Petroleum and Coal

Article **Open Access**

SCALE EFFECTS ON THE HYDRODYNAMICS AND FLOW REGIME TRANSITION OF SLURRY BUBBLE COLUMN: EXPERIMENTAL AND CFD STUDY

*Safaa M.R. Ahmed, Suhaib S. Saleh, Saba A. Gheni**

Department of Chemical Engineering University of Tikrit, Iraq

Received April 21, 2019; Accepted July 1, 2019

Abstract

The Fischer–Tropsch (FT) synthesis on a large scale attracts a lot of attention. It represents a smart innovation to convert low cost natural gas to high-profit fuel and products. Scaling up of such a continuous heterogeneous process needs a very precise determination of hydrodynamic variables with relation to slurry bubble column dimensions and catalyst loading. This study aims to employ a large-scale slurry bubble column in a flow transition study with the aid of computational fluid dynamics. In this study, two flow conditions were considered, periodic and steady state flows. The experimental and computational work have been carried out to study the performance of a scaled-up slurry reactor under the two different modes of operation. The impact of key parameters that enhances or alter the performance of slurry reactor is studied, namely, superficial gas velocity (0.05, 0.1, 0.15, 0.2, 0.25 and 0.35 m/s), solid loading (8, 12 and 15%), and cycle period; short and long periods. A laboratory unit was constructed to conduct this study. A mimic feed and solid loading were used to exclude the impact of chemical reaction and to focus intensively on the hydrodynamics. Air – paraffin oil – silica system was used for the hydrodynamic experiments. The results revealed that the transition flow was accompanied with an observed much lower average liquid flow rate compared to steady state operation at different study conditions of superficial gas velocity average liquid velocity. It also showed that scaling up influenced steady state flow boundaries compared to the same conditions with the lab scale reactor studied previously. On computational part, it was shown that period operation was short and less influent at low liquid flow are and solid loading.

Keywords: *Slurry bubble column; Large scale; period operation; hydrodynamics; CFD.*

1. Introduction

Slurry bubble column reactors are widely utilized nowadays in several applications in chemical and petrochemical processes. These processes include [1]: oxidation, hydrogenation, chlorination, alkylation, polymerization [2], methanol and Fischer–Tropsch (FT) synthesis [3], membrane technology [4], green technology [5] etc. As the international oil price is increasing obviously, the processes of gas-to-liquid transformation in Fischer–Tropsch (FT) technology has gained a lot of attention and turn into a more feasible industrial process [6]. Also, they become an interesting process for research to increase productivity and upgrade the liquified fuel. Slurry reactors are the heart of Fisher-Tropsch technology; therefore, they evoke a large design effort. Despite slurry column reactor shows excellent efficiency of heat transfer, easiness in construction and maintenance continuous catalyst addition, replacement and withdrawing, and a reasonable rate of mass transfer at the interface along with minimal energy input, its multiphase flow behaviors are very complex, and scale-up effects are significant. Also, although design of reactor and catalyst and progressive development of the process, the application of Fischer Tropsch technology is limited because of the large capital, operational and maintenance costs required for the process compared to the available conventional technologies [6]. Thus, more extensive research is still necessary to develop, design and implement a higher performance slurry column reactor [7]. To develop a precise scale-up of the slurry reactor for Fischer–Tropsch process, it is needed to obtain an appropriate characterization of flow pattern and hydrodynamics such solid, liquid and gas holdups, heat transfer performance, residence time distribution, mass transfer at the interface between gas and liquid along with solid catalyst. All these parameters have to be studied against reactor dimensions (reactor diameter and height) and operating conditions in slurry system such as catalyst loading, operating pressure and superficial gas velocity [8].

The objective of the present study is to describe and evaluate the influence of scale up on the performance of slurry reactor as a function of different key operating variables.

2. Experimental work

In the present work, experiments were carried out in a large scale polymethyl methacrylate column (0.45 m diameter and 2.92 m height) designed and constructed in Chemical Engineering Department University of Missouri Science and Technology, USA. Figure 1 shows the experimental rig and specifications of the components are shown in Table 1.

The system mimic Fischer–Tropsch process consists of C_{10}-C_{12} normal paraffine oil (mixture of decane, undecane, and dodecane, supplied from Sasol Chemicals LLC, (USA) Houston TX), compressed air and silica powder. A 241 holes (3 mm diameter) perforated plate diffuser was used and the holes were arranged in a square pitch configuration. Two mass flow meters were used to control gas and oil flow rates. Three superficial gas velocity were tested; 0.1, 0.15, 0.2, 0.25, 0.3 and 0.35 m/s, and three solid loading were examined; 8, 12 and 15% and a constant liquid flow rate of 0.03 m/s. The silica powder was impregnated with paraffin oil for 24 hrs before operation to ensure complete wetting and adequate liquid distribution at the time of experimentation. Five points were monitored along the height of the column via an optical probe to obtain the hydrodynamic measurements; 14, 28, 42, 56 and 70" at the center of the column with tips facing downwards. The details of this innovative instrument were characterized elsewhere [9]. A time-based gas holdup is obtained by the technique and it is different from the one reported by Xue *et al.* [10], which was based on volume. Thus, the local gas holdup obtained in the present study is defined as [10]:

$$\varepsilon_{g,T} = {T_G}/{T} \qquad (1)$$

where, T_G is the time the probe tip spends in the gas phase (bubbles) and T is the total measuring time [10].

Figure 2 shows an illustration of the probe. To ensure accurate experimentation, the probability distribution analysis was employed at the desired operating conditions of the gas hold up and superficial gas velocity. The percentage of standard deviation was determined at less than 10% for the examined operating conditions.

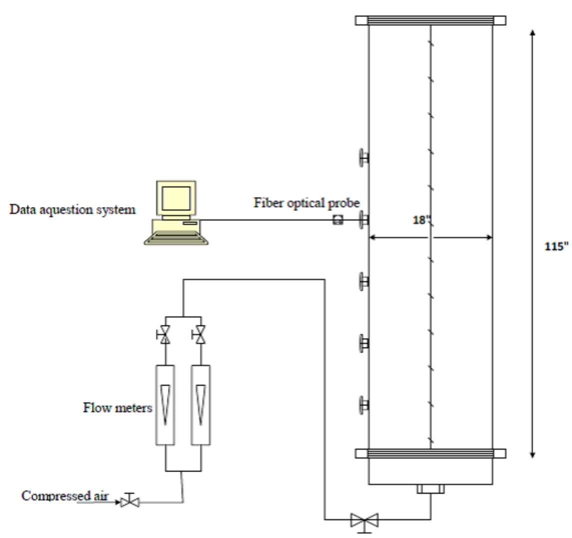


Figure 1. Experimental setup

Table 1. Specifications of experimental setup

Item number	Name	Specifications
1	Slurry bubble column	Vertical polymethylmethacrylate cylinder, 0.45 m diameter, 2.92 m height.
2	Mass flow meters	RS485 flow Range 0-200 L/min, Accuracy ±(2.0+0.5FS) % Response Time ≤2 sec
3	Compressor	Honda GX160 OHV, floating-type, 8-Gallon Twin Tank, 13.7 CFM at 90 Psi
4	Optical probe	Fiber optic cables with glass cores of 200 μm arranged in the geometrical configuration. The bundle is jacketed with four polymer layers.,
5	Computer	Core i5-2450M, hard disk capacity of 1 TB and memory 16 G. 17" monitor
6	Interface and data log-ger	SD card logging with Matlab code. Voltage of 0 V to fit into the processing program. Accuracy 0.5%- offset adjustment possible.
7	Gas distributor	Perforated cupper plate (3 mm dia holes, free plate area 0.13%)

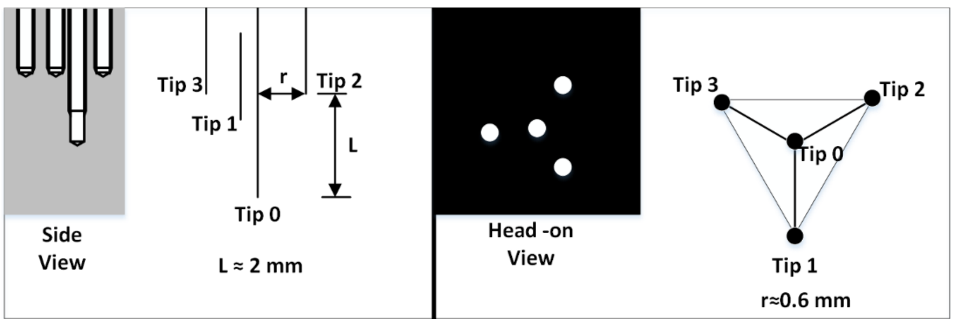


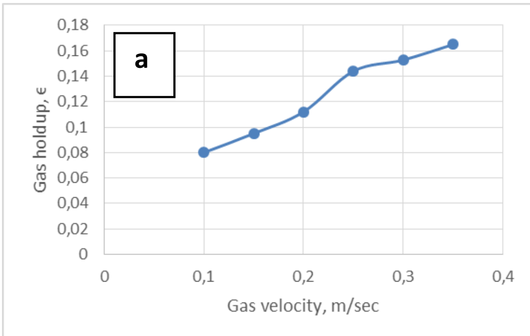
Figure 2. Optical fiber probe [12]

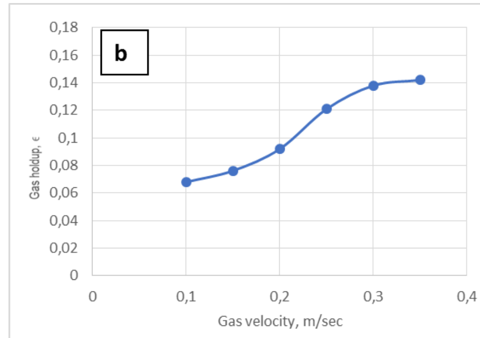
3. Results and discussion

3.1. Steady state operation

In a slurry bubble column, contact between three phases resulted in different flow regimes. Generation of these regimes occur at different flow rates of gas and liquid, flow conditions and physical properties of the interacted materials (gas, liquid and solid). In order to establish a map of transition from homogeneous to heterogeneous regimes, a matrix of experiments was conducted in a broad range of different solid loading and gas flow rates for long cyclic period (steady state operation).

Figure 3 shows the transition boundary from homogeneous to heterogeneous regime as a function of the superficial gas velocity with 8%, 12% and 15% solid loading for air-paraffin oil system. It indicated from Figure 3 that transition from homogeneous at low loading of 8% depends on gas velocity and boarder than the one obtained by Gheni *et al.* [11] with small scale slurry bubble. As solid loading increases to 12%, zone of homogeneous shrinkages and more volume is occupied by clouds and solid. At constant superficial gas velocity of air, a shift towards homogeneous region is observed. As more space is provided in the present work density of solid in this region became less and the homogenous zone gets larger. The flow regimes encountered in the column are established as a result of a balance between the driving forces (inertia and gravity), shear stress and surface tension resisting forces. Thus, adding more solid powder increases surface tension and gravity due to increase of viscosity of slurry system. Also, solid loading incorporates with a low gas flow rate to generate a heavier intertrial force on bubbles flow upward to result in large coalesced bubbles (slugs). The liquid film formed around the bubble in the cylindrical column acquire a uniform thickness because of the circular section and absence of the corners. This gives a reliable mimic accounting for liquid film in slurry bubble system compared to rectangular section mimic reactor utilized elsewhere [12-14] and closer to industrial Fisher Tropsch reactors. The maximum film thickness located at the centerline of the wall in the cross-sectional plane (see Figure 3).





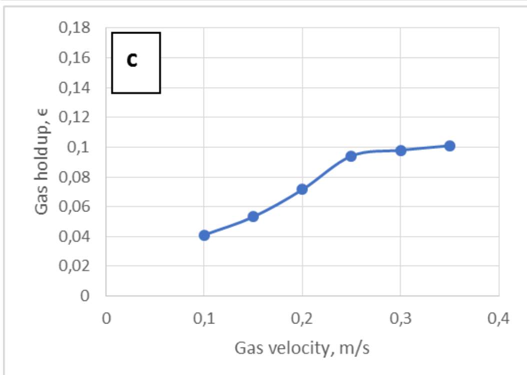


Figure 3. Flow regime transition in oil-silica-air slurry bubble column at different solid loadings (a) 8% (b) 12% (c) 15% at steady state operation

3.2. Periodic operation

One of the main objectives of the present work was to observe the effect of switching liquid flow between ON and OFF modes and cycle period on hydrodynamic parameters of slurry bubble column reactor at a relatively large scale. The periodic parameters were tested under the same conditions examined at steady state study. The unsteady state periodic operation mode has attracted broad attention and a growing interest because many studies have shown the reactor performance can be improved significantly by periodic operation [15-17].

The principle of periodic operation is to force a flowing system to operate continuously in a transient mode rather than relaxing to a steady state [15]. In the present study, the slurry bubble column reactor was operated in a periodic mode at a cyclic period of 5 minute to examine the impact of cyclic operation on hydrodynamics of the slurry bubble column reactor. Figure 4 shows regimes transition at different solid loadings at periodic operation. It is clearly seen that gas holdup obtained at periodic operation is much less than those obtained at steady state. This may attribute to the high surface tension and force of inertia exerted on bubbles dispersed through slurry and they did not let the bubbles to interfere with the oil phase and grow to a larger size bubble. It is also attribute to the short time of contact with oil and residence time in the slurry bubble column. It also shows that operation with higher solid loading resulted in more regimes transitions compared to steady state and instability of operation. However, the low density and moderate density experiments reveal a semi stable transition to heterogeneous flow Although the transition region was boarder, the gas holdup in heterogenous region was almost uniform which is regarded as an important parameter in Fisher Tropsch process. The cyclic operation in slurry bubble column reactor may alter the average interfacial area between gas and liquid, making the determination of mass transfer parameters and experimental acquirement of data in slurry bubble column challenging.

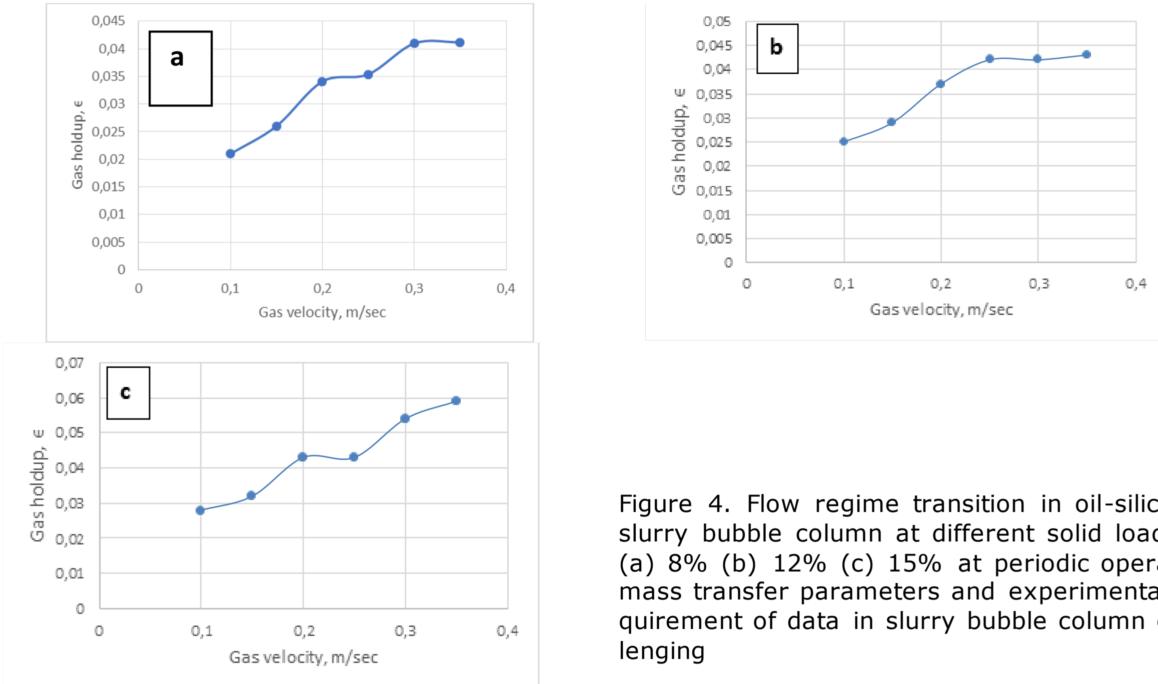


Figure 4. Flow regime transition in oil-silica-air slurry bubble column at different solid loadings (a) 8% (b) 12% (c) 15% at periodic operation mass transfer parameters and experimental acquirement of data in slurry bubble column challenging

3.3. Computation fluid dynamics of the system

In order to validate the experimental observations, computational fluid dynamics (CFD) simulation of a slurry bubble columns operating at steady state and cyclic state is implemented at the examined conditions of this study. A population balance modeling (PBM) was utilized in this part of the study. It has received an unprecedented amount of attention during the past few years from both academic and industrial quarters because of its applicability to a wide variety of particulate processes [18]. To validate the experimental results, PBM was employed and solved numerically using the bubble class method [19]. Figure 5 shows comparison between experimental and simulated results at steady and period states of operation. 12% solid loading and 0.35 gas velocity were chosen as a basis of comparison. It is observed that the local gas holdup for both steady state and simulated results are close at the examined conditions and period results still deviate from both simulated and steady state operations at most of the tested ratios of length to diameter.

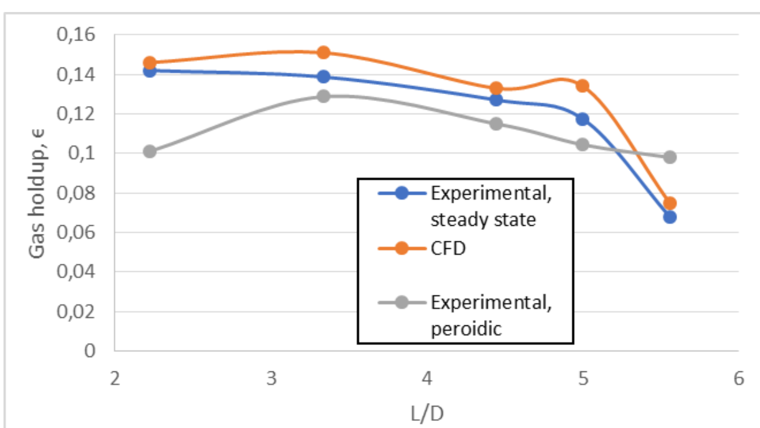


Figure 5. Flow regime transition in oil-silica-air slurry bubble column at 12% solid loadings and 0.35 m/sec gas velocity at steady state and periodic operation compared to CFD simulation at different L/D ratios

4. Conclusions

A large-scale experiment was conducted in a slurry bubble column to visualize and determine the impact of steady state and periodic operation on behavior of paraffin oil-silica powder and air system at different solid loadings and gas flow rates. It was showed that a periodic operation reveals the lowest gas holdup and enhances mixing between phases. It was also shown that regime transition between homogeneous and heterogenous zones are broader than the transition observed previously with water-silica-air system in a small-scale column. The simulated results in CFD showed a good validation of the experimental results of steady state operation and large deviation from the results obtained at periodic operation. Large difference in gas holdup was observed along the height of the column which in turn very influential in industrial applications.

References

[1] Deckwer W-D, Alper E. Katalytische suspensions reacktoren. Chem. Eng. Technol., 1980; 52: 219-228.
[2] Shah YT, Kelkar BG, Godbole SP, Deckwer W-D. Design parameter estimation for bubble column reactors. AIChE J., 1982; 28: 353-379.
[3] Dry ME. The SASOL route to fuels. Chem Tech., 1982; 12: 744-750.
[4] Rahimpour MR, Jokar SM, Jamshidnejad Z. A novel slurry bubble column membrane reactor concept for Fischer–Tropsch synthesis in GTL technology. Chemical Engineering Research and Design. 2012; 90(3):383–396.
[5] Sehabiague L, Basha O, Morsi BI. Recycling of tail gas in Fischer-Tropsch bubble column slurry reactor and its impact on the coal-to-liquid process. In Proceedings of the 30th Annual International Pittsburgh Coal Conference, Beijing, China, 2013.
[6] Nafees A, and Al Hashimi SH. Fischer Tropsch Gas To Liquid Technology (GTL). The Second International Energy 2030 Conference. Abu Dhabi, U.A.E., November 4-5, 2008.
[7] Wang T, Wang J, and Jin Y. Slurry Reactors for Gas-to-Liquid Processes: A Review. Ind. Eng. Chem. Res., 2007; 46 (18): 5824–5847
[8] Krishna R, van Baten J. A Strategy for Scaling Up the Fischer–Tropsch Bubble Column Slurry Reactor. Topics in Catalysis, 2003; 26(1-4): 21-28.
[9] Youssef A and Al-Dahhan MH. Impact of Internals on the Gas Holdup and Bubble Properties of a Bubble Column. Industrial & Engineering Chemistry Research, 2009; 48(17): 8007–8013.
[10] Xue J. Bubble Velocity, Size and Interfacial Area Measurements In Bubble Columns, PhD Dissertation, Washington University, St. Louis 2004.
[11] Ghani SA, Yaqub RJ and Saleh SS. Experimental Study of Volumetric Mass Transfer Coefficients in Slurry Bubble Column Reactor. J. Chem. Eng. Process Technol., 2012; 3: 3
[12] Gheni S, Abdulaziz YI, Al-Dahhan MH. Effect of L/D Ratio on Phase Holdup and Bubble Dynamics in Slurry Bubble Column using Optical Fiber Probe Measurements. International Journal of Chemical Reactor Engineering, 2016; 14. 10.1515/ijcre-2015-0035.
[13] Khodaparast S, Atasi O, Deblais A, Scheid B, and Stone HA. Dewetting of Thin Liquid Films Surrounding Air Bubbles in Microchannels. Langmuir, 2018; 34 (4): 1363–1370.
[14] Ahmed FS, Sensenich BA, Gheni SA, Znerdstrovic D, Al Dahhan MH. Bubble dynamics in 2d bubble column: comparison between high-speed camera imaging analysis and 4-point optical probe. Chemical Engineering Communications, 2015; 202, 1.
[15] Silveston PL, Hanika J. Challenges for the periodic operation of trickle-bed catalytic reactors. Chemical Engineering Science. 2002; 57(16): 3373-3385.
[16] Boelhouwer JG, Piepers HW, and Drinkenburg BAH. Advantages of forced non-steady operated trickle bed reactors. Chem. Eng. Technol,. 2002; 25: 647-650.
[17] Liu G, Duany Y, Wang Y, Wang L. Periodically operated trickle reactor for EAQs hydrogenation: experiments and modeling. Chem. Eng. Sci., 2005; 60: 6270-6278.
[18] Ramkrishna D, Mahoney AW. Population balance modeling. Promise for the future. Chemical Engineering Science, 2002; 57(4): 595-606.
[19] AH Syeda M Boulet, Melchioria T, Lavoie J-M. CFD simulation of a slurry bubble column: Effect of population balance kernels. Computers and Fluids. 2018; 175: 167-179.

To whom correspondence should be addressed: Dr. Saba A. Gheni, Department of Chemical Engineering University of Tikrit, Iraq