Modeling and Simulation of Three Phase Fluidized Bed Characteristics Using MATLAB

A. Sivalingam, T. Kannadasan, M. Thirumarimurugan, and D. Prabhakaran

***Abstract*—In literature, several correlations are available for the prediction of mass transfer characteristics. However, almost no correlations have been so far proposed counting the effect of Archimedes number, which is widely used in calculating the different parameters influencing mass transfer in fluidized bed. Hence an effort has been made by carrying out mass transfer studies in a co-current three phase fluidization system for Newtonian and non Newtonian fluids with and without internals, to propose correlations for Sherwood number relating with solids holdup, Reynolds number and Archimedes number. In this study, various sizes of Gypsum particles, air and water were used as solid, gas and liquid phases respectively. Water was replaced with various concentrations of Carboxymethylcellulose for non Newtonian studies. Experiments were carried out with liquid as continuous phase and gas as discrete phase. The bed height and manometer readings were noted for different gas and liquid velocities. From the recorded data, phase holdups and mass transfer characteristics were determined. From the experimental data, correlations were developed for Sherwood number relating with Archimedes number by dimensional analysis and linear regression analysis. The simulated values were compared with experimental values and verified with R^2 values.**

***Index Terms*—Archimedes number, fluidized bed, gypsum particles, phase holdups.**

I. Introduction

Fluidization has been a pivotal topic of research among the researchers for the past three decades [1]. Since the Winkler process for gasification of coal was on track, the focus on fluidization has been consistently gaining significant importance in industrial phase as well as in academic research. The concept of fluidization in Winkler process was further developed into various successful applications such as FCC (fluid catalytic cracking), Metallurgical process, Sohio process, synthesis of polymers, combustion and in the recent years for the treatment of waste water [1]-[5]. Analogous to such industrial developments, considerable academic research has also been carried out in the field of fluidization. Relative to other multiphase contactors, there are plenty of works available in the three phase fluidization, with most studies directed towards understanding the hydrodynamic characteristics [6]-[8]. Comparatively very few researchers have worked on phase studies as well as mass transfer in such systems [9], [10]. However, significant works have been carried out by researchers so far focusing on the prediction of Sherwood number in three phase systems by proposing different correlations [11].

In this present work, the mass transfer characteristic, Sherwood number of a co-current three phase fluidization system has been studied for different sizes of gypsum particle with both Newtonian and non Newtonian fluids. An effort has been made to study the effect of internals on the Sherwood number by carrying out experiments with and without internals. From the experimental data, correlations were developed for Sherwood number using dimensional analysis and linear regression analysis, which comprise of Archimedes number, Reynolds number and solid holdup. Archimedes number is generally used in calculations of fluid motion due to density difference. According to Goossens [12], the calculation of the Archimedes number is a relatively simple tool for industry to predict the class and the related fluidization behavior of any fluid particle system under consideration. Gupta investigated several correlations for estimation of minimum fluidization velocity, in which Archimedes number has been effectively dealt with [13].

Hence, a significant attempt was made to develop correlations for relating the mass transfer characteristic-Sherwood number with viscous forces and solid holdup for both Newtonian and non Newtonian fluids, in the presence and absence of internals. The regression analysis was carried out with the aid of MATLAB programming and the simulated values were compared with the experimental values graphically and subsequently verified with the R^2 values.

Notations used:
N_{Ar} - Liquid Archimedes number
$N_{Re,m\ liq}$ - Modified Reynolds number for liquid,
N_{Sh} - Sherwood number, $N_{Sh} = K_y a\ \varepsilon\ d_p / D_v\ a$
ε_s - Solid holdup
ρ_l - Liquid density, kg/m^3
ρ_g - Gas density, kg/m^3
ρ_m - Density of manometric liquid, kg/m^3
ρ_s - Density of solid particles, kg/ m^3
CMC - Carboxymethylcellulose
R^2 - Linear Regression Coefficient

II. Materials and Methods

The experimental setup consists of a liquid storage tank from which water is pumped by a centrifugal pump. The flow rate of water and air is measured using a rotameter and an orifice meter, respectively. A schematic diagram of experimental setup is shown in Fig. 1. A vertical Perspex column, 1.6 m tall with internal diameter of 5.4×10^{-2} m and

Manuscript received May 22, 2012; revised October 23, 2012.
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outer diameter of 6×10^{-2} m is used, which consists of three sections: the gas-liquid distributor section, test section and gas-liquid disengagement section. The gas-liquid distributor is located at the bottom of the test section and designed in such a manner that uniform distribution of the liquid and gas can be maintained in the column. The circular gas distributor section made of copper is provided with four protrusions each having I.D. of 1.4×10^{-2} m. The liquid inlet pipe of 2.5×10^{-2} m I.D. is located centrally in this section. The outlet of the test section is at a height of 1.5 m and has a mesh attached to it in order to retain the entrained particles.

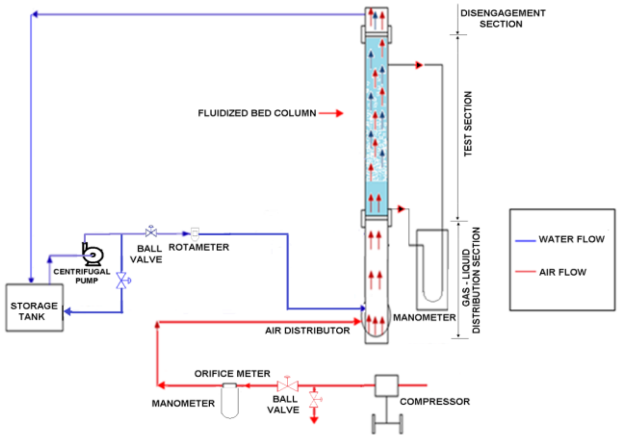

Fig. 1. Experimental setup.

There are two pressure tapings provided at the top and the bottom of the test section which are connected to the manometer for pressure drop measurement. Mercury and Carbon tetra chloride are used as manometer liquids for measuring the pressure drop across the rotameter and the orifice meter, respectively. Gypsum particles of sizes 0.0842×10^{-2} m, 0.1676×10^{-2} m and 0.2818×10^{-2} m are used for Newtonian fluid, water and 0.0767×10^{-2} m, 0.1753×10^{-2} m and 0.2591×10^{-2} m are used for 0.1%, 0.2% and 0.3% of Non Newtonian fluid, CMC for mass transfer studies. The solid particles are supported on a perforated stainless steel mesh containing 300 spaced holes of 0.05×10^{-2} m each. The experiment is conducted with internals and without internals. Internals are coaxially placed ten spherical ceramic balls of 2.5×10^{-2} m diameter fitted on a rod which is used as a promoter. The liquid velocity is kept constant and the gas velocity is varied. For each gas velocity, the fluidized bed height and manometer readings are noted when steady state is attained. The same procedure is repeated for four different liquid velocities with and without internals. Volumetric flow rate, superficial gas velocity and the corresponding bed heights are measured. After thrice the residence time, about 60 ml of the sample solution that is coming out of the fluidized bed is collected and analyzed for its total calcium sulphate content by volumetric titration method.

III. Results and Discussion

The experimental results obtained from mass transfer studies shows the variation of Sherwood number with the variation in important parameters considered in the study. From Fig. 2 to Fig. 5, it is observed that the Sherwood number increases with increase in Modified Reynolds number for both gas and liquid phases in the case of water.

TABLE I: Properties of Gypsum Particles Used.

Particle size d_p(m)	True density kg/m^3
0.000842	2240
0.001676	2143
0.002818	2190
0.0007671	2849.7
0.001753	2744.6
0.002591	2727.5

TABLE II: Properties of Air and Water.

Fluid	Densit y Kgm^{-3}	Viscosit y Nsm^{-2}
Air	1.15	0.000019
Water	995.6	0.0085

TABLE III: Properties of CMC Used.

CMC Conc.%	Density kg/m^3	Viscosity measurement	
		K kg/ms^{2-n}	n
0.1	1180	0.0081	0.93
0.2	1200	0.02	0.88
0.3	1230	0.26	0.85

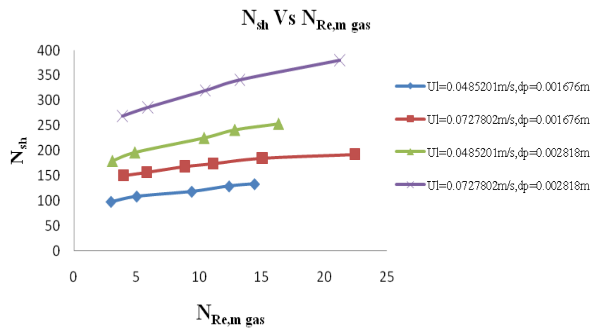

Fig. 2. N_{Sh} vs $N_{Re,m,gas}$ (Without internals).

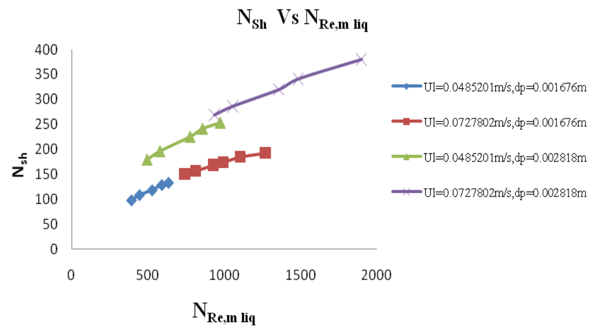

Fig. 3. N_{Sh} vs $N_{Re,m,liq}$ (Without internals).

However, the Fig. 6 and Fig. 7 show that the effect of Modified Reynolds number on the Sherwood number is less pronounced in the case of CMC solution. In the case of water, the presence of internals increases the Sherwood number but for CMC solution, the presence of internals decreases the Sherwood number. For both water and CMC solution, the Sherwood number increases with increasing particle size.

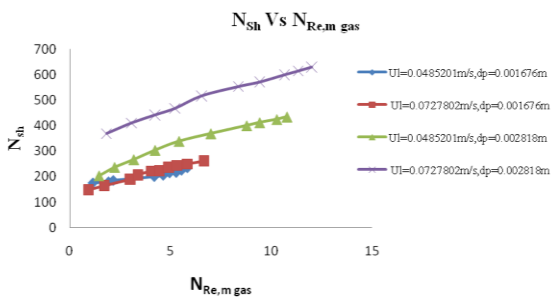

Fig. 4. N_{Sh} vs $N_{Re,m,gas}$ (With internals).

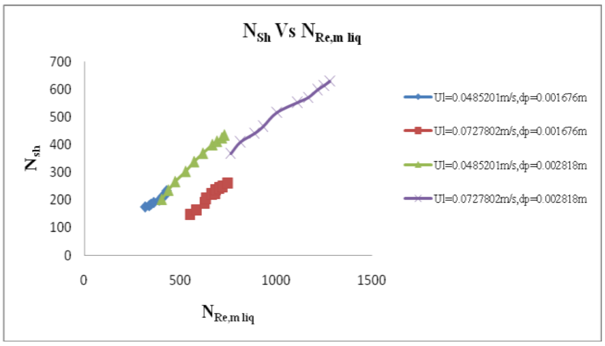

Fig. 5. N_{Sh} *vs* $N_{Re,m,liq}$ (With internals).

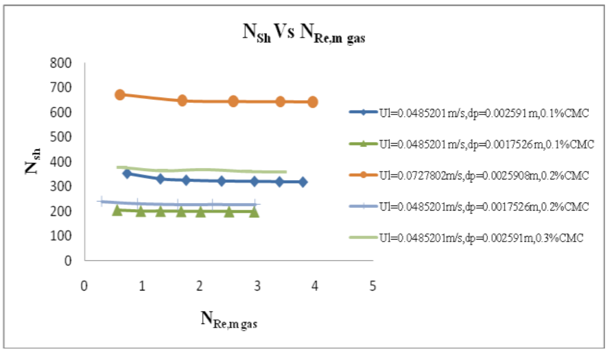

Fig. 6. N_{Sh} *vs* $N_{Re,m,gas}$ (Without internals).

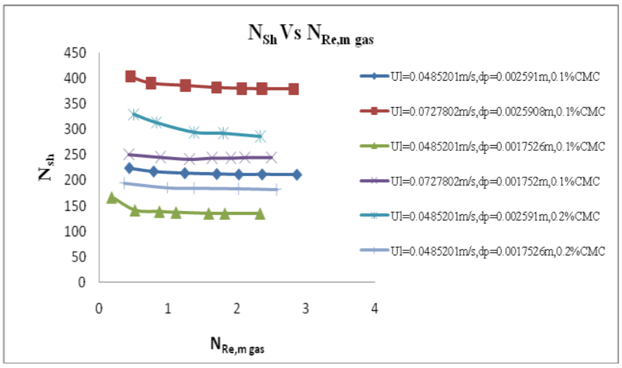

Fig. 7. N_{Sh} *vs* $N_{Re,\ m,\ gas}$ (With internals).

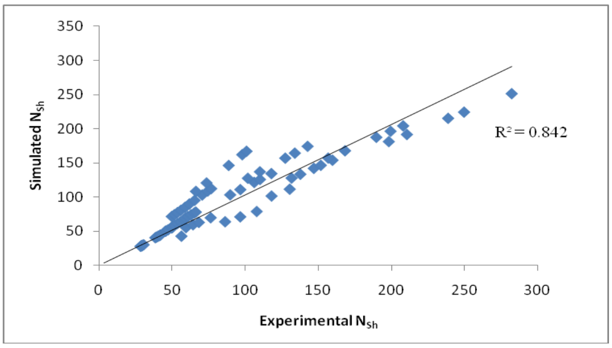

Fig. 8. Simulated N_{Sh} *vs* Experimental N_{Sh} (Without internals, Newtonian).

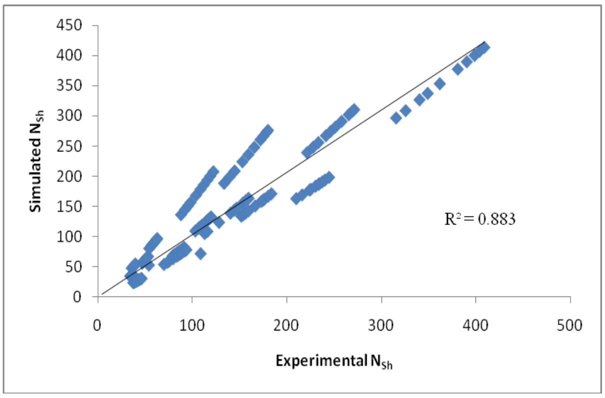

Fig. 9. Simulated N_{Sh} *vs* Experimental N_{Sh} (With internals, Newtonian).

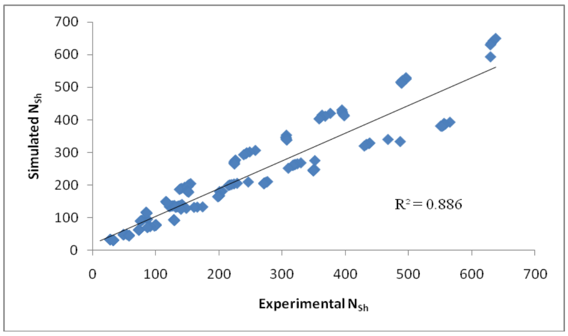

Fig. 10. Simulated N_{Sh} *vs* Experimental N_{Sh} (Without internals, Non Newtonian).

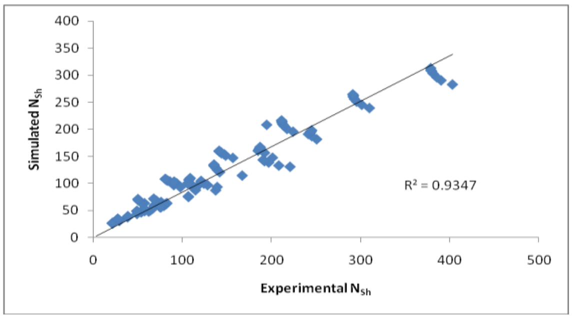

Fig. 11. Simulated N_{Sh} *vs* Experimental N_{Sh} (With internals, Non Newtonian).

It has been observed using hydrodynamic studies that as the Modified Reynolds number (either for gas or liquid) increases, the solids and liquid hold-ups decreases, but the gas hold-up increases for both water and CMC solutions [14]–[17]. Also, it has been found that solids holdup are less, where as liquid and gas holdups are slightly more for CMC solutions than water. An increase in the gas holdup in the system means there are more gas bubbles leading to vigorous mixing, which can result in the reduction in boundary layer resistance and enhancement of mass transfer rate. These effects are more pronounced in CMC solution, which is denser and more viscous when compared to water. Hence, there is a pronounced increase in Sherwood number with increase in Modified Reynolds number for water, but the influence is marginal for CMC solutions.

The presence of internals in the column enhances turbulence and mixing of phases leading to better mass transfer rates. However, these effects are more pronounced in water when compared to CMC solutions. Hence, the observed Sherwood numbers are higher for water with internals in the column. The fluidizing solids, because of their convective motion in the column, help in the breakup of bigger gas bubbles into smaller sizes and also promote efficient dispersion of these bubbles in the column. The combined motion of the smaller gas bubbles and solids can lead to higher turbulence and mixing, which in turn enhances the mass transfer from solid phase to liquid phase. Now, when the solid particle size increases it would be heavier and interactions between heavier solid particles lead to more break up of gas bubbles. Hence, this explains the observed trend of increasing Sherwood numbers with increasing particle sizes. Using the experimental data obtained for Sherwood number, empirical correlations involving dimensionless groups are proposed with the help of dimensional analysis. MATLAB 7.0 software has been used to arrive at the final expressions which are given from Equations (1) to (4).

Water – solids system without internals

$$N_{Sh} = 0.9298\ (\varepsilon_s)^{0.1379}\ (N_{Re,m\ liq})^{0.6030}\ (N_{Ar})^{0.1046} \quad (1)$$

Water – solids system with internals

$$N_{Sh} = 0.1578\ (\varepsilon_s)^{0.1079}\ (N_{Re,m\ liq})^{0.7515}\ (N_{Ar})^{0.2091} \quad (2)$$

CMC solution - solids system without internals

$$N_{Sh} = 3.7818\ (\varepsilon_s)^{1.0665}\ (N_{Re,m\ liq})^{0.9869}\ (N_{Ar})^{0.0599} \quad (3)$$

CMC solution - solids system with internals

$$N_{Sh} = 1.4822\ (\varepsilon_s)^{0.6993}\ (N_{Re,m\ liq})^{0.8928}\ (N_{Ar})^{0.1250} \quad (4)$$

IV. Conclusion

Mass transfer studies were carried out in a co-current three phase fluidization system for Newtonian and non Newtonian fluids. The gaseous medium was air in all the cases. The Newtonian liquid and the non Newtonian liquids used were water and various concentrations of CMC respectively.

Gypsum particles of various sizes were used as solid phase. Mass transfer characteristic of co-current three phase fluidization, were determined in terms of Sherwood number. It was observed from the investigation that the Sherwood number is influenced by gas as well as liquid superficial velocities, whether the liquid is water or CMC solution, whether column has internals or not and also the solid particle size. The presence of internals in the column has not significantly influenced the Sherwood number for mass transfer. This may be due to the fact that the geometry as well as the size of the internals chosen in the work has not contributed to the enhancement of turbulence and mixing of phases.

From the experimental data, correlations were proposed for Sherwood number comprising of solids holdup, Reynolds number and Archimedes number using Linear Regression Analysis. The simulated values were compared with experimental values graphically for Newtonian and non Newtonian fluids, with and without internals. From Fig. 8 to Fig. 11, The R^2 values were found to be closer to 0.9 for all the cases, which implies that the proposed correlations generate satisfactory results with minimal error.

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