation

In this paper, two fluids (Euler-Euler) model which both phases are treated as a continuum has been used. It is assumed that the temperature variation is negligible and model is isothermal. It is assumed that the liquid phase to be incompressible and gas phase has a constant properties. All the bubbles generated at the sparger have equal size and the bubble coalescence and breakage are neglected and sum of the volume fraction of two phases is taken as unity. Single pressure field is assumed to be shared for two phases and no mass exchange can occur between the two phases.

The continuity equation is formulated for each phase without exchange between phases after Reynolds averaging term [9]

$$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla.(\alpha_q \rho_q \vec{u}_q) = 0 \quad (1)$$

here $u_q$ and $\alpha_q$ is the velocity and volume fraction of phase $qth$ respectively. After Reynolds averaging, one can consider the momentum equation for the phase $qt\ h$as follows:

$$\frac{\partial}{\partial t}(\alpha_q \rho_q \vec{u}_q) + \nabla.(\alpha_q \rho_q \vec{u}_q) = -\alpha_q \nabla p + \nabla.\bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} + \sum_{p=1}^{n} k_{pq}(\vec{u}_p - \vec{u}_q) + \vec{F}_{Lorentz} \quad (2)$$

The effect of virtual mass and lift force in this work have been neglected. In the above equation,$\bar{\bar{\tau}}_q$is the stress tensor of the $qth$ phase and calculated by:

$$\bar{\bar{\tau}}_q = \alpha_q \mu_q (\nabla \vec{u}_q + \nabla \vec{u}_q^T) + \alpha_q \left(\lambda_q - \frac{2}{3}\mu_q\right) \nabla.\vec{u}_q \bar{\bar{I}} \quad (3)$$

here $\mu_q$and $\lambda_q$ are shear and bulk viscosity of phase $q$ respectively.

The exchange coefficient for gas-liquid flow has been considered as following form:

$$k_{pq} = \frac{\alpha_q \alpha_p \rho_p f}{\tau_p} \quad (4)$$

The momentum exchange due to drag forces is:

$$F_{drag} = \frac{3}{4}(\alpha_q \rho_p) \frac{C_D}{d_p} (u_p - u_q)|u_p - u_q| \quad (5)$$

$$f = \frac{C_D Re}{24} \quad (6)$$

$$C_D = \begin{cases} 24(1 + 0.15Re^{0.687})/Re & Re \leq 1000 \\ 0.44 & Re > 1000 \end{cases} \quad (7)$$

$$Re = \frac{\rho_q |\vec{u}_p - \vec{u}_q| d_p}{\mu_q} \quad (8)$$

here $C_D$ is drag coefficient, to compute this coefficient the Schiller and Naumenn relation has been used. To apply the effect of magnetic field on the fluid flow, the Lorentz force source term has been added to the momentum equation [13, 14]. It should be mentioned that the Lorentz force describes as $\vec{F} = \vec{J} \times \vec{B}$ .Where $B$ is magnetic field and $J$ is electric current and is equal to$\vec{J} = \sigma\left(\vec{E} + \vec{U} \times \vec{B}\right)$ where $\sigma$ is electrical conductivity and $U$ is velocity field on flow, respectively.

Also it should be noted that in this work since the magnetic Reynolds number $Re_{mag}$(for most liquid metal flows are very high) for sea water (which is used for liquid phase) $Re_{mag} << 1$, onecan neglect the viscous dissipation and induced electric current.

The magnetic field is imposed in radial direction and since the Lorentz force has a direct relation with velocity (i.e., in a system with zero velocity the Lorentz force will be zero), the reactor should be considered in rotation. The standard $k$-$\varepsilon$ turbulence model has been used to simulate the two phase flow system [6, 8].In this study to model turbulence in gas liquid mixture, two additional transport equations are necessary: one for the turbulent kinetic energy (i.e.,$k$) and another for the eddy dissipation rate of turbulence (i.e., ε) [3] as follows:

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla.(\rho_m \vec{u}_m k) = \nabla.\left(\frac{\mu_{t,m}}{\sigma_k}\nabla k\right) + G_{k,m} - \rho_m \varepsilon$$
$$\frac{\partial}{\partial t}(\rho_m \varepsilon) + \nabla.(\rho_m \vec{u}_m \varepsilon) = \nabla.\left(\frac{\mu_{t,m}}{\sigma_\varepsilon}\nabla \varepsilon\right) + \frac{\varepsilon}{k}\left(C_{1\varepsilon} G_{k,m} - C_{2\varepsilon}\rho_m \varepsilon\right) \tag{9}$$

The mixture density and velocity are calculated by:

$$\rho_m = \sum_{i=1}^{N} \alpha_i \, \rho_i$$
$$u_m = \frac{\sum_{i=1}^{N} \alpha_i \rho_i \vec{u}_i}{\sum_{i=1}^{N} \alpha_i \, \rho_i} \tag{10}$$

The turbulent viscosity of the mixture $\mu_{t,\,m}$ is computed as follows:

$$\mu_{t,m} = \rho_m C_\mu \frac{k^2}{\varepsilon} \tag{11}$$

In the above equations $\sigma_k$,$\sigma_\varepsilon$ denotes turbulent Prandtl number for kinetic energy and dissipation rate respectively and $G_{k,m}$is the generation of turbulence kinetic energy in the mixture. Standard values for the k-ε model parameters have been tabulated in Table (1).

**Table 1** Constants used in the k-ε model

| $C_1$ | $C_\mu$ | $C_2$ | $\sigma_k$ | $\sigma_\varepsilon$ |
|---|---|---|---|---|
| 1.44 | 0.09 | 1.92 | 1 | 1.3 |

## 3 Numerical solution

In present paper, 2D axisymmetric model in two states have been investigated numerically: first the reactor has rotational velocity and in the second case it is assumed that to be stationary. Dimension of the geometry and total used grid have been presented in Table (2). At the bottom of the reactor the air coming in the sparger with uniform velocity and the width of the sparger is 0.02 m. It is assumed that all of the bubbles generated in each simulation have equal size. The mentioned coupled non-linear differential equations were discretized with the control volume technique. For pressure–velocity coupling the phase coupled SIMPLE algorithm has been used. Since the investigated case is unsteady problem, used time step size is 0.01s in the all numerical simulations. For each time step the convergence criteria when take place that the sum of the normalized residuals be less than 10e-5.

**Table 2** Grid independency and dimensions of geometry

| Number of cells | width | height | inlet of reactor |
|---|---|---|---|
| 27000 | 0.2m | 0.54m | 0.02m |

### *3-1 Boundary conditions*

All of the walls have been assumed isothermal and the temperature variation of the flow is neglected (see Figure 1). Atmospheric pressure is used at the outlet and at the inlet, only air enters and four different inlet velocities have been considered for it presented in Table (3).

**Table 3** various amount of velocity inlet

| $V_1$ | V2 | V3 | V4 |
|---|---|---|---|
| 0.166m/s | 0.2m/s | 0.25m/s | 0.3m/s |

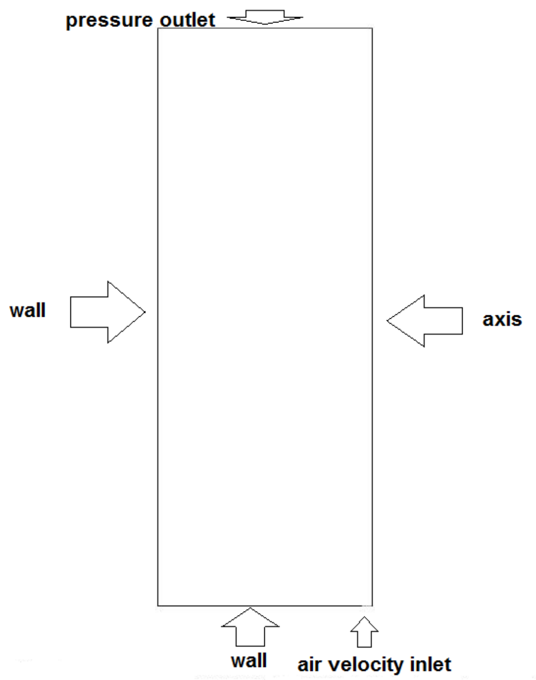
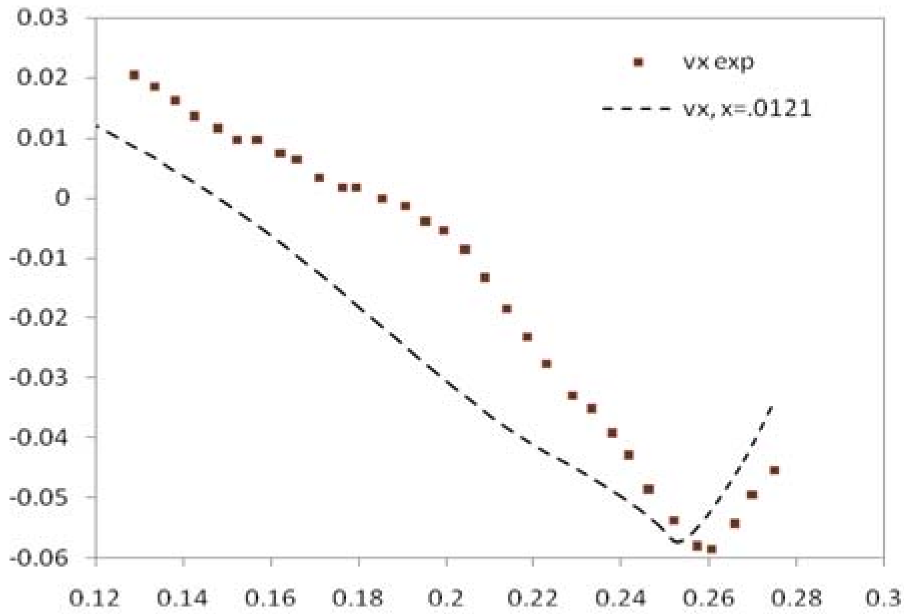


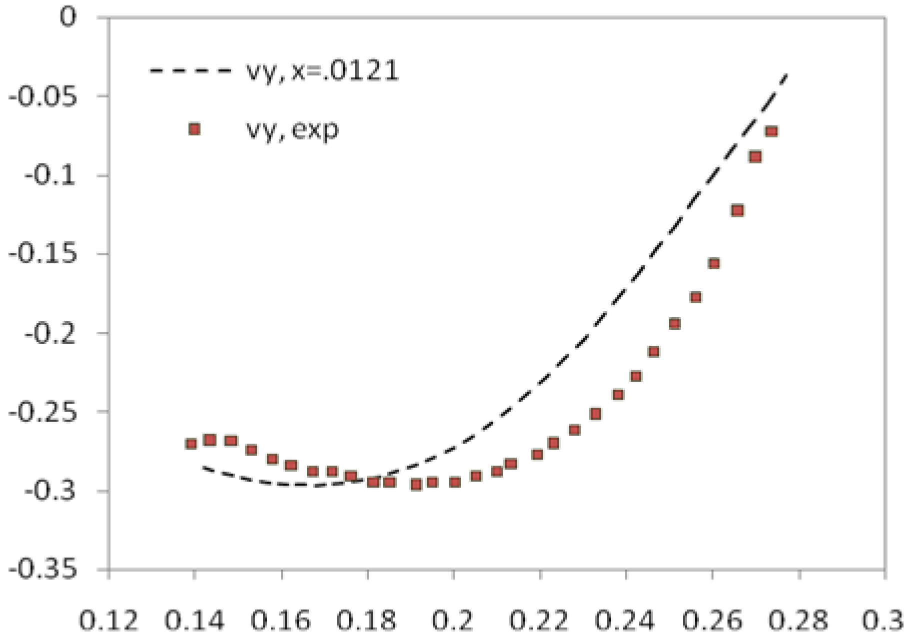

**Figure 1** Schematic of the reactor and used boundary conditions

## 4 Validation

In order to validate this method, obtained numerical data from Euler-Euler method where compared with experimental data [3]. In Figure (2), vertical and horizontal components of velocity were plotted at x=0.0121 m along y axis.




(a)




(b)

**Figure 2** Comparison velocity component of numerical data with experimental data at x=0.0121m along y direction: a)$v_x$ ,b)$v_y$

## 5 Results and discussion

To study the effect of the bubble diameter, three different diameters0.001m, 0.003m, and 0.005m have been considered. Sparger releases the bubble in the primary fluid with uniform velocity0.166m/s and it is assume that the reactor is in stationary state and with no magnetic field. As shown in Figure (3), when the bubble diameter reduces the amount of distributes of the gas phase in the primary fluid increase and the time for reaching the bubbles to the surface is increased.

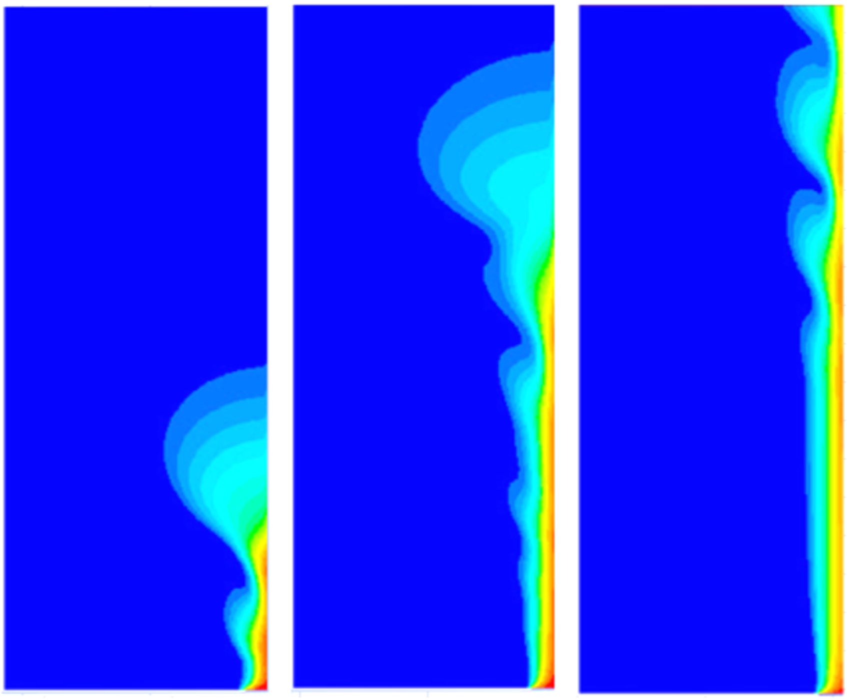


**Figure 3-**(a)

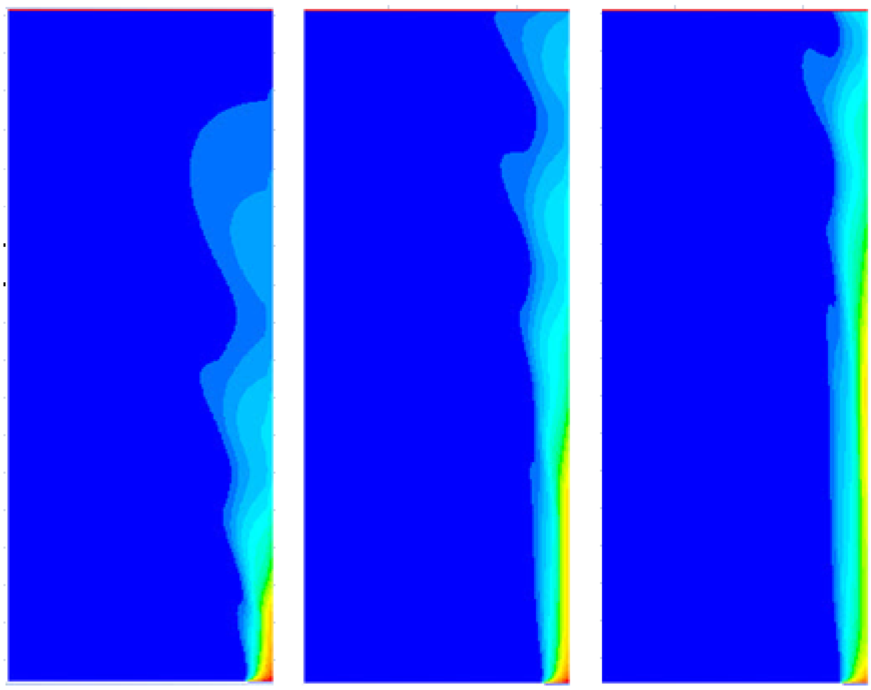


**Figure 3-** (b)

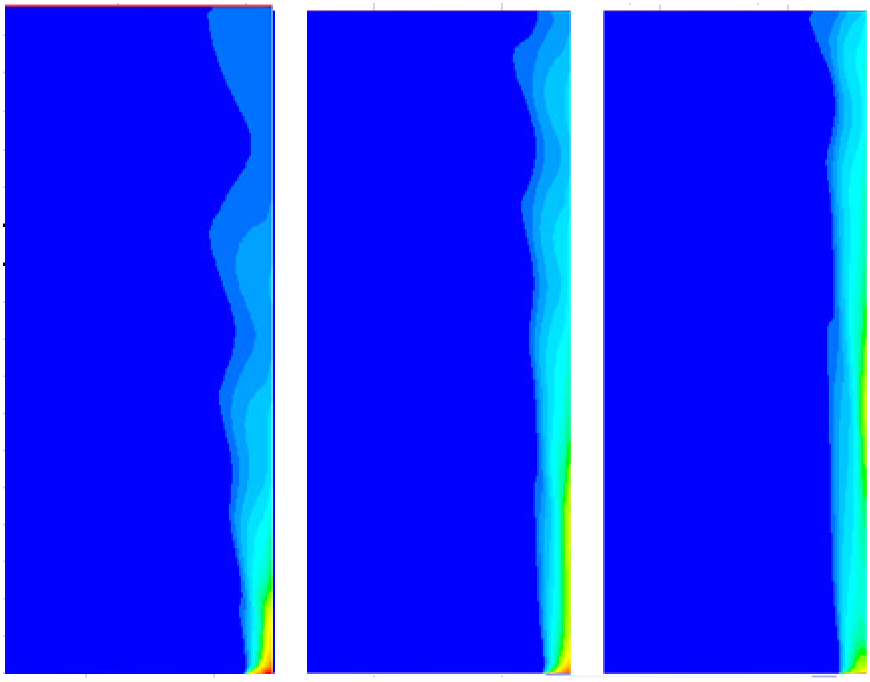


**Figure 3-** (c)

**Figure 3** Contours of volume fraction with $V_{in}$= 0.166m/s, without magnetic field and rotation for bubble diameters: a)0.001m , b)0.003m and c)0.005m

Figure (4) shows the effect of bubble size on the volume fraction in time for three bubble diameter sizes: 0.001m, 0.003m, and 0.005m, respectively. As seen by reducing the bubble size, volume fraction of gas holdup is increased.

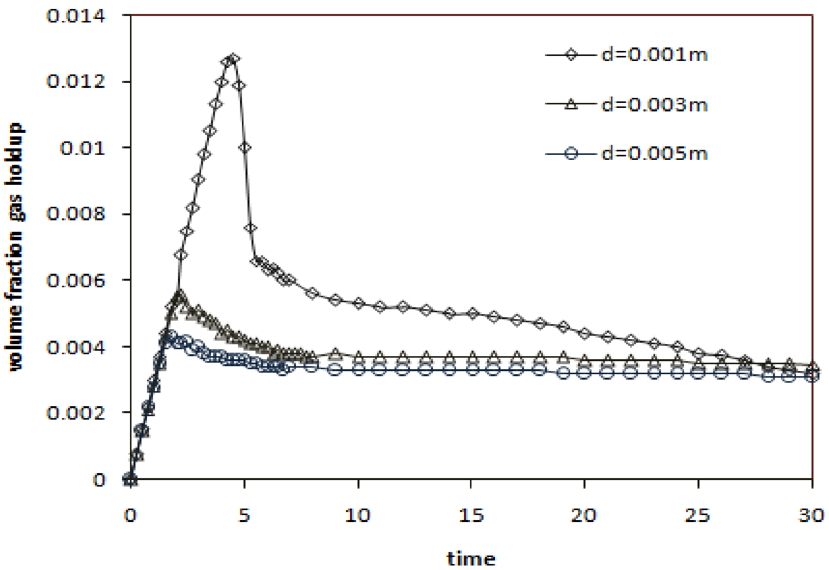



**Figure 4** Effect of bubble diameter on volume fraction gas holdup with time for air velocity inlet 0.166m/s without magnetic field and rotation

Figure (5-a) presents the stream lines without of the rotational velocity and magnetic field. As shown, the stream lines have counter clockwise recirculation because of dragging the liquid by the gas phase. Also Figure (5-b) indicates the stream lines for the case that the reactor is rotated with ω=5rad/s and no magnetic field. Based on the obtained results, the stream lines have counter clockwise direction similar to Figure (5-a), but the vortex tends to near of the left wall. The effect of magnetic field on the stream lines has been presented in Figure (5-c) by considering a magnetic field with Ha=69.2. As seen, there are two vortexes in the stream lines with different recirculation direction in this case.

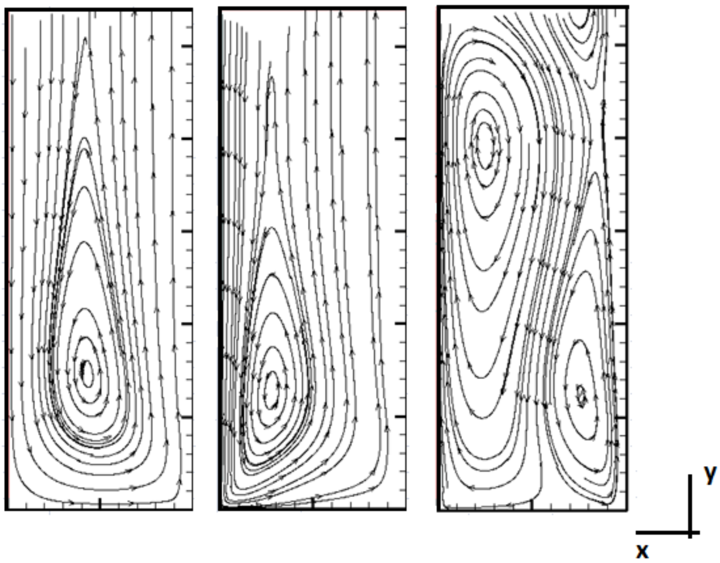



**Figure 5** (a) Streamlins for air velocity inlet 0.166m/s and bubble diameter 0.003m without magnetic field and rotation(b) streamlins for air velocity inlet 0.166m/s and bubble diameter 0.003m with ω=5rad/s,without magnetic field (c) streamlines for air velocity inlet 0.166m/s and bubble diameter 0.003m with ω=5rad/s,Ha=69.2

Effect of magnetic field on liquid phase is more than gas phase because of the electrical conductivity of liquid phase is 4.8 but for gas phase this amount is near zero. Imposing magnetic field on fluid flow makes two vortexes, this vortexes cause better mixing of phases. This effect are shown in Figure (6) and make increase in the amount of gas holdup than the state that we haven't magnetic field in the reactors.

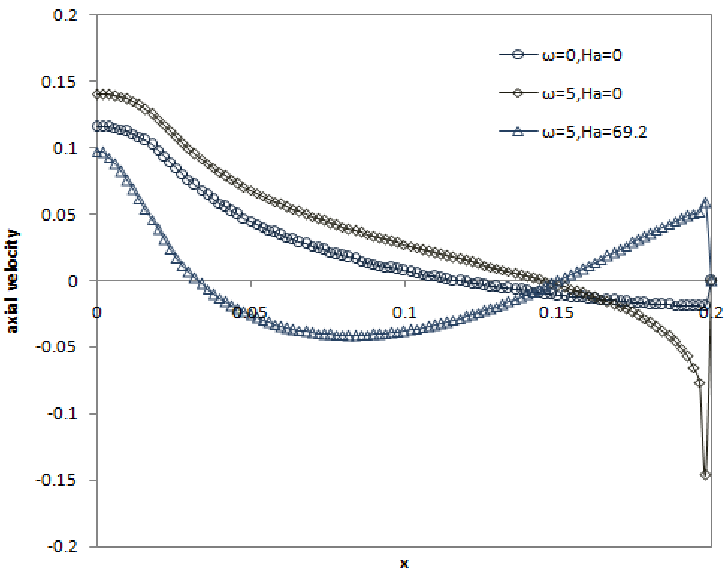



**Figure 6** Axial velocity variation for horizontal line y=0.4m along x direction

Figure (7) presents the axial velocity for horizontal line at y=0.4m along x direction for three different cases: 1) ω=0, Ha=0, 2) ω=5 rad/s, Ha=0 and 3) ω=5 rad/s, Ha=69.2. As seen for cases (1) and (2) the obtained axial velocity profiles along the mentioned horizontal line nearly are similar, but for case (3) a different profile has been achieved because of applying magnetic field. We observe that the axial velocity in cases (1) and (2) changes from positive to negative as we go up along the line because according Figure (5-a) and (5-b) the streamlines are counter clockwise. In the state (3) the axial velocity near the right end and left end point is positive and in the middle of the line is negative because magnetic field makes two vortexes in opposite direction according to the Figure (5-c).

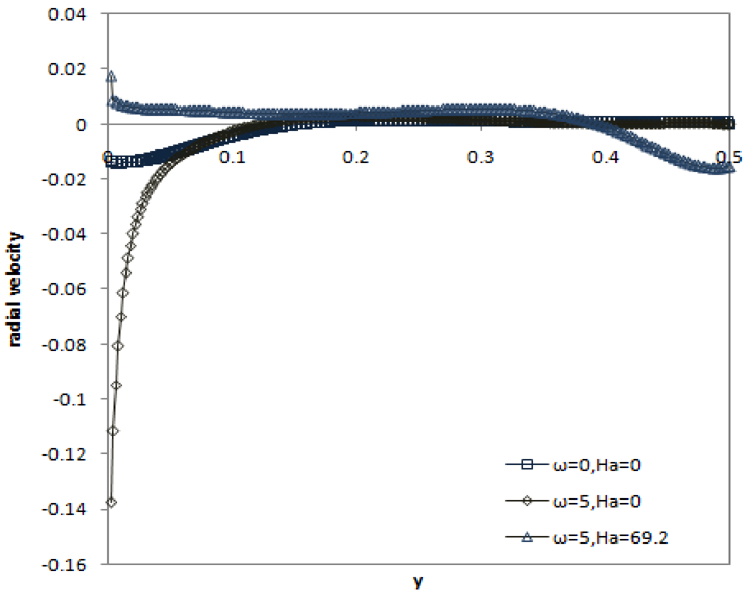



**Figure 7** Radial velocity variation for vertical line x=0.15m along y direction

Figure (8) shows the effect of rotational velocities of fluid on the gas holdup volume fraction in time. Three rotational velocities (i.e., ω) have been examined: ω =0, ω=5 rad/s, and ω=10rad/s. It should be mentioned that for the all cases the velocity of air at the inlet is 0.166m/s and there isn't magnetic field and also the bubble diameter is 0.003m. Based on the obtained results by increasing in ω, the volume fraction is also increased.

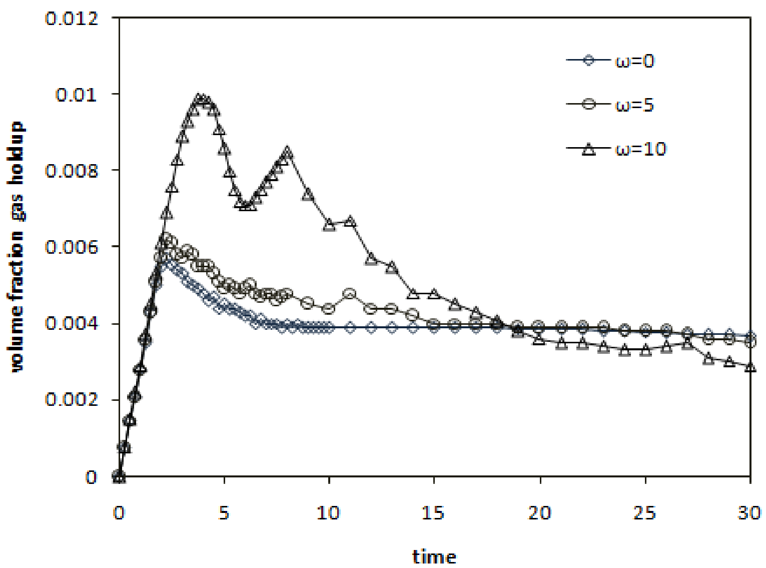



**Figure 8** Effect of rotation of fluid on variation of volume fraction gas holdup with time for air velocity inlet 0.166m/s ,bubble diameter 0.003m and without magnetic field

In the follow the effect of magnetic field on the gas holdup volume fraction variation in time has been presented in Figure (9) in three different Hartman number: Ha=0, Ha=41.5, and Ha=69.2.

In this case also the velocity inlet of air is 0.166m/s and bubble diameter is 0.003m and the primary fluid rotates with ω=5 rad/s inside the reactor. Results show that imposing the magnetic field has effect on increment of gas hold up volume fraction.

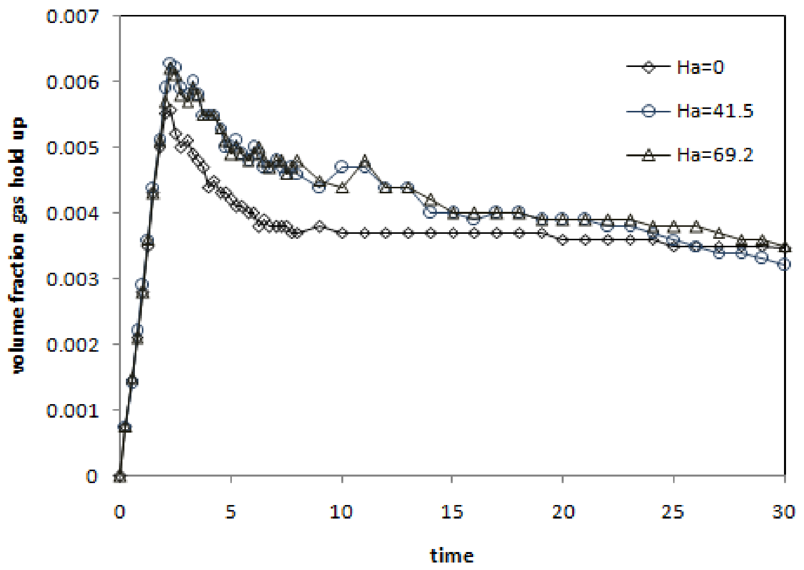



**Figure 9** Effect of magnetic field on variation of volume fraction gas holdup with time for air velocity inlet 0.166m/s ,bubble diameter 0.003m ,ω=5 rad/s

Figure (10) presents that effect of increment in the inlet velocity on the gas hold up volume fraction for four different inlet velocity: v=0.166 m/s, v=0.2 m/s, v=0.25 m/s, and v=0.3m/s. It should be mentioned that in this case the reactor does not rotate and there is not magnetic field and the bubble diameter is 0.003m. Based on the obtained results by increment inlet velocity, the gas holdup volume fraction is also increased.

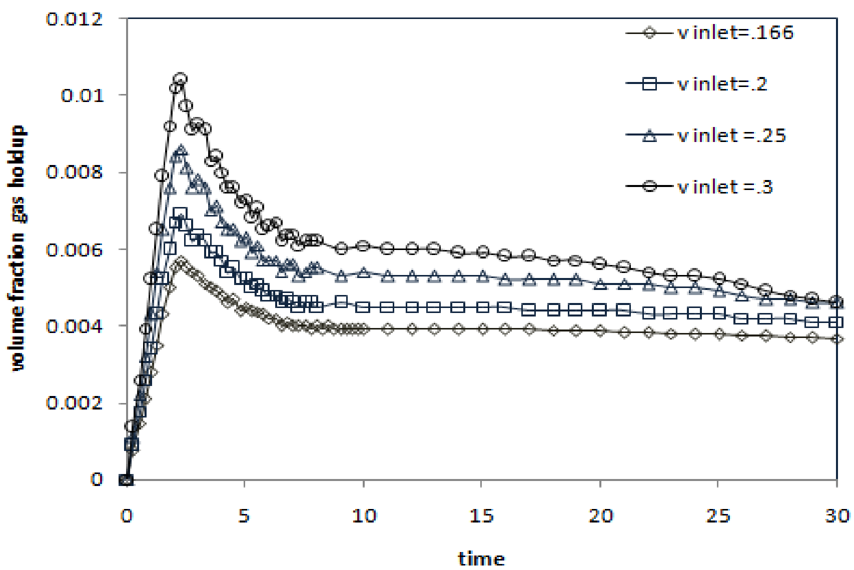



**Figure 10** Effect of vriation of air velocity inlet on volume fraction gas holdup

We can obtain the turbulent kinetic energy as follows: $k = 1/2\left(\overline{u'^2} + \overline{v'^2}\right)$. Figure (11) shows variation of turbulent kinetic energy at point (0.4, 0.15) with time for two cases with magnetic field and without it. As mentioned before this, using Eq. (8), we can obtain turbulent viscosity for Euler-Euler model. Figures (12 and 13) present the turbulent viscosity and turbulent intensity variation with time at same point. Turbulent kinetic energy, turbulent viscosity and turbulent intensity are turbulent characteristic and when these parameters increase make better mixing in reactors. We observe in Figures (11,12, and 13)when we impose magnetic field amount of this parameters are more than the state that we haven't magnetic field so mixing phases increase and cause increase in gas holdup than the state that we haven't magnetic field according Figure (9) .

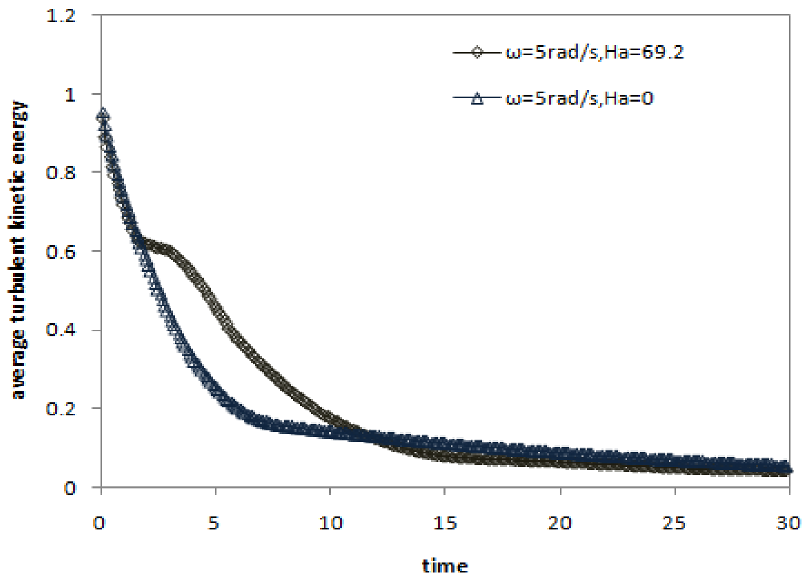



**Figure 11** Variation of average turbulent kinetic energy with time

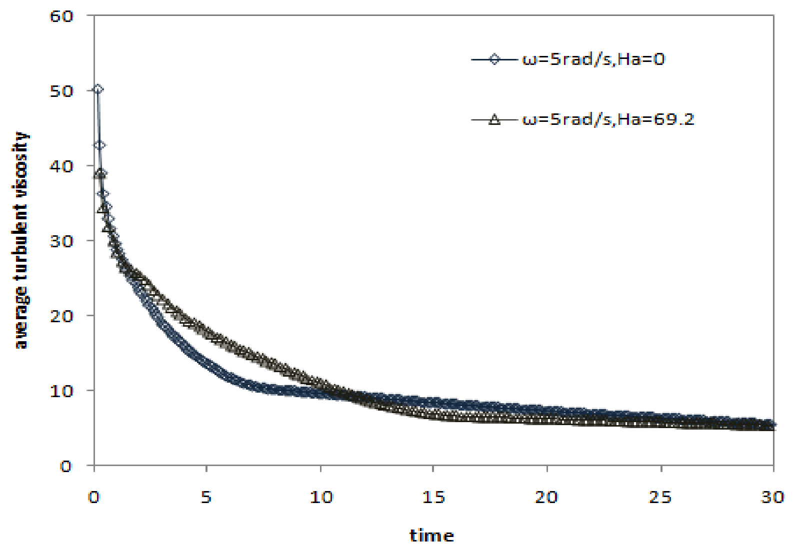



**Figure 12** Variation of average turbulent viscosity with time

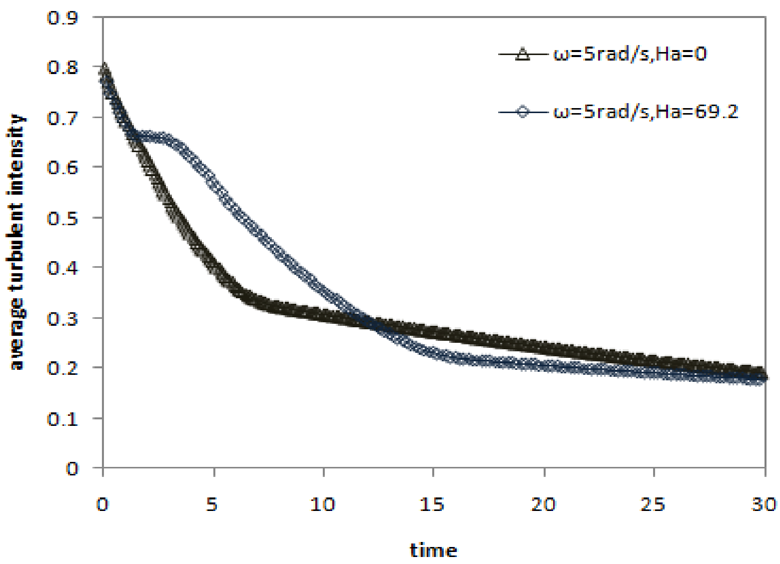



**Figure 13** Variation of average turbulent intensity with time

## 6 Conclusions

In this work Euler-Euler model was used to simulate the bubble column reactor using standard k-ε turbulent model. Different parameters effects on the gas holdup volume fraction and velocity field investigated and based on the results one can conclude:

1) Reduction in bubble size causes increment in the gas holdup volume fraction and the time needed for reaching the bubbles to surface is also increased.

2) Increment in the air inlet velocity makes in the gas holdup volume fraction.

3) Incensement in rotational velocity of fluid inside the reactor causes increment in the gas holdup volume fraction.

4) Applying magnetic field on the fluid shows that increment in Ha number causes increment in the gas holdup volume.

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## Nomenclature

| | | |
|---|---|---|
| $u_q$ | : | velocity of the *qth* phase $[ms^{-1}]$ |
| $u_p$ | : | velocity of the *pth* phase $[ms^{-1}]$ |
| $g$ | : | acceleration due to gravity $[ms^{-2}]$ |
| $k_{pq}$ | : | exchange coefficient of gas- liquid flow $[kg^2m^{-4}s^{-2}]$ |
| $Re$ | : | Reynolds number |
| $Re_{mag}$ | : | magnetic Reynolds number |

| | | |
|---|---|---|
| $d_p$ | : | diameter of the bubbles *[m]* |
| $F_{drag}$ | : | drag force *[N]* |
| $C_D$ | : | drag coefficient ,dimensionless |
| $K$ | : | turbulent kinetic energy *[ms$^{-2}$]* |
| $u_m$ | : | mixture velocity *[ms$^{-1}$]* |
| $C_1$ , $C_2$ , $C_\mu$ | : | empirical constant |
| $G_{k,m}$ | : | generation of turbulent kinetic energy |
| $F$ | : | Lorentz force *[N]* |
| $J$ | : | electric current *[A/m$^2$]* |
| $B$ | : | magnetic field *[Tesla]* |
| $E$ | : | electric field*[v/m]* |
| $Ha$ | | Hartman number $BL\sqrt{\sigma / \mu}$ |

*Greek symbols*

| | | |
|---|---|---|
| $\alpha_p$ | : | volume fraction of the *qth* phase |
| $\rho_q$ | : | density of the *qth* phase *[kgm$^{-3}$]* |
| $\tau_q$ | : | stress tensor of the *qth* phase *[Nm$^{-2}$]* |
| $\mu_q$ | : | liquid viscosity of phase *qth* phase*[pas]* |
| $\rho_m$ | : | mixture density *[kgm$^{-3}$]* |
| $\mu_{t.m}$ | : | turbulent viscosity of the mixture *[kgm$^{-1}$s$^{-1}$]* |
| $\sigma_k$, $\sigma_\varepsilon$ | : | empirical constant |
| ε | : | turbulent dissipation rate *[ms$^{-2}$]* |
| $\sigma$ | : | electrical conductivity of the medium |
| $\omega$ | : | vorticity *[rad/s]* |

*subscripts*

| | | |
|---|---|---|
| $p$ | : | *p*-th phase |
| $q$ | : | *q*-th phase |
| $m$ | : | mixture |
| $k$ | : | refers to turbulence property |
| $\varepsilon$ | : | refers to turbulence property |

**چکیده**

نگهداشت گاز و اندازه حباب پارامترهای مهمی برای شبیه‌سازی و طراحی در راکتورهای ستون حباب است. چونکه بر اساس این پارامترها، منطقه موجود بین گاز و مایع برای انتقال جرم تعریف می‌شود.

در این مقاله، نتایج حاصل از اعمال میدان‌های مغناطیسی بر میدان سرعت و کسر حجمی گاز نگهداشته شده، ارائه شده است. هیدرودینامیک ستون حباب در راکتور با استفاده از مدل اویلر- اویلر و مدل توربولانس k-ε استاندارد با در نظر گرفتن فرض تقارن و روش حجم کنترل بصورت عددی مطالعه شده است. با توجه به نتایج بدست آمده، اعمال میدان مغناطیسی اثرات جزئی در افزایش کسر حجمی گاز نگهداشته شده دارد. اما اعمال میدان باعث ایجاد گردابه در سیستم شده است. علاوه بر این، در کار حاضر اثرات پارامترهای دیگری چون چرخش سیال، اندازه حباب‌ها، و سرعت ورودی در کسر حجمی گاز نگهداشته شده، ارائه شده است.